LIMITS OF WETLAND WAVE DISSIPATION

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Wetlands provide a natural protective buffer against coastal storms by dissipating wave energy, but there is limited quantitative information to evaluate the effectiveness of such natural features over a range of hydrodynamic conditions. Laboratory experiments were conducted in a large-scale flume with artificial vegetation. The measurements show good agreement to the wave dissipation formulation of Mendez and Losada (2004). Drag coefficients correlated well with Reynolds number for the submerged vegetation, but emergent vegetation gave higher coefficients than the submerged vegetation. Applying the drag coefficients derived from the lab, the efficiency of vegetation dissipation was explored analytically. For dense vegetation (400 stems/m^2), it was found that significant reductions in wave height (50%) are possible over tens and hundreds of meters for relative depths (depth times wavenumber) less than 1.5. The distance required to dissipate wave energy increases exponentially as water depth increases. A hypothetical field example using the spectral wave model STWAVE with the Mendez and Losada (2004) expression for wave dissipation is also presented. The field example shows reduction in wave height of 70-80 percent along the shoreline for extensive vegetation coverage during severe wind and surge conditions. These hypothetical simulations demonstrate the potential for vegetation to reduce the storm intensity at the coast by reducing wave height under severe wind and water level conditions. However, the simulations cannot show whether the vegetation's capacity to reduce storm damages can be sustained during storms or over longer periods of time as wetlands evolve.

Keywords: wetlands, vegetation, wave dissipation, STWAVE, engineering with nature

INTRODUCTION

Recent hurricanes have brought severe flooding due to waves and surge to the US Gulf of Mexico (Katrina, Rita, Ike, and Isaac) and Northeast coastlines (Irene and Sandy). Post-storm analysis of Hurricane Katrina (USACE 2006) indicates the importance of wetlands in reducing wave energy (Wamsley et al. 2009). Restoration or construction of wetlands is one solution being discussed to reduce future storm damage in hard-hit areas using Engineering with Nature concepts. Many studies point out the value of wetlands in attenutating waves (e.g., Koch et al. 2009, Gedan et al. 2011, Day et al. 2007, Barbier et al. 2008), but also highlight significant gaps in knowledge: how do wetland properties vary in space and time, at what point does submergence negate the benefits of wetlands, what is the dependence of wetland extent on wave height reduction, and what is the optimal combination of grey and green infrastructure. Through physical and numercial modeling, this paper explores the benefits and limitations of wave attentuation by vegetation on a project scale.

A number of data sets acquired in the lab and field have been used to quantify wave dissipation due to vegetation. These experiments include a number of vegetation types and scales (from small scale laboratory experiments to hurricanes in the field), but most have a very limited range of wave parameters and water levels. Also, few have included emergent vegetation or variable vegetation density.

This paper describes laboratory measurements of wave dissipation by artificial vegetation that mimics *Spartina alterniflora,* a common grass found in brackish intertidal marshes along the Atlantic and Gulf coasts. The laboratory measurements were used to evaluate the wave dissipation formulation of Mendez and Losada (2004) for random waves and to develop a relationship for the drag coefficient for the laboratory vegetation. The effectiveness of vegetation in dissipating wave energy was investigated through analytical methods using a realistic range of wave and water depth parameters. The Mendez and Losada dissipation function was implemented in the steady-state spectral wave model STWAVE (Massey et al. 2011, Anderson and Smith 2014b), and then the model was applied to hypothetical variations of vegetation coverage in Jamaica Bay, New York. Wave heights under severe wind and water level conditions were simulated, and the effectiveness of the vegetation coverage in dissipating wave energy was evaluated.

LABORATORY MEASUREMENTS

A laboratory study investigating dissipation of wave energy by artificial *Spartina alterniflora* was performed at the Engineer Research and Development Center in a large-scale flume (Anderson and Smith 2014a). The concrete flume is 63.4-m long, 3-m wide, and 1.5-m deep, with glass viewing

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windows along the vegetation test section. A plywood false floor was constructed in the flume to elevate the vegetation test section, as shown in Figure 1. Control runs with no vegetation were made prior to adding vegetation to the test section. The artificial vegetation was constructed from 6.4-mm diameter polyolefin tubing, which mimics the motion and buoyancy of natural *Spartina* vegetation. The tubing has a similar diameter to *Spartina*, is flexible under wave action, and remains upright in emergent conditions. The tubing was cut into 0.415-m lengths and installed on the plywood bottom using screws and construction adhesive. The vegetation was installed in a staggered, diamond-shaped pattern with a stem density of 200 stems/m^2. Later, additional stems were installed to achieve a density of 400 stems/m^2. The length of the vegetation field was 9.8 m.

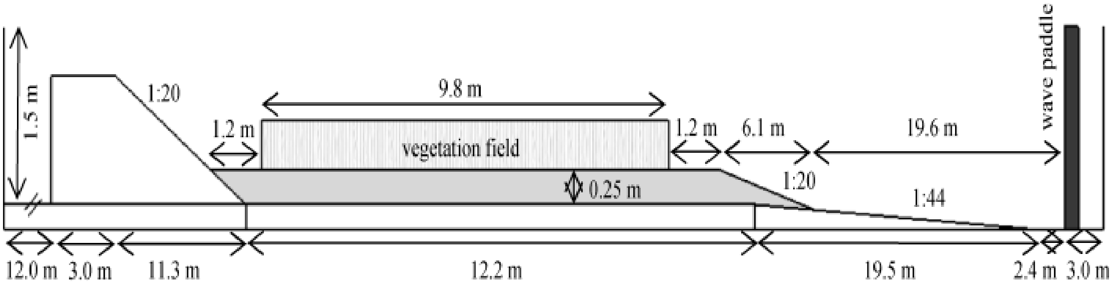

Figure 1. Laboratory configuration.

The study focused on irregular wave trains with wave heights of 5.0 – 19.2 cm, peak periods of 1.25 – 2.25 sec, water depths of 30.5 – 53.3 cm (in the vegetation section), and stem densities of 0, 200 and 400 stems/m^2. Waves were measured with 13 single-wire capacitance wave gauges. A three-gauge array was located near the wave generator to estimate wave reflection in the flume, one gauge was 0.9 m seaward of the vegetation field, and nine gauges were variably spaced within the vegetation field. Wave gauges were sampled at 25 Hz for 8 minutes. Three water depths were used in the tests: 30.5, 45.7, and 53.3 cm, which correspond to a wetted stem length to water depth ratio of 1.36 (emergent), 0.91, and 0.78. Experiments were highly repeatable over three replications. The maximum standard deviation was less than 3 mm for the measured wave heights. Figure 2 shows a photograph of the vegetation under wave action. The range of stem Reynolds numbers ($Re = u_c b_v/\nu$, where u_c is the maximum horizontal orbital velocity at the top of the stems, b_v is the stem diameter, and ν is the kinematic viscosity of water) for the tests was 550 to 2100. The range of Keulegen-Carpenter numbers ($KC = u_c T_p/b_v$, where T_p is the peak wave period) was 27 to 103.

Figure 2. Artificial vegetation under wave action.

DRAG COEFFICIENT PARAMETERIZATION

The bulk drag coefficient C_D for the flume measurements was calculated from the lab data based on the empirical model proposed by Mendez and Losada (2004):

$$\varepsilon_v = \frac{1}{2\sqrt{\pi}}\rho C_D b_v N\left(\frac{gk}{2\sigma_p}\right)^3 \frac{\sinh^3 k_p\alpha d + 3\sinh k_p\alpha d}{3k_p\cosh^3 k_p d} H_{rms}^3$$

where ε_υ is the energy dissipation per unit area, ρ is the density of water, N is the density of the vegetation in stems/m^2, g is acceleration due to gravity, k_p is the peak wave number, σ_p is the peak angular wave frequency, α is the ratio of the stem length to the water depth, d is water depth, and H_{rms} is the root-mean-square wave height. The bottom friction coefficient (C_{bfr}) was estimated from runs without vegetation assuming an exponential form for the wave height dissipation,

$$H_{mo2} = H_{mo1}\exp\left(\frac{a u_{rms}\Delta x}{c_g}\right)$$

Where $a = C_{bfrg}/g\,(\sigma_p/(\sinh k_p d))^2$ and solving for the bottom friction coefficient:

$$C_{bfr} = -\ln\left(\frac{H_{mo2}^2}{H_{mo1}^2}\right) g\left(\frac{T_p}{2\pi}\right)^2 \frac{\sinh^2 k_p d}{u_{rms}}\frac{c_g}{\Delta x}$$

where H_{mo} is the zero-moment wave height (the subscript 2 indicates the most landward wave gauge and subscript 1 indicates the gauge at the seaward end of the vegetation patch), c_g is the group celerity, T_p is the peak wave period, u_{rms} is the amplitude of root-mean-square horizontal wave velocity, and Δx is the distance between the seaward and landward gauges. The bottom friction coefficient was estimated as a function of Reynolds number as $C_D = 4620/Re + 0.0144$. With the bottom friction coefficient parameterized, the drag coefficient was then estimated from:

$$\frac{\partial H_{mo}^2}{\partial x}c_g = -\frac{C_{bfr}}{g}\left(\frac{2\pi}{T_p}\frac{1}{\sinh\ kd}\right)^2 H_{mo}^2 u_{rms} - \left(\frac{g^2 T_p^{\,3}}{2\sqrt{2\pi}L_p^{\,3}}\right)\frac{\sinh^3 k\alpha d + 3\sinh k\alpha d}{3k\cosh^3 kd} H_{mo}^3 C_D b_v N$$

where L_p is peak wave length, and α was capped at a value of 1.0. Again, an exponential form was assumed for the wave height decay, and C_D was solved for each run as:

$$C_D = \frac{-\ln\left(\frac{H_{mo2}^2}{H_{mo1}^2}\right) - \frac{C_{bfr}}{g}\left(\frac{2\pi}{T_p}\right)^2 \frac{1}{\sinh^2 kd} u_{rms}\frac{\Delta x}{c_g}}{\frac{g^2 T_p^{\,3}}{2\sqrt{2\pi}L^3}\frac{\sinh^3 k\alpha d + 3\sinh k\alpha d}{3k\cosh^3 kd} H_{mo}\frac{\Delta x}{c_g} b_v N}$$

Figure 3 shows the relationship between C_D and the Reynolds number. Although the expression for drag coefficient will vary based on vegetation type, the data clearly show the expected linear relationship of exponential wave energy dissipation with vegetation density (the 200 and 400 density data sets fall on the same line). The drag coefficient is independent of vegetation density. Considering only the data from the submerged vegetation runs, the regressed expression for C_D is given by $C_D = 910/Re + 0.22$ with a standard error of 0.034. The cluster of data lying above this line (at $C_D \approx 1$) is from the emergent cases. The drag coefficient is approximately 15-20 percent higher for the emergent cases, perhaps because the stem motion with the waves wets an additional portion of the stem. For these tests, removing the cap of 1.0 on α (increasing the value α to 1.36 for the 30.5 cm water depth) collapsed these outlaying points into alignment with the submerged points, but clearly this would not be a general result. Additional experiments are currently ongoing to explore the transition from submerged to emergent conditions. The fit to the KC number for submerged conditions was $C_D = 39/KC + 0.22$ with a standard error of 0.12.

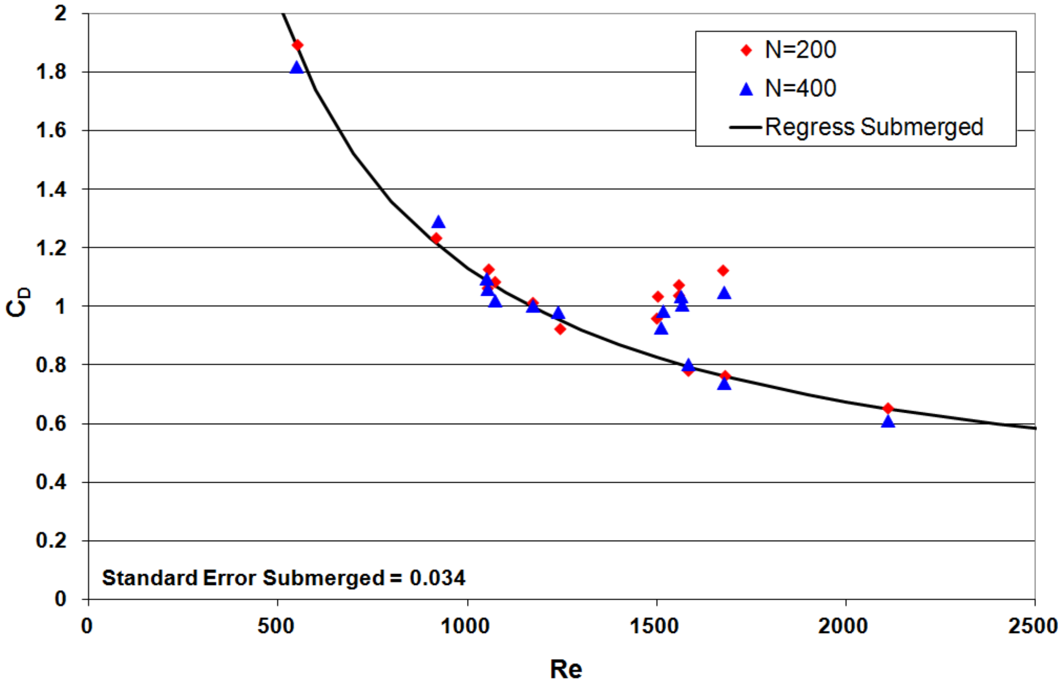

Figure 3. Drag Coefficient from lab experiments as a function of Reynolds Number.

EFFECTIVENESS OF VEGETATION

Applying a realistic range of wetland and wave parameters, the expression for C_D derived from the lab data were applied to evaluate the effectiveness of vegetation in dissipating waves. Assuming an exponential form of wave decay

$$H_{mo2} = H_{mo1} \exp\left(\frac{-bH_{mo}\Delta x}{c_g} \right)$$

where

$$b = \frac{g^2}{2\sqrt{2\pi}} C_D b_v N \left(\frac{k_p}{\sigma_p} \right)^3 \frac{\sinh^3 k_p \alpha d + 3\sinh k_p \alpha d}{3k_p \cosh^3 k_p d}$$

and solving for the distance to decay the wave height by 50 percent, $\Delta x_{50\%}$, the following equation was derived:

$$\Delta x_{50\%} = \frac{-\ln(0.25)c_g}{\frac{g^2}{2\sqrt{2\pi}} C_D b_v N \left(\frac{T_p}{L} \right)^3 \frac{\sinh^3(k\alpha d) + 3\sinh(k\alpha d)}{3k\cosh^3(kd)} (0.75H_{mo})}$$

The vegetation is assumed to have a diameter of 0.006 m, a length of 0.5 m, and a density of 400 stems/m^2. The water depth was varied from 1 m to 10 m, periods ranged from 3 to 12 sec, and the wave height applied was a maximum depth-limited height (Smith et al. 1997):

$$H_{mo_{\max}} = 0.1L\tanh(kd)$$

Only submerged vegetation cases were considered. The results are shown in Figure 4. The degree of submergence strongly impacts the distance required to dissipate wave energy, and the relative distance required to reduce the wave height by 50 percent increases exponentially with water depth (note the log scale). For values of *kd* greater than 1.5, the wetland becomes ineffective. For large surges, hundreds of meters or even many kilometers of wetlands are required to provide the same protection from waves as tens of meters of wetlands in near emergent conditions. Although waves with long periods are more effectively dissipated, that effect is exaggerated in Figure 4 through the nondimensionalization by wave length (wave length increases much more with water depth for a 12 sec wave than a 3 sec wave). The incident wave height has a relatively small impact on the distance required to dissipate the wave height by 50 percent. This analysis neglects the regeneration of waves if strong winds continue to pump energy into the waves as they propagate through the wetland.

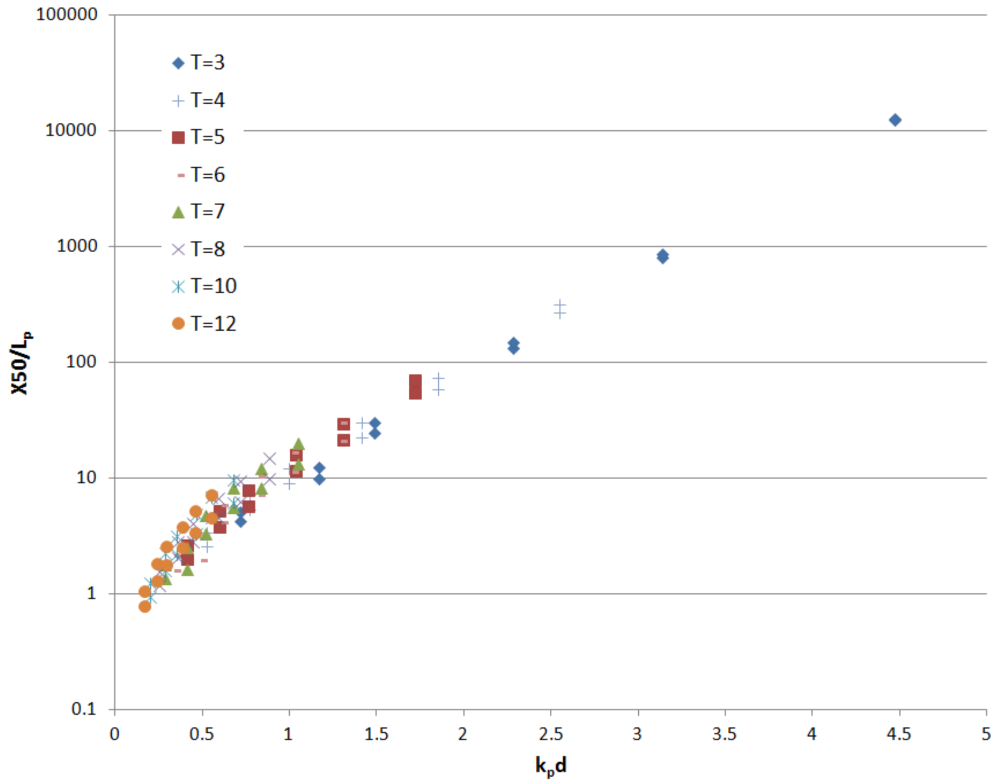

Figure 4. Nondimensional distance to dissipate 50 percent of wave height as a function of relative depth, for a range of wave periods and water depths.

FIELD EXAMPLE

The Mendez and Losada (2004) expression for wave dissipation due to vegetation was implemented into the STWAVE spectral wave model (Anderson and Smith 2014b, see also Suzuki et al. 2011) with input parameters of spatially-variable C_D and vegetation properties (diameter, length, and density). STWAVE was applied for hypothetical storms to provide an example of the impact of wetlands in reducing wave height on a landscape scale. The wetland area modeled was Jamaica Bay, New York. Jamaica Bay is bounded by Rockaway Peninsula to the south and has a connection to the Atlantic through Rockaway Inlet to the southwest. Jamaica Bay has been suffering wetland loss in the past century. The existing bathymetry for Jamaica Bay within the STWAVE domain is shown in Figure 5. The STWAVE grid resolution is 50 m by 50 m, and the domain is 8,250 m by 10,750 m. Four vegetation coverages were developed for the area (Figure 6), including no vegetation, existing vegetation, moderately increased vegetation, and extensively increased vegetation. For the moderate and extensive vegetation, the bathymetry was also altered to provide realistic depths in vegetated areas. The vegetation in the area is *Spartina alterniflora* in the low marsh, *Spartina patens* in the high marsh, and *Phragmites* in the disturbed marshes. In vegetated areas, the parameters were set to constant values of $C_D = 0.35$, $N = 400$ stems/m^2, $b_v = 0.006$ m, and vegetation length = 0.4 m. These values were not measured in the field, but are consistent with the literature (e.g., Jadhav et al. 2013). For each vegetation/bathymetry configuration, three wind and water level conditions were applied: 18.5 m/s winds with a 1.3 m superelevation of the water level, 22.1 m/s winds and a 2.0 m superelevation of the water level, and 26.0 m/s winds with a 2.9 m superelevation of the water level. These relate roughly to a 99-percent, 10-percent, and 1-percent annual water level exceedence. A constant wind direction from the south was applied.

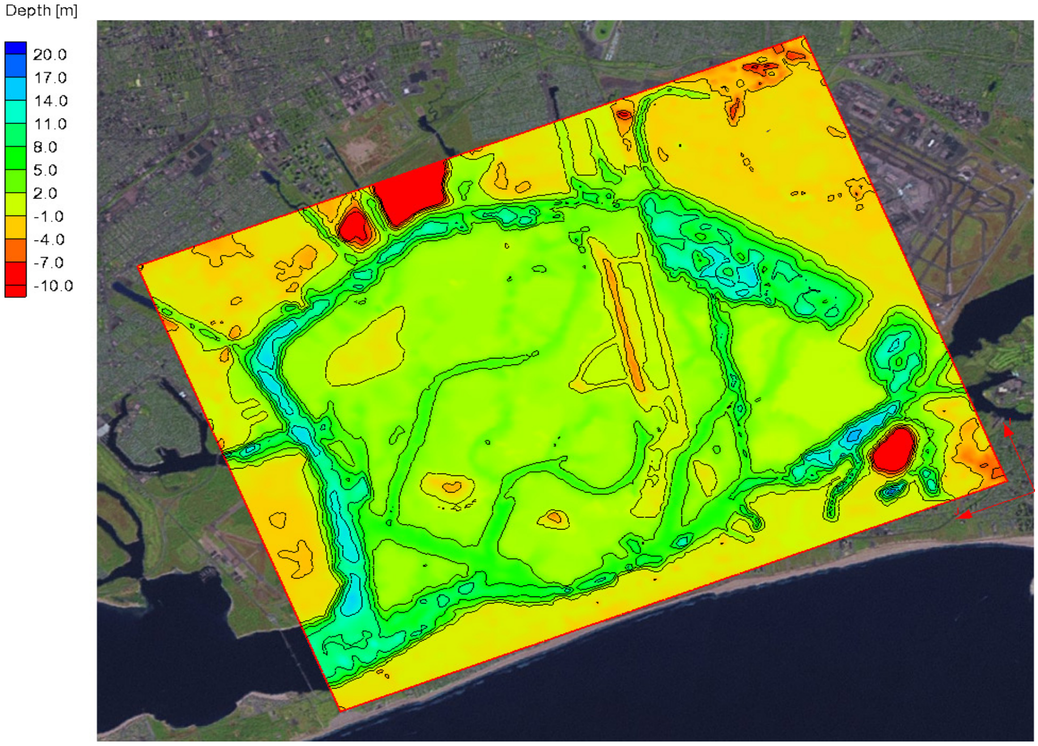

Figure 5. Existing bathymetry in Jamaica Bay (relative to mean sea level).

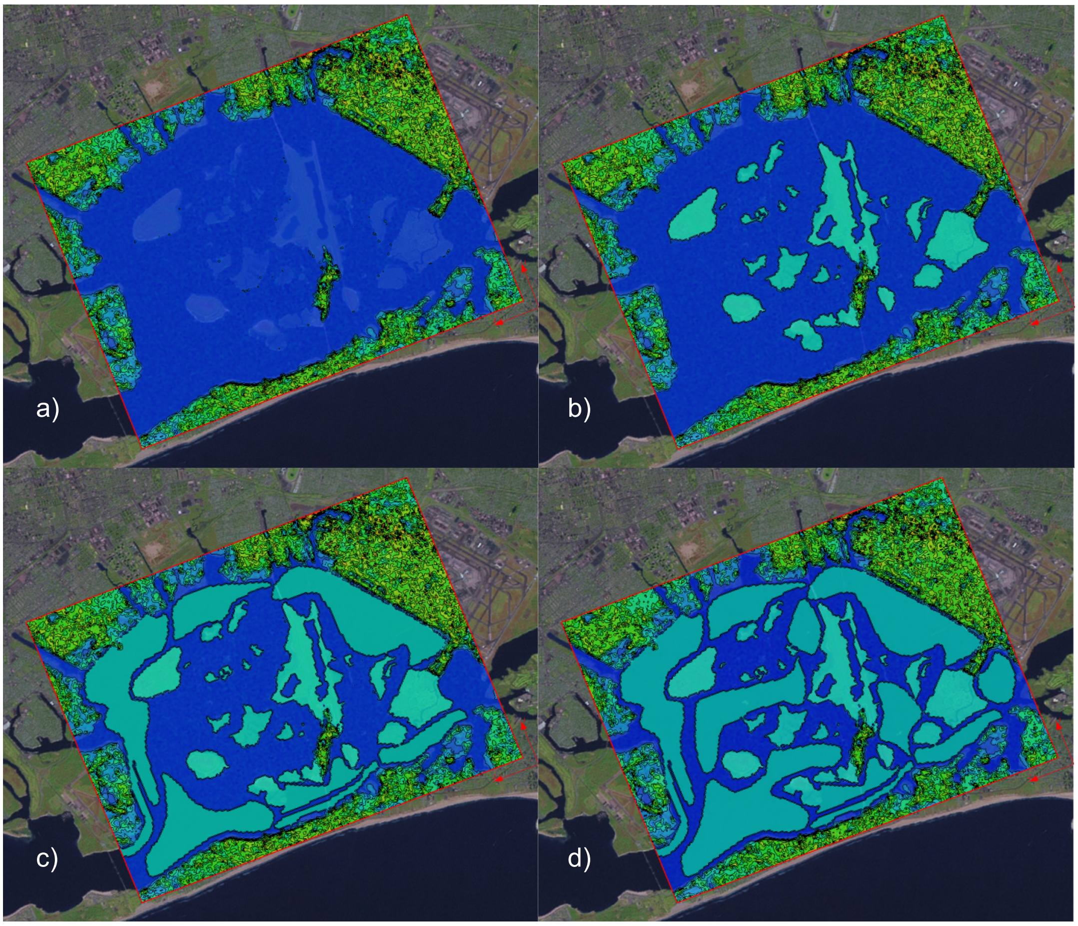

Figure 6. Vegetation coverages for a) no vegetation, b) existing vegetation, c) moderate vegetation, and d) extensive vegetation (ight blue indicates vegetated areas).

Figure 7 shows the wave heights for the most severe of the three cases, south wind of 26 m/s and elevated water level of 2.9 m, for all four vegetation coverages. The trends for the other wind and water level simulations were similar. Waves grow from south to north, with the largest waves on the northern shoreline of the bay. The complexity of the wave height patterns result from a combination of depth-limited wave heights over shallow bathymetric features and from vegetative dissipation. Both the moderate and extensive vegetation coverages show significant reductions in wave height along the shoreline of the bay. Even the limited existing vegetation shows benefits in reducing wave height. However, the vegetation parameters applied in these simulations were idealized and the actual height, diameter, and density of the existing vegetation may be less effective in dissipating wave energy.

Figure 8 shows the percent wave height reduction for the extensive vegetation coverage compared to the no vegetation case for the maximum wind and surge. Large regions on the northern shoreline of the bay have wave height reductions of 70-80 percent. Part of the wave height reduction is attributed to the vegetation and part is from the bathymetric changes required to sustain vegetation. Figure 9 separates these two factors (note that the combined depth-limited breaking and the vegetation damping are not linear, so the separation is not linear). Figure 9a shows the percent wave height reduction due to vegetation only by turning the vegetation dissipation off and on for the extensive vegetation case. Figure 9b shows the percent wave height reduction due to the bathymetry modifications by comparing the extensive vegetation bathymetry with vegetation turned off and the existing bathymetry case. These simulations show that the majority of the dissipation along the shoreline is due to the vegetation, while some of the dissipation hot spots in the interior of the bay are due to bathymetry modifications made to support the vegetation. The moderate vegetation coverage also provides significant protection to the shore, but with less vegetation in the central bay, wave heights impinging on the vegetated areas are higher, which could reduce the robustness and sustainability of the wetland.

These idealized simulations demonstrate the potential for vegetation to provide shoreline protection by reducing wave height under severe wind and water level conditions (approximately 1-percent annual exceedence). However, the simulations cannot show whether the vegetation can be sustained in the short term (throughout a severe storm event) and the long term (e.g., is organic and mineral sedimentation sufficient to keep up with subsidence and sea level rise).

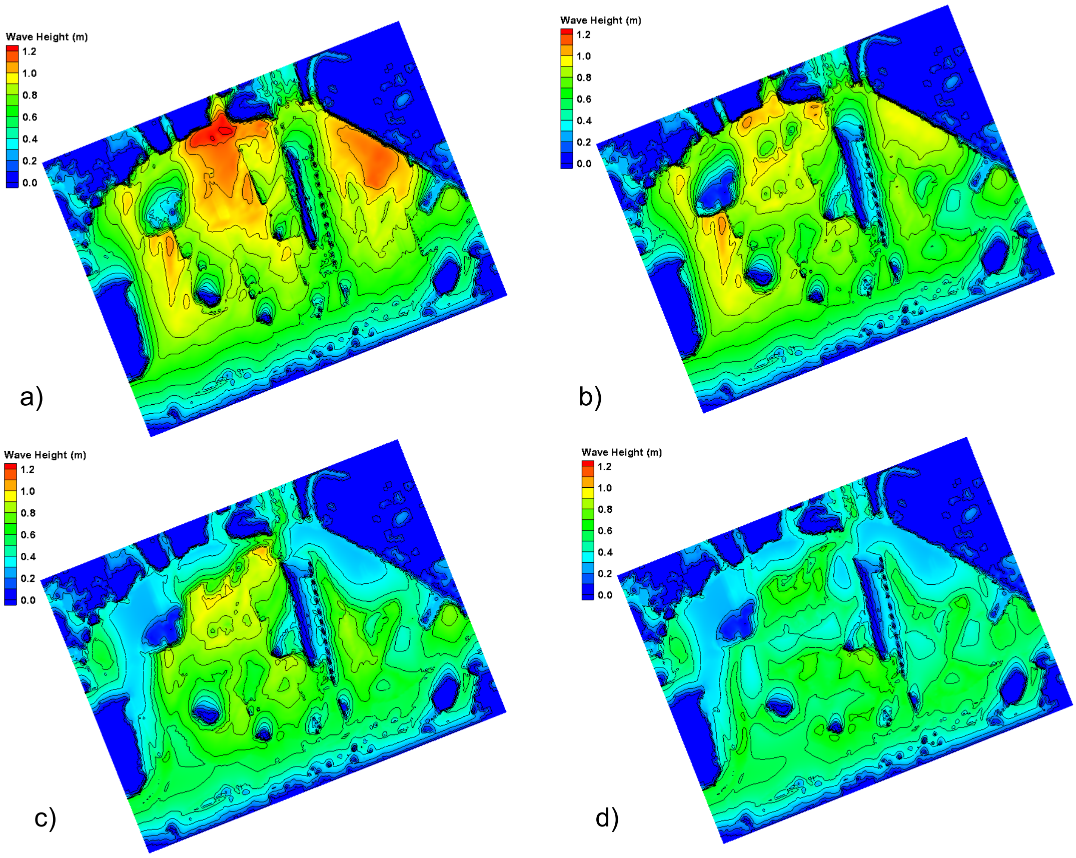

Figure 7. Wave heights for 26.0 m/s south winds and 2.9 m superelevation of the water level for a) no vegetation, b) existing vegetation, c) moderate vegetation, and d) extensive vegetation.

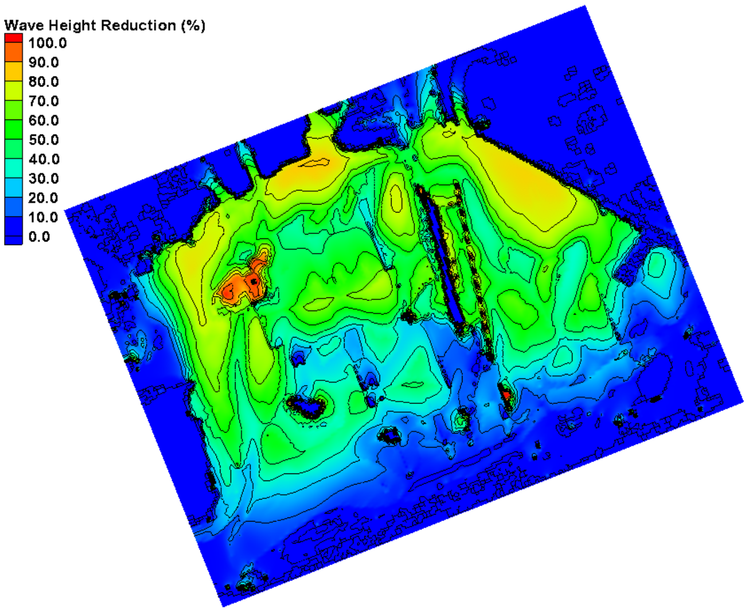

Figure 8. Percent wave height reduction for the extensive vegetation coverage compared to the no vegetation case.

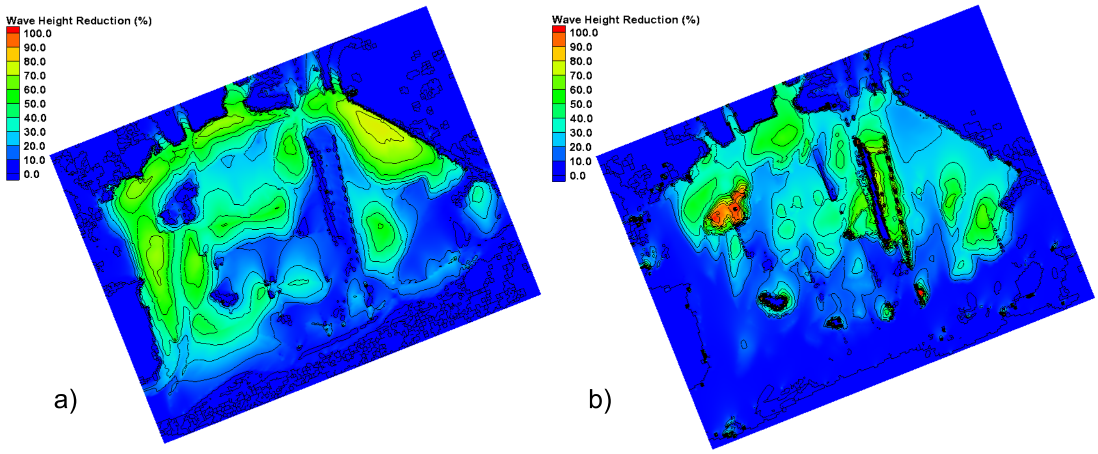

Figure 9. Percent wave height reduction for a) wave height reduction due to vegetation only (the extensive vegetation bathymetry with and without vegetation activated), and b) wave height reduction due to bathymetry only (the extensive vegetation bathymetry compared to the existing bathymetry without vegetation activated).

SUMMARY

Wetlands are a natural protective buffer from coastal storms. Tall, dense vegetation can significantly dissipate wave energy, even under moderate surge conditions. Laboratory experiments discussed herein showed good agreement for wave dissipation as compared to the formulation of Mendez and Losada (2004) using a calibrated drag coefficient. For the artificial vegetation flume experiments by Anderson and Smith (2014a), the drag coefficient correlated well with Reynolds number for the submerged vegetation. The drag coefficients for emergent vegetation were higher than that given by the relationship for submerged vegetation. Additional lab experiments are being performed to study wave dissipation for a range of emergent conditions. Applying the drag coefficients derived from the lab and realistic wave and vegetation conditions, the efficiency of vegetation dissipation was explored through analytical methods over a range of wave periods and water depths. For dense vegetation (400 stems/m^2), it was found that significant reductions in wave height (50%) are possible over tens and hundreds of meters for relative depths (kd) less than 1.5. The distance required to dissipate wave energy increases exponentially as the water depth increases.

The Mendez and Losada (2004) expression for wave dissipation due to vegetation was implemented in the STWAVE spectral wave model with spatially-variable C_D and vegetation properties. A hypothetical field example was provided for Jamaica Bay, New York, using STWAVE. The field example showed reduction in wave height of 70-80 percent along the shoreline for extensive vegetation coverage during severe wind and surge conditions. The reductions in wave height were caused by vegetation-induced dissipations as well as depth-limited breaking. The bulk of the dissipation along the shoreline was due to the vegetation, while some of the dissipation hot spots in the interior of the bay were due to bathymetry modifications necessary to support the vegetation. These hypothetical simulations demonstrated the potential for vegetation to provide a reduction in coastal storm hazards by dissipating wave energy under severe wind and water level conditions. The simulations cannot show, however, whether the vegetation can be sustained in the short term, throughout storm events, and in the long term.

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