# Understanding and predicting wave erosion of marsh edges

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[1] Margin lateral erosion is arguably the main mechanism leading to marsh loss in estuaries and lagoons worldwide. Our understanding of the mechanisms controlling marsh edge erosion is currently quite limited and current predictive models rely on empirical laws with limited general applicability. We propose here a simple theoretical treatment of the problem based on dimensional analysis. The identification of the variables controlling the problem and the application of Buckingham's theorem show, purely on dimensional grounds, that the rate of edge erosion and the incident wave power density are linearly related. The predictive ability of the derived relationship is then evaluated, positively, using new long-term observations from the Venice lagoon (Italy) and by re-interpreting data available in previous literature.
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## 1. Introduction

[2] Tidal marshes evolve "horizontally", as a result of lateral erosional processes, and "vertically", as a net result of (organic and inorganic) deposition, surface erosion, and relative sea level rise. Much attention has been devoted to the understanding and description of the processes which lead to observed equilibria in the vertical direction, or lack thereof, producing a rather comprehensive understanding of the controlling biological and physical processes [*Allen*, 1990; *Morris et al.*, 2002; *D'Alpaos et al.*, 2007; *Kirwan and Murray*, 2007; *Marani et al.*, 2007; *Mudd et al.*, 2009; *Marani et al.*, 2010]. On the contrary, "lateral" evolution mechanisms have received comparatively much less attention, even though marsh degradation associated with edge erosion is arguably the chief mechanism by which marshes in coastal areas worldwide are being lost [*Schwimmer*, 2001; *Gedan et al.*, 2009; *van de Koppel et al.*, 2005; *Mariotti and Fagherazzi*, 2010]. Briefly, the current process understanding relates the erosion of a cliffed marsh edge (see Figure 1) to the fluctuating forces exerted on the margin by wave impact, which produces the removal of the bank material. Vegetation may reduce erosional processes in the root zone, but cannot prevent the undercutting of the margin, such that its role in reducing lateral erosion is uncertain [*Feagin et al.*, 2009]. Bank instability due to water table fluctuations forced by the tide and erosion associated with tidal currents are typically negligible [*Schwimmer*, 2001], and waves are usually recognized as the dominant erosional agent. This conceptual framework has been collectively built by relatively numerous literature contributions on the erosion of cliffed margins, often not in relation with tidal marshes [*Gelinas and Quigley*, 1973; *Rosen*, 1977, 1980; *Kamphuis*, 1987; *Sunamura*, 1992; *Wilcock et al.*, 1998; *Schwimmer*, 2001; *Feagin et al.*, 2009; *Mariotti and Fagherazzi*, 2010], but we still lack a systematic understanding of existing observational evidence, whose interpretation usually takes the form of empirical relationships with little general validity.

[3] Here we use dimensional analysis to produce a theoretical interpretation of a large set of observations of marsh retreat rates in the Venice lagoon associated with wave energy estimates obtained from observed wind-forcing and a wave model. The results show that indeed a general interpretation of marsh margin erosion mechanisms is possible, yielding a theoretically based predictive expression linking margin retreat to the impinging wave power density.

## 2. Dimensional Analysis

[4] Previous work seeking expressions for a margin retreat rate, $R$ (e.g., in m/yr), take the form of an empirical power law of the type $R = a \cdot \overline{P}_i^b$, where $\overline{P}_i$ is the mean power density (computed over a sufficiently long and representative period) of incident waves (i.e., wave power per unit length of the marsh margin, expressed in W/m) and $a$ and $b$ are site-dependent parameters, with $b$ = 1.10–1.37 [*Gelinas and Quigley*, 1973; *Rosen*, 1977, 1980; *Kamphuis*, 1987; *Sunamura*, 1992; *Schwimmer*, 2001]. Some of these works do not deal with tidal marshes, but are often referred to in the tidal literature as specific works are relatively rare [*Schwimmer*, 2001]. Recently, *Mariotti and Fagherazzi* [2010] proposed another non-linear relation, of the type $R = c \cdot (\overline{P}_i - P_c)$, where $P_c$ is a critical threshold below which no erosion occurs.

[5] These approaches, however, do not try to derive the erosion rate from a theoretical framework, and rather simply rely on empirical regressions or ad hoc assumptions. Here we attempt to construct a rational and more general framework, based on dimensional analysis. As commonly observed in many marshes worldwide [*Möller et al.*, 1999; *Schwimmer*, 2001; *van de Koppel et al.*, 2005], we consider the schematic case of a vertical cliff margin facing a nearly horizontal tidal flat having mean depth $d$ with respect to mean sea level (Figure 1). This configuration refers to the widely observed case in which resuspension by waves and tidal currents are able to remove the material deposited in front of the margin as a result of erosive processes. The height of the cliff with respect to the tidal flat bottom is $h$. We note that this is a relevant quantity for the description of erosion processes as $V = R \cdot h$ is the volumetric erosion rate, i.e., the volume of sediment per unit length of the margin which must be removed in order to produce a retreat rate equal to $R$. We also note that this same volume of sediment must be removed for

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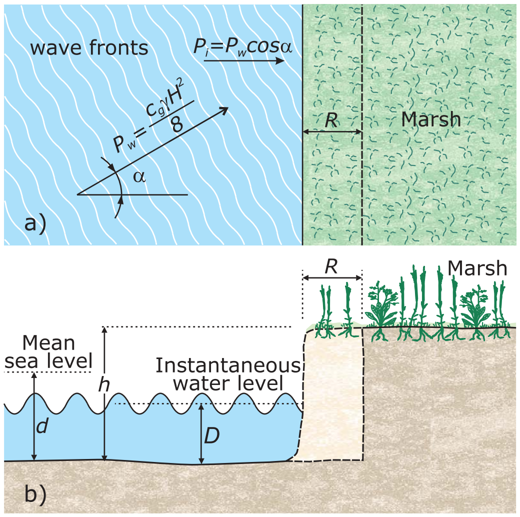


**Figure 1.** (a) The power density associated with incoming waves, $P_w$, is distributed on the marsh margin according to the cosine of the angle between the direction of wave propagation and the normal to the marsh margin itself. (b) Identification of the variables controlling the erosion of a cliff marsh margin.

erosion to proceed at rate $R$, irrespective of whether it is removed progressively or in discrete slump blocks. It is reasonable to assume that the mean absorbed power density, $\overline{P}_a$, necessary to produce $R$ will be dependent on the work required to remove the volume $V$. Further, we assume that the mean power density absorbed by the marsh margin is proportional to the mean incident wave power density, $\overline{P}_a = \epsilon\overline{P}_i$, where $0 < \epsilon < 1$ is an absorption coefficient. Finally, to complete the list of relevant variables, one must consider the sediment properties (including possible strengthening effects associated with plant roots), here represented by an (effective) "cohesion" term, $c$ ($Nm^{-2}$), expressing the susceptibility of the soil to be removed by incident waves. We have thus identified the following list of variables necessary to produce a description of cliff erosion processes: (1) $R$ $[L\ T^{-1}]$: retreat rate; (2) $\overline{P}_i$ $[M\ L\ T^{-3}]$: mean wave power density striking the cliff face; (3) $h[L]$: cliff face height with respect to the tidal flat bottom; (4) $d[L]$: tidal flat bottom depth with respect to mean sea level; (5) $c[M\ L^{-1}\ T^{-2}]$: sediment effective "cohesion", where length, $L$, time, $T$, and mass, $M$, are the fundamental units entering the dimensions of the variables defining the problem.

[6] We now apply the well-known Buckingham's, or Π, theorem of dimensional analysis, establishing that, if a process is described in terms of $N_v$ dimensional variables ($N_v = 5$ in the present case), which are expressed in terms of $N_u$ fundamental units (here $N_u = 3$), then it can be described in terms of $N_v - N_u$ non-dimensional groups [*Langhaar*, 1951]. It follows that the description of marsh margin erosion can be formulated in terms of $N_v - N_u = 2$ non-dimensional parameters, which can be freely chosen among all possible couples of independent non-dimensional groups. We choose the following two non-dimensional groups:

$$\Pi_1 = \frac{Rhc}{\overline{P}_i}$$

$$\Pi_2 = \frac{h}{d}$$

The erosion process is then described by a relationship between the two non-dimensional groups:

$$\frac{Rhc}{\overline{P}_i} = f\left(\frac{h}{d}\right) \qquad (1)$$

where $f()$ is an unknown function to be determined experimentally. It is important to note that equation (1) directly derives from the identification of the governing parameters and from Buckingham's theorem and that it establishes that both $\overline{P}_i$ and $R$ must appear linearly in the relationship linking them. Equation (1) thus establishes the linear dependence between $\overline{P}_i$ and $R$ on purely theoretical grounds. The ability of such a theoretical result to interpret experimental data must now be verified.

## 3. Materials and Methods

### 3.1. Data

[7] We use three sets of aerial photographs (Figure 2) acquired in 1955, 1970, and 2004, of several eroding marshes in different areas of the Venice lagoon not exposed to major boat traffic (which would induce increased retreat rates, not related with wind-forcing). All images were georeferenced to an accuracy of ±0.1 m, and the two couples of images (1970–1995 and 1995–2004) were superimposed to obtain a map of the eroding margins. The margins were then approximated through broken lines, i.e., using a suitable number of straight segments (Figure 2), which allow to uniquely define the direction orthogonal to the margins themselves, later used to compute the incoming wave power density. This latter quantity was estimated by assuming that wind and wave propagation directions coincide. We then considered hourly observations of wind (speed and direction) and tidal forcing for the entire year 2004 in two couples of stations, assumed to be representative of the typical "wind" and "tidal climate" in the northern and in the southern lagoon of Venice (see the auxiliary material for summary statistics on wind speed and direction).[1] These data, together with bathymetric information providing appropriate water depths for each of the two couples of images investigated, were used to generate a one-year sequence of hourly wind-wave heights. Such a sequence was assumed, in turn, to be representative of the typical wave forcing for each of the study areas throughout the periods of study (1970–1995 and 1995–2004).

### 3.2. The Wave Model

[8] The model used to simulate the wind waves is a version of the model developed by *Fagherazzi et al.* [2006] and *Carniello et al.* [2005, 2011]. Using an approach similar to the one described by *Young and Verhagen* [1996] and *Breugem and Holthuijsen* [2007], we first estimate the wave period $T = 3.5(gD/U^2)^{0.35} \cdot U/g$, on the basis of the observed wind speed, $U$, and the instantaneous value of the water depth, $D$.

[9] We then determine the wave number $k = 2\pi/\lambda$ ($\lambda$ being the wavelength) through the linear wave theory expression of phase celerity: $c_p = \lambda/T = (g/k\tanh(kD))^{1/2}$.

[10] Next, we assume that, owing to the relatively shallow depth characterizing tidal basins, the wavefield adapts rapidly to wind-forcing and requires a relatively short fetch (2–3 km)

[1]Auxiliary materials are available in the HTML. doi:10.1029/2011GL048995.

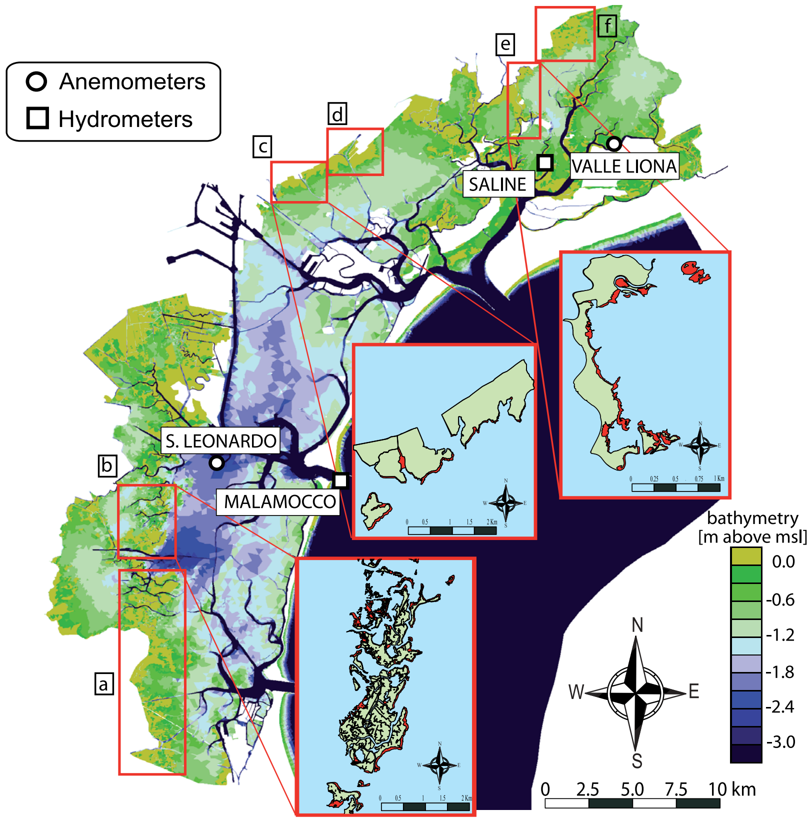


**Figure 2.** (a–f) Position of the study marshes considered in the Venice lagoon. Retreat (in red in the insets) is determined on the basis of aerial photographs for several segments along the margins of the six marshes. Also indicated are the tidal gauges (square symbols) and the anemometric stations (circles).

to attain fully developed conditions. As a consequence, neglecting temporal and spatial variations, a local equilibrium of wave energy sources and sinks is assumed, i.e., [*Fagherazzi et al.*, 2006]:

$$S_w(k, D, U, E) + S_{bf}(k, D, E) + S_{wc}(E) + S_b(E) = 0 \qquad (2)$$

where $E = \gamma H^2/8$ is the wave energy per unit length of the wavefront and $H$ is the significant wave height. $S_w = \psi_1(k, d, U) + \psi_2(U)E$ is the energy flux transmitted by the wind to the water surface [*Willmarth and Wooldridge*, 1962; *Barnett*, 1968]; $S_{bf} = -\psi_3(k, d)E$ is the flux of energy dissipated by bottom friction [*Collins*, 1972]; $S_{wc} = -\psi_4(k, d)E^3$ is the flux of energy dissipated by white capping [*Komen et al.*, 1984]; and $S_b = -\psi_5(H, k)E$ is the flux of energy dissipated by breaking of the waves. $\psi_j$ ($j$ = 1,5) are known functions reported in detail by *Fagherazzi et al.* [2006].

[11] Equation (2) allows the estimation of $E$, of $H = (8/\gamma \cdot E)^{1/2}$, and of the power density associated with the wavefront:

$$P_w = \frac{c_g \gamma H^2}{8} = c_g E \qquad (3)$$

$c_g$ being the wave group celerity:

$$c_g = \frac{1}{2} c_p \left(1 + \frac{2kD}{\sinh(2kD)}\right) \qquad (4)$$

The systematic and sequential application of the above relations thus produces hourly time series of the wave power density for the two areas of the Venice lagoon considered. We note that, because of the widespread erosion experienced in the Venice lagoon over the twentieth century due to an overall negative sediment balance [*Marani et al.*, 2007] (the 1970 bathymetry was used for the analysis of the 1970–1995 period, while the 2002 bathymetry was used for the 1995–2004 period), the tidal measurements used to force the wave model (from year 2004) correspond to different water depth time series at the locations considered here. In turn, this determines different time series of wave power density for the two periods analyzed.

[12] For a marsh margin forming an angle $\alpha$ with the wave propagation direction (Figure 1), the instantaneous incident wave power density is:

$$P_i = P_w \cos\alpha \qquad (5)$$

For each segment used to approximate the marsh margins, the hourly observed wind direction allows us to compute the time-dependent value of $\alpha$ and, through equation (5), we can then compute the hourly incident wave power density, $P_i$. An estimate of $\overline{P}_i$ for each margin segment is finally obtained by averaging the hourly values, $P_i$, by exclusion of those time intervals in which the measured tidal level is above the marsh platform elevation. In this case, in fact, the energy absorbed by the scarp face decreases sharply [*Tonelli et al.*, 2010], such that the contribution to the erosion of the margin is in this case negligible. To further support this choice we also performed estimates of $\overline{P}_i$ which included contributions from time intervals in which the water level is above the marsh surface. We found that the scatter in the

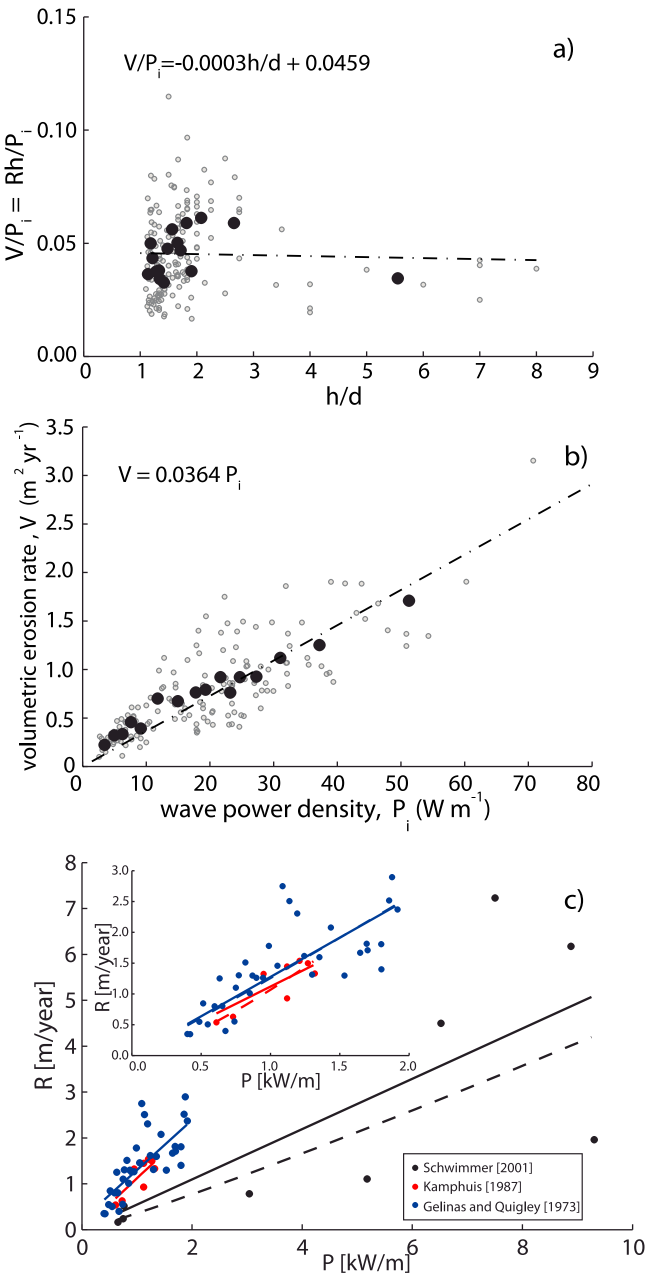


**Figure 3.** (a) The linear regression of $V/\overline{P}_i$ versus $h/d$ gives a slope of 0.0003, supporting the independence of $V/\overline{P}_i$ from $h/d$ (see equation (1)). (b) This, in turn, supporting a proportionality between $V = R \cdot h$ and $\overline{P}_i$ ($R^2 = 0.61$). Solid black circles indicate values obtained by averaging data over regular 'bins' to emphasise the overall trends ($R^2 = 0.89$ for Figure 3b). (c) Summary of the observations from *Gelinas and Quigley* [1973], *Kamphuis* [1987], and *Schwimmer* [2001]. Solid lines indicate the linear fits, while the dashed lines indicate the power law fits. The inset in Figure 3c is a blowup of the region closer to the origin.

observational relation between $V$ (or $R$) and $\overline{P}_i$ is significantly increased, thus corroborating the above choice.

## 4. Results

[13] We plot $V/\overline{P}_i = R \cdot h/\overline{P}_i$ versus $h/d$ in Figure 3a, which, according to equation (1), provides an experimental characterization of $f(h/d)/c$. We find that $f(h/d)/c = R \cdot h/\overline{P}_i$ does not appreciably depend on $h/d$ in the range of values covered by the data. It is thus appropriate to take $f(h/d)/c$ as approximately constant: $f(h/d)/c \simeq a$. This simplifies the description of the problem and establishes the following proportionality:

$$V = R \cdot h = a\overline{P}_i \tag{6}$$

Figure 3b shows that indeed the experimental data (160 data points) from different parts of the lagoon and from different observational periods, are approximated quite well by a proportionality relationship between $\overline{P}_i$ and $V$, as indicated by equation (6). Single experimental points do exhibit a marked scatter, due to the several sources of uncertainties involved in the estimation of both the erosion rates and the wave power density values (e.g., image registration errors, image discretization errors, wind measurement instrumental errors, errors associated with the spatial heterogeneity of the wind field, wave model approximations, as well as the spatial variability of sediment properties and vegetation cover). The average values, however, are in very good agreement with a linear relationship, as shown by the "binned" points (solid black circles in Figure 3a), obtained by averaging experimental points over several non-overlapping sub-intervals.

## 5. Discussion

[14] On the basis of dimensional analysis and observations we have derived a linear relationship between the rate of volumetric margin retreat $V = R \cdot h$ (i.e., expressed in $m^2$/yr) and the mean annual wave power density, $\overline{P}_i$, which, if the cliff height, $h$, at a given site is constant in time, also implies a linear relationship between linear margin retreat $R$ (i.e., expressed in m/yr) and $\overline{P}_i$. The most commonly accepted view, on the contrary, assumes a power law relation between $R$ and $\overline{P}_i$ [*Schwimmer*, 2001; *Kamphuis*, 1987]. We suggest that such a power law assumption is the result of a subjective interpretation of the existing data, which can equally well be interpreted by the theoretically justified linear relationship (6) between retreat and mean incident power density (note also that the power law exponent proposed by *Schwimmer* [2001], $b$ = 1.1, is quite close to unity). Figure 3c summarizes the data available in the previous literature, which, in lack of cliff height information, have been plotted in the retreat versus power density plane. The graphical interpretation of the different datasets yields quite different slopes, which can be ascribed to differences in sediment properties (e.g., glacial till for *Gelinas and Quigley* [1973] and marsh sediment for *Schwimmer* [2001]), but also to the possibly different procedures used to estimate/measure incident wave energy, not fully described in some of the previous literature. The data are compared with power law and linear fits, the latter stemming from equation (6) when (the unknown) depth is assumed to remain constant during the time of the observations at each study site. Indeed, Figure 3c does not allow to conclude in favor of either the linear or the power law model on statistical grounds alone. Under such circumstances the linear model, supported by the results in Figure 3b and by theoretical arguments, appears to be preferable. We also note that the dimensional analysis approach proposed here has the significant advantage of allowing us to pool together all the available observations, irrespective of the specific cliff height

characterizing each single study site. This allows the derivation of more robust statistics and a greater generality of the conclusions that may be drawn from a statistical analysis applied collectively to diverse study sites. The specific value of the proportionality constant linking power density and retreat in equation (6) is clearly site-dependent (e.g., it contains the effective cohesion term, $c$, which must be a function of sediment and vegetation properties) and requires the analysis of site-specific data. However, the robustness of the common trend emerging in Figure 3b, in spite of the several possibly neglected spatial heterogeneities (e.g., in wind forcing, depth, material, vegetation cover), the theoretical support afforded by dimensional analysis, and the compatibility with previous literature results, provide a remarkable support on the wide validity of the proposed proportionality between $R$ and $\overline{P}_i$.

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