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APPENDIX G

Coastal Resilience and Wave Attenuation

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Tidal Wetlands as a Resiliency Strategy

Tidal salt marshes, whether natural or nature-based, can provide critical protection to coastal communities by substantially attenuating wave heights and therefore wave energy, reducing storm surge levels and durations, and mitigating coastal erosion (Campbell et al., 2005; Anderson et al., 2011; Gedan et al., 2011; Shepard et al., 2011 and 2012; Renaud et al., 2013; Bridges et al., 2015; Guannel et al., 2015; SmarterSafer, 2015; Sutton-Grier et al., 2015). Although there is increasing understanding of the performance of the ecosystems services and coastal protection provided by natural and natured-based nonstructural and hybrid features, the number of factors affecting their performance (including geomorphology, ecology and hydrodynamics) as well as the variation within each factor, has hindered our ability to predict the success of a living shoreline for a particular location based on its performance at a different locations (Pinsky et al., 2013; Bridges et al., 2015). Additionally, the effect of vegetation on surge elevations and wave height has only be studied in low energy conditions, thus the feasibility of relying on tidal marshes to provide coastal protection during storm conditions is not well-understood (Anderson et al., 2011; NRC, 2014). Improved understanding of the interdependency of these factors in diverse site conditions may enable coastal managers reduce the construction of traditional erosion control structures and encourage the use of ecosystem based approaches to mitigate coastal vulnerability (Spaulding et al., 2014).

1 Wave Attenuation

Tidal marsh restoration and creation have been shown to mitigate coastal erosion in low wave energy conditions. Marsh vegetation extensive root systems help to maintain the existing soil, thus reducing sediment transport while plant stems attenuate wave energy (CCRM, 2010). The ability of marsh vegetation to attenuate wave energy has been well-documented in field and laboratory studies using real and artificial vegetation (e.g., Kobayashi et al., 1993; Nepf, 1999; Knutson et al. 1982; Tschirky et al., 2000; National Research Council, 2014). The majority of these studies have been performed in small to medium wave heights; presumably since salt marshes are most likely to be exposed to low wave heights conditions (Shepard et al., 2011).

Most wave attenuation has been shown to occur in the first few meters of the seaward edge of a marsh, for gradual and abrupt marsh edges (Möller and Spencer, 2002; Shepard et al., 2011). Knutson et al. (1982) observed in their study of wave dampening in two tidal marshes of closely packed, tall stems of cordgrass (*Spartina alterniflora*) that on average more than 50% of small amplitude wave energy (wave heights of 0.15 - 0.18 m) was dissipated in the first 2.5 m of marsh, and 100% was dissipated in 30 m. Through physical modeling of typical northwest European saltmarsh vegetation, Brampton (1992) determined that most of the wave attenuation occurred in the first tens of meters of the seaward edge of the marsh. Möller and Spencer (2002) observed similar results in their field studies of three saltmarshes in England. It is therefore misleading to calculate the average rate of attenuation across the marsh width (Gedan et al., 2011) since it has been shown that over 40% of incoming wave energy is dissipated with in the first 10 m of the marsh seaward edge. Möller and Spencer (2002) found that on average, the remaining 60% is attenuated over the following 28 m. Thus, even a narrow fringe marsh is effective in attenuating wave energy (Möller and Spencer, 2002, Gedan et al., 2011). However, at high wave energy sites, an abrupt edge reduces the wave heights, but leads to near continuous erosion of the marsh face, which is obviously an unsustainable condition that will cause narrowing of the marsh width over time (Möller and Spencer, 2002).

The ability of vegetation to attenuate wave energy is affected by vegetation characteristics (e.g. stem height, stiffness, buoyancy and density, marsh width [Bouma et al., 2005; Möller , 2006; Shepard et al., 2011; Sheng et al., 2012]), and wave conditions (e.g., incident wave height, period and direction), as well as water depth and tidal amplitude (Augustin et al., 2009). In addition, many vegetation characteristics are modified with wave action (e.g., stems bend, relative stem height, orientation [Anderson et al., 2011]) and through seasonal and spatial variations in vegetation height, foliage and coverage (Möller and Spencer, 2002). Although understanding of the effectiveness of marsh plants to attenuate wave heights is critical in evaluating their ability to provide coastal protection, the variety of tidal marsh plants and the complexity in quantifying vegetative characteristics in the field makes it difficult to determine the effect of marsh vegetation on wave attenuation (Wayne 1976; Knutson et al. 1982; Möller et al.1999; Tschirky et al., 2000; Möller and Spencer, 2002; Mendez and Losada, 2004; Cooper, 2005; Möller, 2006; Bradley and Houser 2009). Despite these complexities, it is generally accepted that wave attenuation is increased with marsh width, stem density, and decreased water depth (Tschirky et al., 2000; Anderson et al, 2011). However, no clear correlation of wave attenuation with wave height has been determined. In their laboratory study of artificial sea grass, Cavallaro et al. (2010) observed a correlation of increasing wave attenuation with increasing wave height; however, Bradley and Houser (2009) observed an inverse correlation of wave attenuation with wave height in a sea grass field (Anderson et al., 2011).

Predicting wave attenuation through vegetation remains difficult because the process is non-linear and highly variable, spatially and temporally (Shepard et al., 2011; Pinsky et al., 2013). Mendez and Losada (2004) stated that, "The variability of wave damping is very large and trying to define a generalized behaviour of the 'plant-induced dissipation' is absolutely impossible." Because marsh vegetation drag coefficients are rarely reported in the literature, there is a lack of understanding of variation of the drag coefficient with vegetation characteristics such as geometry, buoyancy, density, stiffness, degrees of freedom and spatial configuration) as well as wave height, period and direction (Mendez and Losada; 2004; Pinsky et al., 2013).

Through field studies of wave attenuation through sea grass bed in low wave energy environments (significant wave heights, Hs, on the order of 0.1 m), Bradley and Houser (2009) observed a decrease in wave attenuation with an increase in Reynolds number. At lower Reynolds numbers ($200 < R_e < 800$), the vegetation sways with the direction of the flow, resulting in higher drag coefficients. As incident wave heights increase, the blades become increasing rigid and extend in the direction of the flow. The effective roughness of the sea grass bed decreases as the vegetation becomes more streamlined leading to reduced drag. Bradley and Houser (2009) conclude that because the observed drag coefficients are an order of magnitude smaller than predicted by existing models for rigid and swaying vegetation, wave attenuation through sea grass is a result of vegetation density and extent rather than the drag on each individual blade. Bradley and Houser point out that because the focus of their field study was low wave energy conditions, it is not necessarily valid to use these results to predict the drag response in higher Reynolds number conditions ($R_e > 1000$) where the vegetation canopy has collapsed.

The relationship between wave attenuation and wave period also remains poorly understood. Through field studies, Möller et al. (1999) found salt marshes attenuated wave energy equally at all wave periods. Bradley and Houser (2009) found that wave attenuation is greater at higher frequencies when the vegetation is moving out of phase with the peak wave velocity while at lower frequencies the blades move in phase with the waves resulting in little wave attenuation. However, Tschirky et al. (2000) observed no clear trend in their field and laboratory studies.

The composition of salt marsh vegetation varies widely due to spatial and temporal changes, competition between, as well as competition between individual plants of the same and different species. Salt marshes may be composed primarily of one species (e.g. invasive phragmites) or a more diverse community of vegetation. Given the complexities of evaluating wave attenuation through one species of marsh vegetation, it is unsurprising that there have been few studies evaluating diverse marsh communities. Nor are numerical models similar to those for evaluating the performance of hard structures for coastal defense available for predicting the performance of marsh vegetation (Arkema et al., 2013; National Research Council, 2014).

Studies have also found mixed results on the effect of water depth on wave attenuation in wetlands. Gedan et al. (2011) resolved the conflicting observations of Danard and Murty (1994) of an inverse correlation of water depth and wave attenuation with that of Möller et al. (1999) who found that wave attenuation in wetlands increases with water depth. Gedan et al. (2011) observed that wave attenuation is minimal when the water depth is large or small relative to plant height. Wave attenuation is largest when the ratio of water depth to plant height is on the order of 1- 2 (Gedan et al., 2010).

A further complication in evaluating the effectiveness of marsh grass for attenuating waves is the seasonal variation in vegetation characteristics such as the presence of foliage and vegetation height, which can result in a temporal variation in the coastal protection provided (Shepard et al., 2011).

Not surprisingly, numerical models similar to those for evaluating the performance of hard structures for coastal defense are unavailable for predicting the performance of marsh vegetation (Arkema et al., 2013; National Research Council, 2014). Yet evaluation of the effect of marsh vegetation at reducing wave height is critical for predicting the performance of vegetation for shoreline protection (Anderson et al., 2011).

2 Shoreline Stabilization

Numerous studies have discussed the ability of marsh vegetation to stabilize shorelines by reducing sediment transport, increasing marsh elevation and producing biomass (National Research Council, 2014). As with attenuation in marshes, the capability of marsh vegetation to trap sediment is dependent on a number of factors: sediment supply, tidal range (which governs the duration of inundation), marsh elevation, and vegetation characteristics such as density, height and biomass production (Shepard et al., 2011). However, there is some controversy regarding the role of marsh vegetation on shoreline stabilization. Feagin et al. (2009) though laboratory and field experiments, found that salt marsh vegetation does not significantly mitigate shoreline erosion along the seaward edge of a marsh and that modification of the soil was the primary process through which salt marsh vegetation reduces erosion. The elevation of the seaward edge of the marsh is vitally important to the health and stability of the marsh because unless a minimum elevation is maintained, marsh plants will be constantly flooded with the resulting in loss of vegetation and edge instability. Processes that help maintain or increase marsh surface elevation such as sediment deposition and root production affect marsh surface elevation and contribute to shoreline stability (Shepard et al., 2011). Gedan et al. (2011) in their review of biophysical models, field tests and laboratory experiments also concluded that coastal vegetation protects shorelines from erosion and wave damage by reducing flow velocities and increasing sediment deposition and soil cohesion. Although the consensus leads toward favors the conclusions of Shepard et al. and Gedan et al., the importance of soil type and geographical setting should not be neglected (Feagin et al., 2009).

3 Storms: Surge and Waves

The effectiveness of living shorelines to provide coastal protection during storms is of particular importance yet their performance capabilities during storm conditions are poorly understood (Pinsky et al., 2013; Gittman et al., 2014). Extreme weather events (such as Hurricanes Irene and Sandy) and projected sea level rise has led to increased interest in the vegetation to attenuate coastal flooding and wave action. It has long been accepted that salt marshes have the potential to slow and absorb flooding from storm surges by reducing flood peaks and durations through storage and drainage of flood waters, however, their effectiveness is difficult to determine (Augustin et al., 2009; Wamsley et al., 2010; Shepard et al., 2011). Studying the effect of Hurricane Irene on shore erosion in North Carolina, Gittman et al. (2014) determined that although vegetation density was reduced by the hurricane, marshes had recovered to pre-storm conditions. They concluded marshes, with and without sills, are more durable and provide better protection from storm-induced erosion in Category 1 hurricane conditions as compared to bulkheads. Möller et al. (2014) found that 60% of the wave attenuation during storm events is due to vegetation and that even when waves were sufficiently large to damage plant stems, the vegetation prevented soil erosion (Sutton-Grier et al., 2015).

Most of our knowledge about the ability of marshes to attenuated flood waters is from freshwater wetlands. Predictions of the capability of marshes to attenuate waves and store storm water are usually based on rules of thumb. For instance, for freshwater wetlands the U.S. Environmental Protection Agency (EPA) uses the rule, “A one-acre wetland can typically store about three-acre feet of water, or one million gallons,” which is based on a 1963 Army Corps of Engineers report that evaluated the attenuation of storm surge for seven Louisiana storms (Shepard et al., 2011). However, wave attenuation and flooding mitigation are too complex for such a simple approximation (Resio and Westerink, 2008). Marsh characteristics, variations in coastal geology, bathymetry and exposure, and storm specific parameters such as duration, intensity, size and track all affect the attenuation of waves and flooding (Resio and Westerink, 2008; Gedan et al., 2011; Sheng et al., 2012). Additionally, as noted above, the rates of attenuation varies as the waves traverse the marsh. After 50 years of study, we still do not understand storm surge and wave attenuation in marshes well enough to develop models suitable for coastal planning of marsh protective services (Shepard et al., 2011). The limited observations reported in the literature are insufficient to evaluate the importance of different types and composition of marsh vegetation, and storm and site characterizes on the drag coefficient and Reynolds stresses (Sheng et al., 2012).

Numerical models of the capability of marshes to reduce flooding have been developed, but they are typically tuned to a particular marsh configuration and storm characteristics. Numerical models must accurately describe storm conditions, attenuation parameters and coastal geometry to be of value to coastal planners in predicting flooding (Resio and Westerink, 2008). Since no data exist on the capability of salt water marshes to reduce flooding for validation, (Shepard et al., 2011; NRC, 2014) models to predict the wave attenuation and floodwater storage capability of marshes should be used with caution.

The ability of vegetation to attenuate short-period waves has been studied through field and laboratory experiments (e.g., Knutson et al., 1982; Kobayashi et al., 1993; Möller et al., 1999; Nepf, 1999; Tschirky et al., 2000; National Research Council, 2014); however, the effects of longer period storm waves may not scale linearly and so the observations from short-period waves are not necessarily applicable (Feagin et al., 2010). Longer period storm waves increase the water level over a longer period of time and with greater force on the vegetation than short waves. Thus the plants are more likely to bend with the flow, reducing the drag coefficient and wave attenuation (Bradley and Houser; 2009; Pinsky et al., 2013). The decrease in drag coefficient in turbulent flows is critical because storm conditions are highly turbulent. Failure to account for this can over-estimate wave attenuation in storms by approximately 20 – 1600%, thus to protect coastal communities, marshes may need to be larger than thought previously (Pinsky et al., 2013).

Storm waves are typically accompanied by storm surge. Waves are attenuated more in emergent vegetation where the height of the plant exceeds the water depth than in conditions where the top of the plant is submerged and thus does not affect the top of the water column where wave orbital velocities are greatest (Anderson et al., 2011). However, Fonesca and Cahalan (1992) point out that even a relatively low rate of attenuation can be effective when waves traverse large marsh widths (Anderson et al., 2011).

One of the difficulties in assessing the effectiveness of living shorelines for storm protection is the variability in storm characteristics. Vegetation is more effective protection during fast moving storms. In slow moving storms, surge will have more time to increase, sometimes building over through multiple tidal cycles as in Hurricane Sandy (Sutton-Grier et al., 2015). The increased water depth from storm surge will cause waves to break further inland, causing an abrupt marsh edge to move landward (Feagin et al., 2009). Feagin et al. (2009) suggest that the threshold for erosion at a marsh edge is low, and that the vegetation roots may even act as erosive forces. Unlike previous studies, they found that the roots did not bind the soil.

Despite the complexity of storm effects on storm surge and wave attenuation, field and modeling observations show that salt marshes can provide shoreline protection during storms (Shepard et al., 2011; Möller et al., 2014). During and immediately following a storm, marshes may experience a decrease in plant density and marsh elevation, but as the marsh recovers from the storm deposition of suspended sediments can increase marsh elevation (Shepard et al., 2011). Improved understanding of the relationships among vegetation characteristics (e.g., plant height, density and marsh width) and storm conditions (surge elevation, duration, wave heights) is needed to estimate the erosion protection provided by non-structural and hybrid living shorelines (Sheng et al., 2012).

4 Sea Level Rise

Coastal communities are becoming increasingly interested in the capability of living shorelines to provide natural protection from sea level rise (SLR). Natural salt marshes exist in low lying areas that will be the first to experience the effects of SLR, yet salt marshes migration is limited by coastal development so researchers have investigated the ability of salt marshes to maintain their surface elevation relative to sea level rise (Morris et al., 2002; Shepard et al. 2011). The long term stability of a marsh is dependent upon the sea level, primary plant production and sediment accumulation which regulate the marsh elevation relative to mean sea level (Morris et al., 2002). Natural marshes exposed to large variations in tidal range and marshes with high sediment concentrations will be best able to adapt to large increases in SLR (Morris et al., 2002; Kirwan et al., 2010). Morris et al. (2002) developed a model that suggests a marsh ecosystem will be stable against sea level rise when the marsh elevation exceeds the optimal level for primary production and unstable when the marsh elevation is less than optimal. The optimal range varies regionally, dependent upon tidal range, vegetation, salinity, nutrient loading, and climate (McKee and Patrick, 1988; Morris et al., 2002). Researchers have concluded that salt marshes are better able to maintain their position against gradual sea level rise than mitigate erosion from storm waves (Feagin et al., 2009; Gedan et al., 2011).

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