Wave dynamics in coastal wetlands: A state-of-knowledge review with emphasis on wetland functionality for storm damage reduction

By

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ABSTRACT

Wetlands and other marine vegetation afford protection against wave action in coastal environments. In particular, wave attenuation by wetlands is important for protecting mainland areas from erosion and damage, both during low-energy and high-energy wave conditions. However, this critical role of vegetation to dampen wave forces and change wave setup, particularly when vegetation is emergent and near-emergent as is common in coastal wetland regions, is not fully understood at present. Here, we present the state-of-knowledge in both steady and oscillatory vegetated hydrodynamics, noting shortcomings and research needs.

ADDITIONAL KEYWORDS: Wave attenuation, energy dissipation.

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Coastal wetlands are widespread along the U.S. coast and are comprised of low- and high-marsh plant species which thrive in intertidal wetted regions. Two of the most prevalent wetland plant species are *Spartina alterniflora,* a reed-like low-marsh plant, and *Spartina patens*, a grass-like high-marsh plant. During coastal storms, higher elevation vegetated regions like coastal prairies also impede flow and waves. These coastal vegetated regions provide a rich habitat for fish and crustaceans among others, and which are critically important for sustaining the coastal ecosystem. The overall health of a wetland is known to depend strongly on water quality and sediment transport, among other factors, which are in turn strongly dependent on wave-induced and steady flow hydrodynamics.

The devastating damage by Hurricanes Katrina and Rita sparked much interest in coastal wetlands. This interest centers around the role of wetlands in reducing storm surge (includes wave setup) and wave height as hurricanes propagate inshore. From an engineering perspective, coastal wetlands afford natural shoreline protection by reducing wave energy, and these vegetation regions have the potential to reduce storm surge and damage. Yet while it is widely recognized that wetlands likely reduce storm surge and wave energy, this potentially critical role of wetlands to mitigate storm damage is not well understood at present. Since flow resistance and wave attenuation are likely to be greatest when the vegetation is emergent, in areas exposed to significant wave energy (e.g. open coast or large lake or bay) wave hydrodynamics dominate during initial inundation by wave setup as this super-elevation of the water level can add dramatically to the already elevated wind-driven surge at the coast. This interaction between vegetation and waves is further complicated by spatial variations in both the vegetation and wave fields, making it a highly three-dimensional process. Thus, characterization of both daily and storm hydrodynamics in coastal wetlands are critically important in order to better protect these natural resources and to better understand their functionality for storm damage reduction. However, the exact influence of wetlands on wave hydrodynamics, and of wave hydrodynamics on wetlands' sustainability, are not well understood at present. There still remains a critical need to characterize wave hydrodynamics through and over vegetation (Dean 2006; U.S. Army Corps of Engineers [USACE] 2006).

Here, we first describe the potentially critical role of wetlands in mitigating storm damage then discuss the state of knowledge in vegetated steady and oscillatory hydrodynamics, noting shortcomings and research needs as they relate to wetland functioning for coastal engineering analysis and applications.

RELEVANCE OF WETLANDS IN STORM DAMAGE REDUCTION

Coastal storm damage results from four main physical processes. First, wind-generated surge elevates water level above normal tide level, causing flooding. Second, the barometric pressure gradient results in a relative water level rise in the low-pressure region of the storm. Third, wave forces result in significant damage to infrastructure and the coastal landscape. Fourth, wave setup adds to the already elevated wind-surge level and can be as much as 30% to 60% of the total storm water level (Dean and Bender 2006; USACE 2006). All four of these processes may be dampened in the presence of vegetation (Day *et al.* 2007). With regard to wave forces, it is widely accepted that vegetation dissipates wave energy by effectively increasing bottom friction and drag within the water column. More specifically, the local turbulence generated by individual plant stems results in energy dissipation. Wave attenuation by vegetation depends on plant type, stem density (fraction of vegetation impeding the flow cross-section), plant spatial coverage, plant mechanical properties, water depth (which relates to topography and bathymetry), and wave conditions (e.g. Möller and Spencer 2002; Méndez *et al.* 1999; Dubi and Tørum 1996). Camfield (1977) noted that wave attenuation in vegetation can be up to 100 times that when propagating over an unvegetated bottom of the same depth, but Ward *et al.* (1984) noted that as the vegetation becomes submerged, less wave attenuation occurred.

VEGETATED STEADY-FLOW HYDRODYNAMICS

Nepf (2004) categorized vegetation state into three types based on fundamental differences in flow behavior: emergent, near-emergent*, and deeply submerged (Figure 1, steady current arrows). Emergent vegetation is classified by the condition that the water depth (h) is equal to the submerged plant height (l_s) ($h/l_s = 1$). Near-emergent vegetation is classified by depths no more than twice the plant height ($1 < h/l_s < 2$) while deeply submerged vegetation is classified by depths greater than 10 times the plant height ($h/l_s > 10$). Intuitively, one can see that the relative impact of vegetation will be greater during emergent conditions where the vegetation field impedes the entire vertical velocity profile than during deeply submerged conditions where the vegetation field primarily impedes flow near the sea bottom.

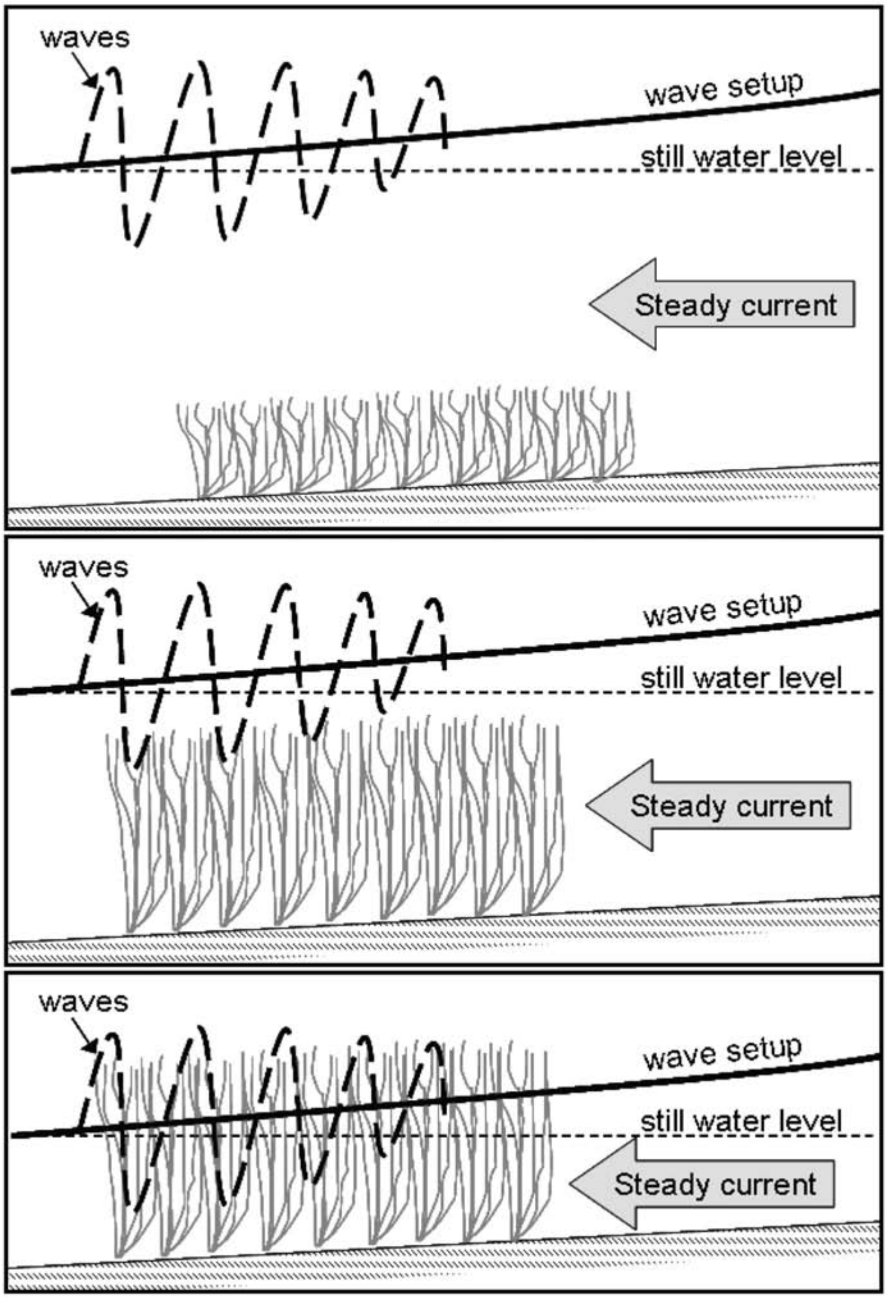

Figure 1. Steady flow (current arrow) and wave hydrodynamics (oscillating free surface elevation) in deeply-submerged (top pane), near-emergent (center pane), and emergent (bottom pane) vegetation (modified from Nepf [2004]).

The collective effect of a vegetation field on flow resistance is represented by bottom friction and by drag within the water column. Here, the drag coefficient may be based on the collective behavior of the plant stems (Hosokawa and Horie 1992; Burke and Stolzenbach 1983; Petryk and Bosmanjian 1975) and is a function of the plant stem diameter and stem density (Nepf 2004). In this form, the vertical velocity profile must be considered to capture vegetation influences throughout the water column. However, flow sheltering by upstream vegetation reduces the resistance provided by downstream vegetation (Nepf 2004). Thus, vegetation geometry and spatial plant coverage affect the vegetation's ability to slow the flow. In the 1990s, vegetation was modeled using depth-integrated approaches with empirical roughness coefficients like Manning's *n* (e.g., Guardo and Tomasello 1995; Hosokawa and Furukawa 1994; Kadlec 1990; Kadlec 1995). However, such approaches rely on a prescribed relationship between resistance and water depth, which is problematic since vegetation elevation and stem density vary spatially (Nepf 2004). In 1999, Nepf presented a drag relationship for depth-integrated steady flow through emergent vegetation that matches laboratory and field observations. While Wallace and Cox (2000) suggested that for submerged flow over seagrass vegetation height was reduced by 67% as it flattened under a 20-cm/s current, the extent to which these depth-integrated methods account for changes in resistive properties under high-velocity conditions as vegetation flattens is not known. Moreover, the validity of these steady-flow characteristics for describing nearshore (phase-averaged wave)

** Nepf (2004) uses the term "depth-limited" for the near-emergent conditions discussed here. We have opted to use "near-emergent" in this paper to distinguish this vegetated flow condition from the use of "depth-limited" to describe wave conditions.*

wave-driven circulation and wave setup has not been investigated.

Recent turbulence-scale steady-flow vegetated hydrodynamics studies include investigations of turbulence, boundary layers, and individual stem wake structure (e.g., Lightbody *et al.* 2007; Ghisalberti and Nepf 2006; Lightbody and Nepf 2006; Tanino *et al.* 2005; Serra *et al.* 2004). Nepf *et al.* (1997) showed that emergent vegetation stem wakes dominate over bottom boundary layer effects, while White and Nepf (2003) presented a theory for dispersion by randomly placed cylindrical vegetation stems. In submerged vegetation, Ghisalberti and Nepf (2004, 2006) showed that shear layer formation over submerged vegetation is limited in thickness and for flexible vegetation excites an oscillation in the vegetation canopy. These studies have all shown that the fine-scale steady flow structure is altered significantly in the presence of vegetation, and it is this fine-scale structure that governs collective vegetation field flow properties. However, no investigations have been conducted to specifically determine these fine-scale properties under the unsteady, oscillating flow conditions important to wave hydrodynamics.

VEGETATED WAVE HYDRODYNAMICS

Wave attenuation by vegetation (Figure 1, free surface oscillation) was evaluated in a number of field and laboratory studies, and results showed that wave height is reduced by up to 5% per 1 m of propagation over submerged vegetation (e.g., USACE 2003; Løvås and Tørum 2000) and by 0.2% to 28% per 1 m of propagation through emergent vegetation (e.g., Tschirky *et al.* 2000; Möller *et al.* 1999; Fonseca and Cahalan 1992). Fonseca and Cahalan (1992) concluded from laboratory experiments that for seagrass, wave attenuation was most pronounced when h/l_s was small (closer to 1). Knudsen *et al.* (1982) reported that wave energy was completely removed as small-amplitude waves propagated a 30-m distance through emergent vegetation. Tschirky *et al.* (2000) concluded from laboratory experimentation that wave attenuation increases linearly with propagation distance and increases with stem density for emergent vegetation conditions. Tschirky *et al.* (2000) also concluded that, for emergent vegetation, wave attenuation decreases with increasing depth. Bouma *et al.* (2005) presented experimental data that indicated wave attenuation for emergent plants with stiff leaves is three times larger than that for emergent plants with flexible leaves. However, the turbulence-scale wave-induced flow structure about plant stems and leaves has yet to be quantified.

Dean (1978) introduced a simple approach for predicting wave attenuation by emergent vegetation and showed that wave height reduction was a function of drag coefficient, stem diameter and spacing, water depth, and wave propagation distance. Dalrymple *et al.* (1984) developed an analytical model for submerged vegetation based on conservation of wave energy using linear wave theory. This model described wave attenuation by kelp by approximating the kelp stems as a series of rigid cylinders. Mendez and Losada (2004) extended this wave-energy approach for mildly-sloping shallow water scenarios and for breaking waves.

Kobayashi *et al.* (1993), using conservation of momentum and employing linear wave theory, developed an analytical model for wave attenuation over submerged vegetation by approximating the vegetation as rigid cylinders. Here, experimental data were used to calibrate the drag coefficient so that it accounted for vegetation motion effects. Several researchers have refined the work of Kobayashi *et al.* (1993). Asano *et al.* (1993) added vegetation motion resulting from one wave frequency, while Méndez *et al.* (1999) developed an approach which accounted for irregular waves and vegetation motion. Ota *et al.* (2004) developed an analytical model for waves and currents over vegetation which agreed with laboratory data. Most recently, Lima *et al.* (2007) conducted laboratory experiments using flexible submerged synthetic vegetation and proposed a nonlinear-theory based average force which accounts for large stem displacements. Recently, oscillatory flow through submerged stiff canopy, representative of coral reefs and including laboratory experimentation, has been studied by Lowe *et al.* (2006, 2005a, 2005b) to evaluate velocity structure, mass transport, and wave attenuation also based on momentum principles. While it is recognized that wave attenuation by vegetation is spatially variable, research in this area is limited; Asano (2006) presented a momentum-based quasi-two-dimensional theory for oblique wave propagation through vegetation.

While empirically-based approaches can be calibrated based on field measurements to give a first approximation of conditions in a heterogeneous environment, the above momentum- and energy-based models, however, have not specifically addressed the fully three-dimensional problem of the collective effects of a heterogeneous vegetation field. Specifically, these physics-based models have not been expanded to include spatial variation in the plant field – namely stem density, plant type, plant height (as it relates to submergence), or spatial variation in wave forcing and topography (e.g., presence of channels and vegetated flats). Elwany *et al.* (1995) noted that these analytical models cannot accurately determine wave attenuation because the collective friction effect of a heterogeneous vegetated region – a three-dimensional characteristic – is unknown, and Méndez *et al.* (1999) noted that measured data are not sufficient to validate these analytical models.

The literature on wave-current interaction and phase-averaged, nearshore hydrodynamics in vegetation is limited. In the presence of waves, flow velocity is changed by the transfer of momentum during wave breaking (i.e. wave radiation stresses), which drives nearshore circulation and wave setup, and enhanced wave bottom friction. Løvås and Tørum (2000) reported that wave breaking was reduced when waves propagated over a submerged artificial kelp bed. Ota *et al.* (2004) presented laboratory studies of wave-current interaction over submerged vegetation and concluded that empirically derived resistance coefficients for flow through vegetation in the absence of waves are too large for applications in the presence of waves. Ota *et al.* (2004), through calibration to laboratory data, suggested that an appropriate drag coefficient for wave-current interaction is about half the magnitude of that for the current-only case.

Dean and Bender (2006) were the first to present a physical approach for determining wave setup in vegetation based on wave energy and using nonlinear wave theory; their results indicate wave setdown occurs in the presence of vegetation. However, this approach for describing wave setup in vegetation has not yet been tested with laboratory or field data.

While the presence of vegetation will surely influence the wave-induced vertical velocity field by impacting both oscillatory velocities and phase-average currents like undertow, research on these phenomena has yet to be conducted.

In summary, the state-of-knowledge in vegetated wave hydrodynamics is limited by the availability of measured data. Moreover, neither the turbulence-scale oscillatory flow interaction with individual plant stems, the three-dimensional effects of vegetation on large-scale coastal hydrodynamics, nor the vertical wave-induced velocity structure have yet been studied in detail.

CURRENT PRACTICE IN NUMERICAL SIMULATION

When evaluating existing conditions and design alternatives for erosion control and storm damage reduction in regions where wetlands are present, it is prudent to consider vegetative effects in the engineering analysis. Evaluation of coastal vegetation influences on wave attenuation and nearshore hydrodynamics is accomplished today by approximating the vegetative influence via bottom friction (*f*) where this term approximates the drag force throughout the water column as a drag force along the bottom surface per unit lateral area:

$$f = C_D(l_s d/\Delta Sh) \tag{1}$$

where d is average plant width (i.e. diameter for cylindrical stems), ΔS is the average lateral plant spacing, and C_D is the drag coefficient for the individual plant. For example, when the plant stem is idealized as a rigid cylinder, C_D varies with Reynolds number and is dependent on the projected area into the flow direction (dl_s). Current practice in the use of short-wave (both spectral models [i.e. STWAVE, SWAN] and time-resolving models [i.e. COULWAVE or other Boussinesq]) and depth-integrated long-wave (i.e. ADCIRC, Delft3D-Flow) numerical models to accomplish engineering analysis treat vegetative effects by specifying a constant bottom friction value for the entire simulation (i.e. Augustin *et al.* in review; Day *et al.* 2007; USACE 2006). While these models account for the influence of depth by using a quadratic friction relationship, this approach is problematic because the vegetated flow regime changes with depth of plant field submergence. For example, Augustin *et al.* (in review) showed that for wave attenuation, the behavior of C_D at the plant stem level becomes progressively less dependent on wave period as the vegetation becomes near-emergent then emergent. This indicates that, for practical engineering purposes, a revised friction formulation is needed to appropriately account for vegetative effects on the flow field.

The use of fully three-dimensional numerical models like large eddy simulation (LES) or Reynolds Averaged Navier Stokes (RANS) models have the potential to account for the plant field effects in the vertical as well as in the horizontal (in two dimensions). However, research in this numerical application is ongoing (e.g. Stoesser *et al.* 2006; Palau *et al.* 2007) and not yet accessible to the coastal engineering community at large. Specifically, application of these models requires consideration of individual plant stems as discrete elements within the computational grid, and such methods are still under development (e.g. Stoesser *et al.* 2006; Palau *et al.* 2007). Furthermore, the computational requirements of LES and RANS simulations render it impractical for most engineering studies, particularly those to investigate storm impacts on a regional spatial scale.

Most numerical efforts to date have focused on turbulence-scale vortex shedding in regularly-spaced arrays of cylindrical rigid stems. Preliminary findings with LES showed that vortices shed by one plant stem are modulated by adjacent plant stems in both the along-flow and cross-flow directions, indicating that turbulence-scale flow phenomena vary with stem density (Palau *et al.* 2007). While LES and RANS models are fully capable of simulating unsteady flow conditions like those under waves, published research has focused on steady flow conditions only. It is likely that future results of these fine-scale simulations will be useful in augmenting experimental data for developing larger-scale parameterizations for use in engineering models.

RECOMMENDATIONS FOR FUTURE STUDY

In light of the known environmental importance of wetlands and their potential consideration in coastal engineering analysis, further research on vegetated wave hydrodynamics is needed to appropriately quantify vegetation effects for coastal engineering applications. Specifically, quantitative and controlled field experiments in vegetation fields are sparse making it difficult to reliably extrapolate or interpret empirical formulae. Laboratory experimentation has largely focused on regularly spaced synthetic plant arrays or on real vegetation. However, more controlled experiments with known degrees of plant spacing randomness will help to elucidate turbulence-scale phenomena such as impact on vortex modulation by adjacent plants. Quantitative measurements of bulk parameters like wave attenuation and collective resistance and of turbulence-scale flow fields are required to better understand how turbulence-scale phenomena like vortex shedding and interaction relate to bulk wave field properties. Specifically, high-resolution velocity field measurements with particle image velocimetry or other technology should be collected to elucidate small-scale flow features at the plant stem level. Numerical analysis with LES and RANS models should be continued and expanded to include oscillatory flow.

This experimental and numerical work should focus on determining bulk- and turbulence-scale vegetated wave dynamics as a function of stem density, plant stem planform arrangement, and plant type (flexibility), and as a function of hydrodynamic conditions including incident wave conditions and level of submergence. Three-dimensional variation in these parameters must also be considered at both the local plant and regional scale. Specifically, heterogeneous changes in the wave field on a regional scale induced by the combined influence of spatial variations in the plant field, bottom topography, and incoming hydrodynamic conditions should be investigated.

Of particular importance to storm damage reduction is better quantification of vegetative effects on both storm surge and wave setup, which cannot be achieved without further research on vegetated wave dynamics. Therefore, future research should also consider the relative influence of flow regime on energy dissipation and momentum transfer both at the plant-stem level to elucidate the fundamental physics and at a regional scale to better describe vegetative influences on large-scale circulation and water levels. This additional experimental and numerical work will improve the parameterization of bulk drag or frictional effects in three dimensions for practical engineering purposes.

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