Wave Attenuation in Salt Marshes

By

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Abstract

Salt marshes can provide several ecosystem services including shoreline protection. One of the ways marshes do this is by attenuating waves. However, the rate at which waves are attenuated by marshes is highly variable. Previous studies have found that the rate of wave attenuation varies with water depth, vegetation characteristics, bottom profile, and wave conditions. This study examined how these factors affect wave attenuation rate at four marsh sites in coastal North Carolina with different vegetation and bottom profile characteristics. The rate of wave attenuation was found to increase with decreasing water depth and increasing vegetation height and increasing vegetation density. Sites with short vegetation, which is submerged more of the time, had larger rates of decrease in wave attenuation with increasing depth than sites with tall vegetation. Waves with long periods were attenuated less than waves with short periods. Attenuation rates were much less and decreased more with increasing water depth during storm conditions than during normal conditions at the same site.

1. Introduction

Salt marshes provide many benefits to humans, including protection from storms and the stabilization of shorelines (Barbier et al., 2011). Coastal wetlands are estimated to provide $23.2 billion in storm protection every year in the United States (Constanza et al., 2008). Marshes help shoreline stabilization by increasing vertical accretion (Morris et al. 2002), reducing erosion, and increasing the surface elevation of the area (Shepard et al., 2011). One of the ways in which salt marshes provide these benefits is through wave attenuation.

Wave attenuation is a well-observed phenomenon in salt marshes whereby wave energy is decreased over the salt marsh. Wave attenuation is important for protecting the shoreline from erosion due to wave energy. There are large variations between the findings of studies investigating how much wave attenuation occurs. One study of *Spartina alterniflora* in Virginia marshes found that most wave energy dissipated in the first 2.5 meters, and almost no wave energy remained at 30 meters (Knutson et al., 1982), while another study in north Norfolk, England found that wave height reduction was 61% over 180 meters (Möller et al., 2001). The table below shows data from several different studies and demonstrates how wide the observed rates of wave attenuation have ranged in various studies.

Table 1. Previous Studies Wave Attenuation Rates. The table below shows the rates of wave attenuation found in previous, and the plant species in the marshes of each of those studies.

Paper	Wave Height Reduction	Length of Transect	Plant Species	Notes
Knutson et al., 1982	94%	30 m	Spartina alterniflora	Waves were generated by a boat
Möller et al., 2001	61%	180 m	Not Reported	
Jadhav et al., 2013	37.5%	27.7 m	Spartina alterniflora	During a tropical storm
Cooper, 2005	91%	428 m	*Puccinellia maritima* and *Salicorinia europaea*	
Cooper, 2005	64%	542 m	Atriplex portulacoid and Spartina alterniflora	

Cooper, 2005	78%	387 m	*Atriplex portulacoid* and *Salicorinia europaea*	
Yang et al., 2012	38%	15.5 m	*Spartina alterniflora*	
Möller et al., 2014	13.8-19.5% Depending on wave period and height	40 m	*Elymus athericus, Puccinellia maritima,* and *Atriplex prostrata*	Experiment done in a large wave tank with simulated storm surge conditions

Differences in wave attenuation among previous studies are due to several factors. Differences in the vegetation characteristics at different sites can affect the rates of wave attenuation. An increase in vegetation density can cause an increase in wave attenuation (Anderson and Smith, 2014). Additionally, taller vegetation can also increase the rate of wave attenuation. This is due to the fact taller vegetation reaches the upper part of the water column a, where the orbital velocity is the greatest and therefore it can cause drag there (Tempest et al., 2015). *Spartina alterniflora* is a common marsh species in North Carolina where this study was conducted and previous studies have found that when compared to shorter plant species, *Spartina alterniflora* results in greater wave attenuation (Tempest et al., 2015).

Differences in marsh topography can also affect wave attenuation rates. Obstacles such as oyster reefs can act as breakwaters and reduce wave energy (Scyphers et al., 2011). Additionally, wave height can increase due to shoaling, where waves increase in height when they reach shallower water, often before eventually breaking and losing energy. This wave breaking contributes to the overall loss in energy of the waves (Mendez and Losada, 2004).

Finally wave and water conditions can also affect wave attenuation rates. Waves with longer periods are often less attenuated than waves with shorter periods. This could be due to the

motion of the vegetation. A study 2009 study found that seagrass moved in phase with the lower frequency waves, but out of frequency with the higher frequency waves causing them to be attenuated more (Bradley and Houser, 2009). The same mechanism could occur in saltmarshes, although the grasses typically found in coastal North Carolina marshes, Spartina alterniflora and Juncus roemerianus. Additionally, the Keulegan Carpenter number, which is the ratio of wave orbital excursion to plant diameter, increases with increasing wave period, and the larger the Keulegan Carpenter number, the smaller the drag coefficient of the vegetation (Mendez and Losada, 2004). Water depth can also affect attenuation rates in that less attenuation occurs in deeper water. Plant height affects how influential water depth is on the rate of wave attenuation. A case study with marshes in Yangtze estuary in China found that the ratio of water depth to plant height was inversely correlated with the attenuation rate (Yang et al., 2012). At greater water depths, more vegetation is submerged and therefore, it has little effect on the upper part of the water column where the orbital velocity is greatest (Augustin et al., 2009).

This study examines several of the factors that influence wave attenuation rates: vegetation height, vegetation density, marsh bottom topography, water depth, and wave period. We did this by examining wave heights at four different sites where these characteristics differed, whereas many previous wave attenuation studies only examine one or two sites. Additionally, this study compares wave attenuation data from one marsh site during storm and everyday (normal) conditions.

2. Methods

A. *Data Collection*

Four salt marsh sites were chosen to study wave attenuation, Crab Point, Deerfield, Pine Knoll Shores and Bogue Watch (Figure 1). These sites were all in Carteret County, North

Carolina. Bogue Watch is on the North side of Bogue Sound and Pine Knoll Shores is on the

South side. Crab Point is on the Southwest side of the Newport River Estuary and Deerfield is

on the Northeast side. The GPS coordinates of each of the sites are in Table 2. The vegetation

communities of these marshes are dominated by *Spartina alterniflora*, with some *Juncus*

roemerianus present at Pine Knoll Shores.

Figure 1. Locations the four study Sites in Carteret County, North Carolina. Study sites are

indicated with yellow markers.

Table 2. Site and Deployment Characteristics.

| Deployment	Coordinates	Dates Recorded	Vegetation Type	Vegetation Height (cm)	Vegetation Density (m^{-1})
Crab Point- 1st Deployment	34.75179°N 76.70914°W	08/29/2016- 09/1/2016	Spartina alterniflora	Mean: 55.1 Std. Dev.: 43.8	Mean: 0.72 Std. Dev.: 0.52
Deerfield	34.76158°N 76.66827°W	09/16/2016- 09/19/2016	Spartina alterniflora	Mean: 55.4 Std. Dev.: 38.1	Mean: 1.63 Std. Dev.: 1.99
Bogue Watch	34.70691°N 76.96760°W	10/17/2016- 10/20/2016	Spartina alterniflora	Mean: 20.6 Std. Dev.: 11.1	Mean: 1.95 Std. Dev.: 0.69
Pine Knoll Shores	34.69596°N 76.84181°W	11/11/2016- 11/14/2016	Spartina alterniflora and Juncus roemerianus	Mean: 44.2 Std. Dev.: 29.4	Mean: 1.30 Std. Dev.: 1.19
Crab Point- 2nd Deployment (storm)	34.75179°N 76.70914°W	10/07/2016- 10/10/2016	Spartina alterniflora	Mean: 55.1 Std. Dev.: 43.8	Mean: 0.72 Std. Dev.: 0.52
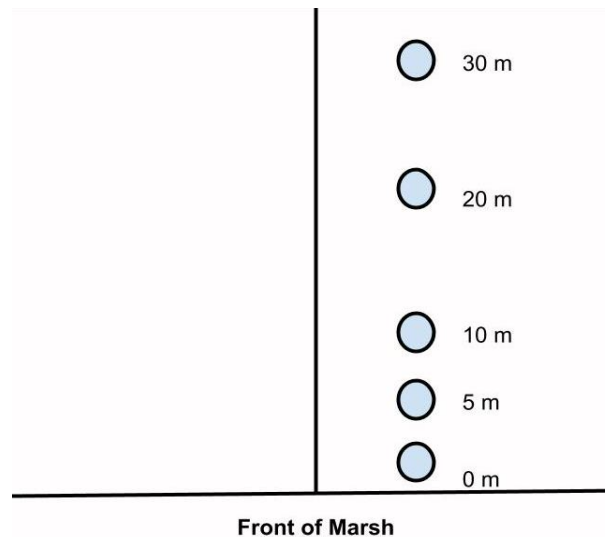
Front of Marsh

Figure 2. Sensor Locations in the Salt Marsh. The sensors are indicated by blue circles. The front of the marsh is labeled at the bottom and is where the marsh meets the body of water, either the Newport River or Bogue Sound.

At each site, five pressure sensors (RBR XR-620D) were placed in the ground at zero, five, ten, twenty, and thirty meters from the marsh edge, along a line perpendicular to the shoreline (Figure 2). The instruments were mounted pressure sensor upward so that the top of the sensor and pressure measurement was 5 to 10 cm above the surface of the marsh. The sensors were left at the marsh sites for six days, where they measured pressure at a rate of 6 Hz. Of the 5 sensors, four recorded data for 6 days and 1 sensor recorded for only 3 days. The sensors were deployed twice at Crab Point, once during normal conditions and a second time during the passage of a category 1 hurricane, Hurricane Matthew. Hurricane Matthew passed, at its closest, approximately 70 miles East of the sites on October 9th, 2016 when it's sustained winds were at 70 knots (130 km/hr) (Stewart, 2017). The maximum sustained wind speed observed in the vicinity of the sites, at the NOAA NDBC Beaufort station (BFTN7), was 20 m/s (70 km/hr) from the North. The sensors were deployed once at all other sites. The dates of the data recorded for each deployment are in Table 2.

The elevation of the marshes was measured in a 5-m by 5-m grid using a laser level (Topcon RL-H3C) and stadia rod, which allowed measure of the elevation of the marsh surface relative to a known benchmark. Figure 3 below shows the elevations along the shore-

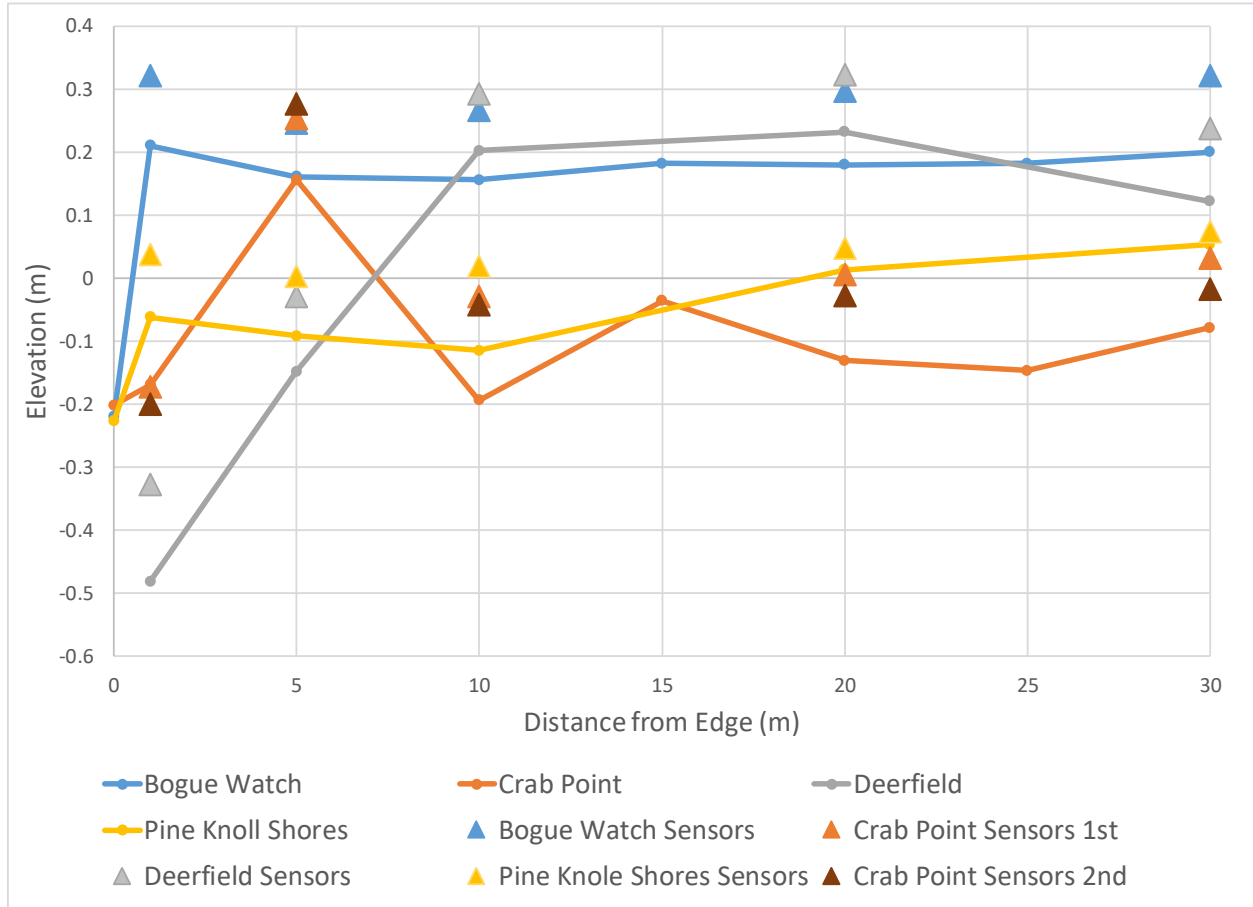perpendicular transect of each marsh where the sensors were placed.

Figure 3. Marsh surface elevation, relative to NADV 88, of the shore-perpendicular transect along which pressure sensors were placed. 0 m corresponds to the seaward edge of the marsh. The elevations of the sensors are marked with triangles.

Bogue Watch rises steeply in the first meter then flattens out. The first sensor was placed on the initial flat part of the marsh, at 1 m. Crab Point has an oyster berm at 5 m and then has relatively little change in elevation thereafter. Deerfield has a steep slope within the first 10 meters, but then remains basically flat. Pine Knoll Shores has a small rise in the first meter, and then gradually rises in elevation.

Spatially specific data on marsh vegetation species and the shoot height, diameter, and density of each species were obtained from the NOAA Ecological Effects of Sea Level Rise project (Voss, C., unpublished data). The vegetation was sampled in three haphazardly placed 25-cm by 25-cm quadrats placed at 1 m, 5 m, 10 m, 20 m, and 30 m from the edge of the marsh, around the area wave attenuation was measured. See Table 2 for the mean plant heights and densities.
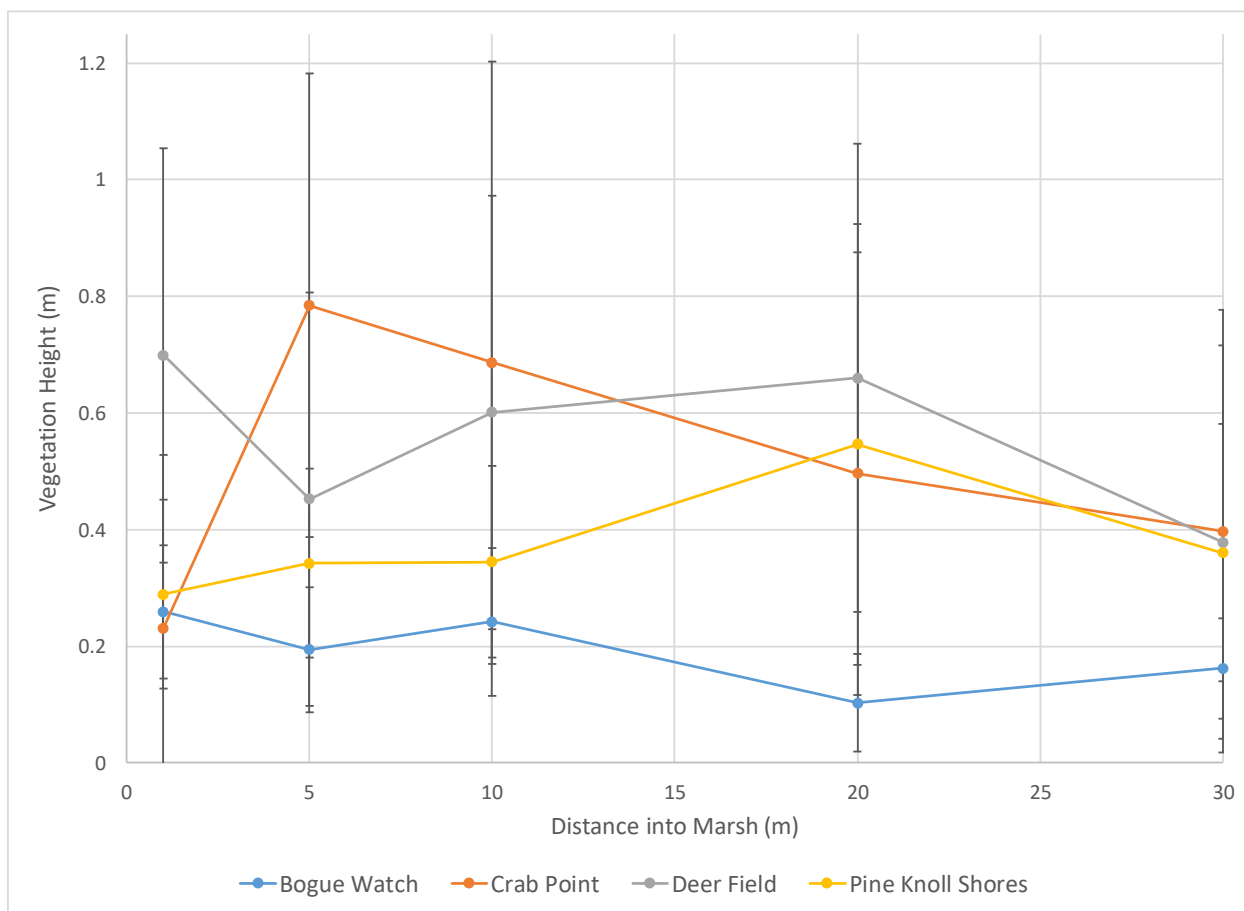

Figure 4. Vegetation height throughout the marsh from 1 m from the seaward marsh edge to 30 m. Values plotted are the mean height from three 25 cm x 25 cm sampling quadrats. The error

bars are the standard deviation of the vegetation heights across the three quadrats at each distance in the marsh.

Bogue Watch consistently has the shortest vegetation. Crab Point has very short vegetation near the marsh edge, followed by the tallest average vegetation in any of the marshes at 5 m. The vegetation then gets shorter from 5 m to 30 m from the marsh edge. There was a large variability in vegetation height within each site. The differences in heights at each site was larger than the differences between sites. Deerfield has tall vegetation overall and has vegetation heights most similar to those at Crab Point. Pine Knoll Shores has shorter vegetation in comparison, though it is still taller than Bogue Watch.
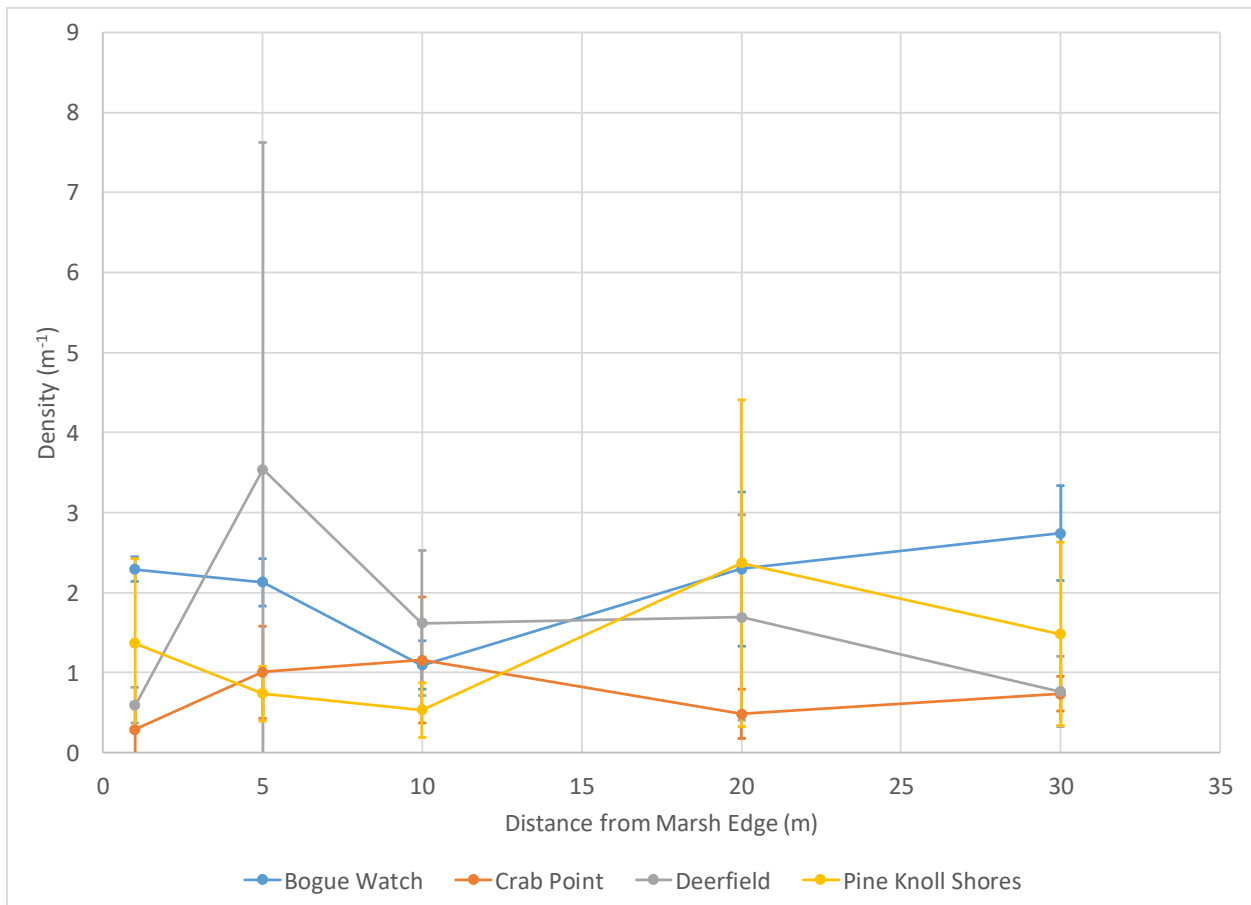
Figure 5. Vegetation Density in each marsh from 1 to 30 m from the marsh edge. Vegetation density is number of plants in each quadrat multiplied by the mean diameter of plants in that quadrat divided by the area in the quadrat (625 cm^2). Densities plotted are the mean values for three quadrats at each distance from the marsh edge and error bars indicate standard deviations.

Bogue Watch has a high vegetation density throughout the marsh, though at 5 m from the marsh edge there is a notable decrease in density, compared to the rest of the site. Crab Point has low vegetation density throughout the marsh. Deerfield has a large peak in vegetation density at 10 m from the marsh edge. Pine Knoll Shores has a smaller peak in vegetation density at 20 from the marsh edge.
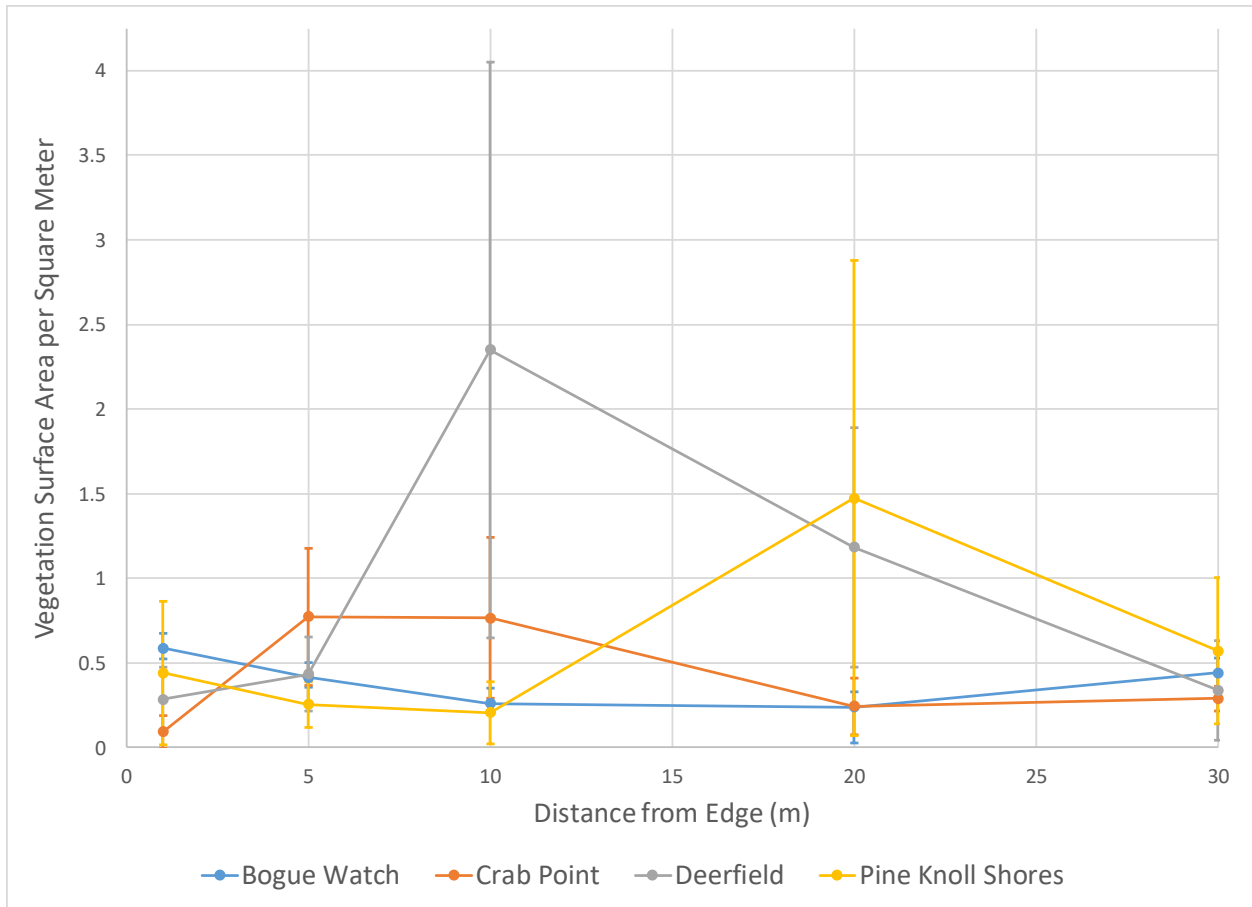
Figure 6. Vegetation frontal surface area in each marsh from 1 to 30 m from the marsh edge. Vegetation frontal surface area is number of plants in each quadrat multiplied by the mean diameter of plants multiplied by the mean height of the plants in that quadrat divided by the area in the quadrat (25 cm^2). Surface areas plotted are the mean values for three quadrats at each distance from the marsh edge and error bars indicate standard deviations.

Bogue Watch has low vegetation frontal surface area throughout the marsh. Crab Point has low vegetation frontal surface area at 1, 20, and 30 m from the edge of the marsh, but a larger vegetation density at 5 and 10 m. Deerfield has a large peak in vegetation frontal surface

area at 10 m from the marsh edge. Pine Knoll Shores has a smaller peak in vegetation frontal at 20 m from the marsh edge.

B. Analysis

In order to isolate the pressure that was caused by the water above each sensor, atmospheric pressure was subtracted from the total pressure measured by the sensor. Atmospheric pressure came from NOAA's National Data Buoy Center, from the Cape Lookout station. The pressure record was divided into 5-minute intervals and the mean pressure was calculated for each interval. Then, using the density of water (1000 kg/m^3), the water depth above each sensor was calculated from the mean pressure. I then created a pressure spectrum, which is the variance of pressure per unit frequency versus frequency. This spectrum was then converted to a surface elevation spectrum, using the relationship between wave height and pressure from linear wave theory (Dean and Dalrymple, 1984):

$$S = \frac{p}{(\rho g)^2}\left(\frac{\cosh k(h+z)}{\cosh kz}\right)^2 \qquad\qquad (1)$$

Where S is the surface elevation spectrum, p is pressure, ρ is density, g is acceleration due to gravity, k is wavenumber, z is distance above the marsh bottom, t is time, H is wave height, and h is water depth. At high frequencies the noise in the data overwhelms the actual data, causing an overestimation of the surface elevation variance actually occurring at those frequencies. The spectrum was therefore cut off above a threshold frequency. The cutoff frequency was determined by the point at which the spectrum was below 80 times the noise

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floor. A f^4 decay was placed on the end of each spectrum beyond the cutoff frequency to estimate the waves at the high frequencies (Jones and Monismith, 2007).

The integral of the surface elevation spectrum was then computed to get the total variance of the surface level fluctuations. We then took the square root of this variance to get the standard deviation, and then multiplied that by four to get the significant wave height. The mean incident significant wave heights for each deployment are in Table 3.

In order to calculate the mean period (T_m), the following equation was used:

$$\frac{\int_0^{nf} f\,F(f)df}{\int_0^{nf} F(f)df} = T_m^{-1} \qquad (2)$$

Where f is frequency and F(f) is the water surface elevation spectrum, and nf is the smallest frequency of wave able to be measured. See Table 2 for the mean of the mean periods of the incident waves observed during each deployment.

3. Results

A. *Conditions during deployments*

There were a variety of water depth ranges during each of the deployments (Figure 6), with maximum depths over the marsh platform ranging from 0.6 m to over 1.2 m. The second deployment at Crab Point, which was during storm conditions, had some the deepest depths, with

depths reaching above 1.2 m at one point. The first deployment at Crab Point had the next

deepest depths, with maximum depths above 1 m. The deployments at Deerfield, Bogue Watch,

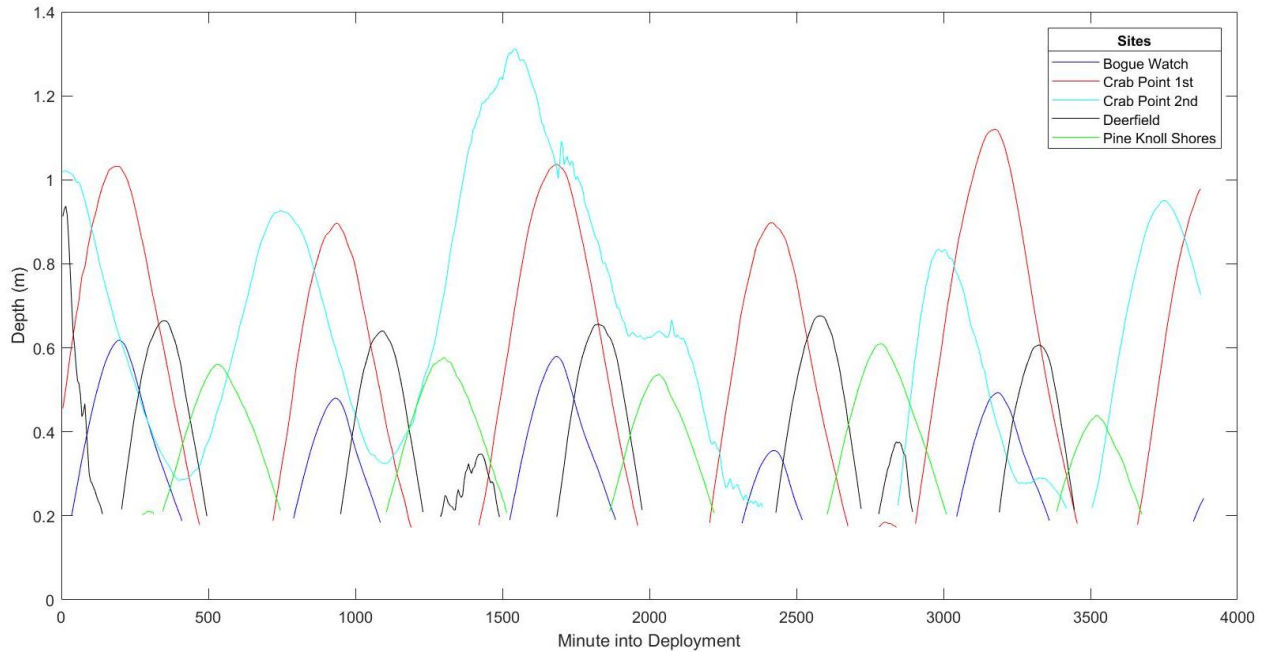and Pine Knoll Shores had much shallower depths by comparison.

Figure 7. Water depths at the 10-m sensor in a time series throughout the deployments. The gaps

in the time series represent times where there was not at least 10 cm of water above the sensor.

Incident significant wave height also varied significantly between deployments at

different sites (Figure 7). The deployment with the largest waves was the second Crab Point

deployment, which was during storm conditions. Deerfield had the smallest waves, with most of

the waves never going above 0.10 m. During all the deployments during regular conditions,

waves remained mostly small, with most of the wave heights less than 0.20 m. Table 3

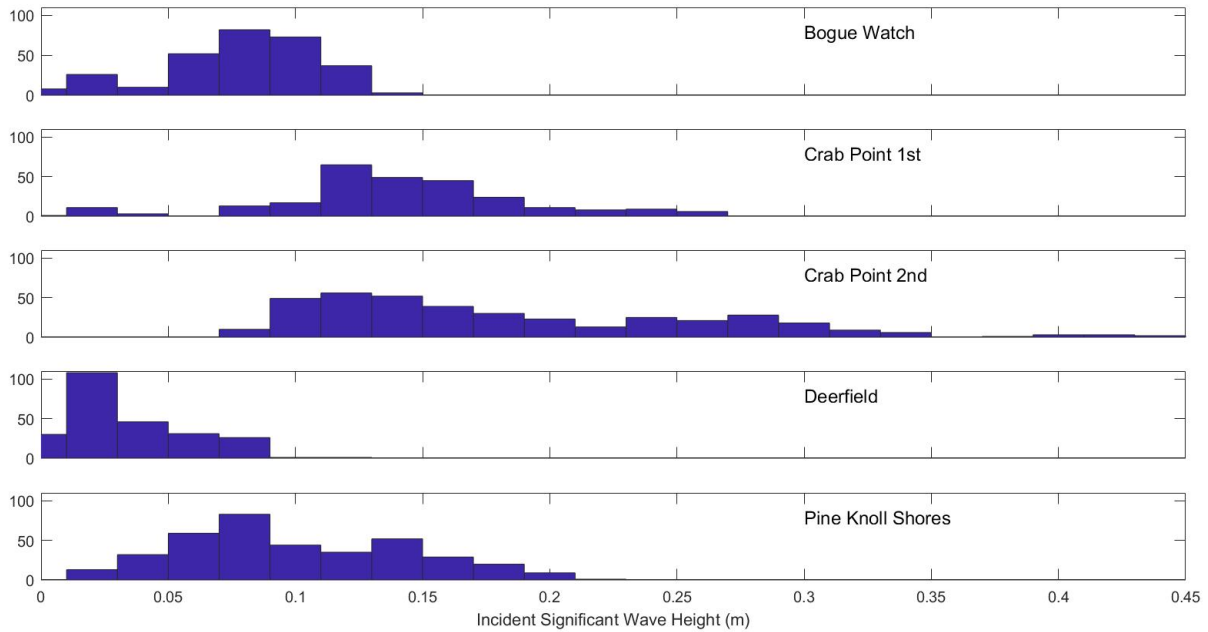summarizes the mean wave heights at all deployments.

Figure 8. Incident Significant Wave Height Histograms during each deployment. On the x axis is the significant wave height and on the y axis is the number of 5-min intervals that had this significant wave height. Each separate plot represents a separate deployment.

Table 3. Wave Conditions During Deployments.

Sites	Significant Wave Height (cm)	Mean Period (s)
Crab Point- 1st Deployment	Mean: 14.11 Std. Dev: 4.87	Mean: 1.19 Std. Dev: 0.21
Deerfield	Mean: 3.44 Std. Dev: 2.31	Mean: 1.56 Std. Dev: 0.51
Bogue Watch	Mean: 7.78 Std. Dev: 3.04	Mean: 0.98 Std. Dev: 0.19
Pine Knoll Shores	Mean: 10.04 Std. Dev: 4.49	Mean: 1.47 Std. Dev: 0.28
Crab Point-2nd Deployment (storm)	Mean: 18.60 Std. Dev: 7.73	Mean: 1.73 Std. Dev: 0.33

The second deployment at Crab Point, during storm conditions, had the largest waves and the waves with the longest periods. During regular conditions, Crab Point had the largest waves, followed in decreasing order by Pine Knoll Shores, Bogue Watch, and Deerfield. Deerfield had the waves with the longest periods during regular conditions, followed in decreasing order by Pine Knoll Shores, Crab Point, and Bogue Watch.

B. *Wave Attenuation*

The reduction of height of the waves was calculated by dividing the significant wave height at each sensor by the incident significant wave height. I split the reductions in wave height into categories based on different water depths during the deployments (Figures 9-12).

Deerfield shows little attenuation in the first ten meters, followed by a steep drop off in wave height beyond this distance from the marsh edge (Figure 9). This could be due to the vegetation density and the topography at Deerfield. The density of the vegetation is low at Deerfield at 0 and 5 m, but is very high at 10 m (Figure 5). A greater density in vegetation would provide greater resistance to the propagation of wave energy in the marsh by causing an increase in friction. Additionally, the topography at Deerfield rises from the edge of the marsh to 10 m from the marsh edge (Figure 3). This could cause shoaling, which would cause an initial increase in wave height. Therefore, in the first 10 m from the marsh edge there would be both a decrease in wave height at Deerfield due attenuation and an increase in wave height due to shoaling.

At Crab Point, wave attenuation was also likely influenced by topography. During the first deployment there, most wave height is lost in the first 10 m from the marsh edge (Figure

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10). This is may be due to the oyster berm that occurs at 5 m from the marsh edge at the site (Figure 3). The oyster berm would cause a loss of energy from the waves due to bottom friction and possibly wave breaking, thus reducing their height.

Pine Knoll Shores (Figure 12) and Bogue Watch (Figure 11) have less wave attenuation than the first deployment at Crab Point (Figure 10) and Deerfield (Figure 9), especially at higher water depths. This may be due to the fact that the vegetation at Pine Knoll Shores and Bogue Watch is shorter than the vegetation at Crab Point and Deerfield (Figure 4). Taller vegetation would affect the wave motion throughout more of the water column, so it reduces wave height more than shorter vegetation.

All deployments show the general trend of less wave attenuation at deeper depths. However, this trend differs in its strength between different deployments. The trends in wave height attenuation with increasing water depth are summarized in Figure 13 and Table 4. The first deployment at Crab Point (Figure 11) and Deerfield (Figure 9) do not have as dramatic a difference in attenuation rate between different water depths as Pine Knoll Shores (Figure 12) and Bogue Watch (Figure 11). Again, this may be due to the fact the vegetation at Crab Point and Deerfield is taller than vegetation at Pine Knoll Shores and Bogue Watch. Figure 14 supports this hypothesis and shows how the taller the vegetation, the greater the rate of decline of wave attenuation with increasing depth.

The first and second deployments at Crab Point have very different patterns of wave attenuation. The second deployment (Figure 13), which was during storm conditions, does not show as much wave attenuation as the first deployment (Figure 10). Additionally, there is greater separation of rates of attenuation between water depths during the second deployment. Water levels were slightly higher during the second deployment, but that does not explain all of the

difference between the two deployments, since during similar water depths wave attenuation

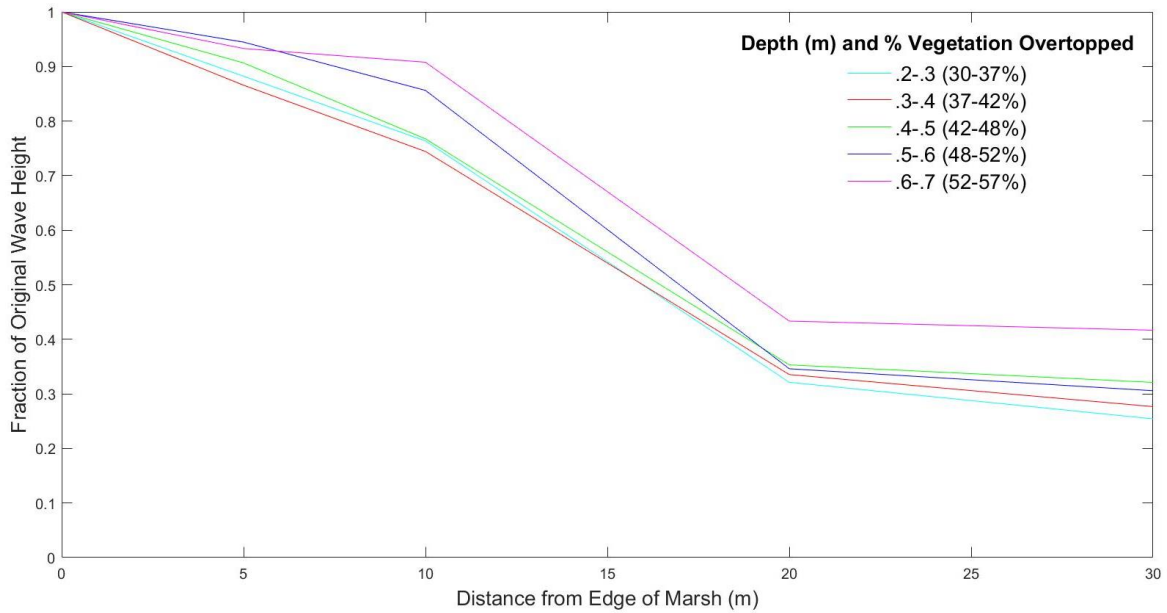rates were smaller during the second deployment.

Figure 9. Wave height reductions (y-axis) at different distances from the marsh edge (x-axis) at

Deerfield. Each colored line represents a different water depth range. The numbers in

parentheses in the legend show the percentage of vegetation overtopped (completely submerged)
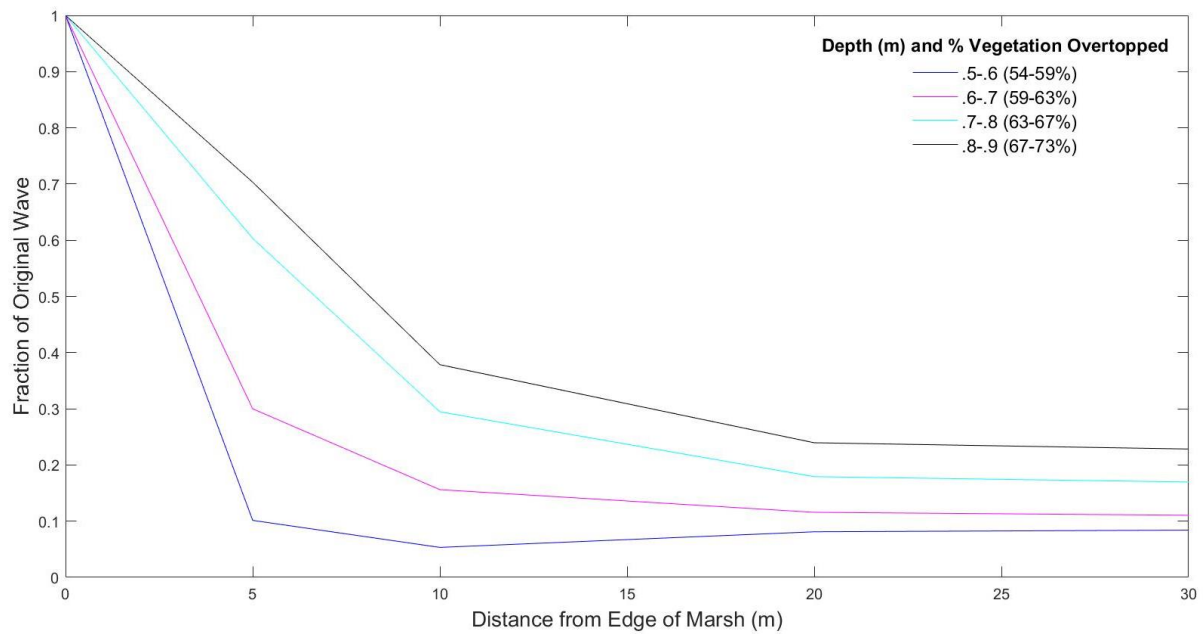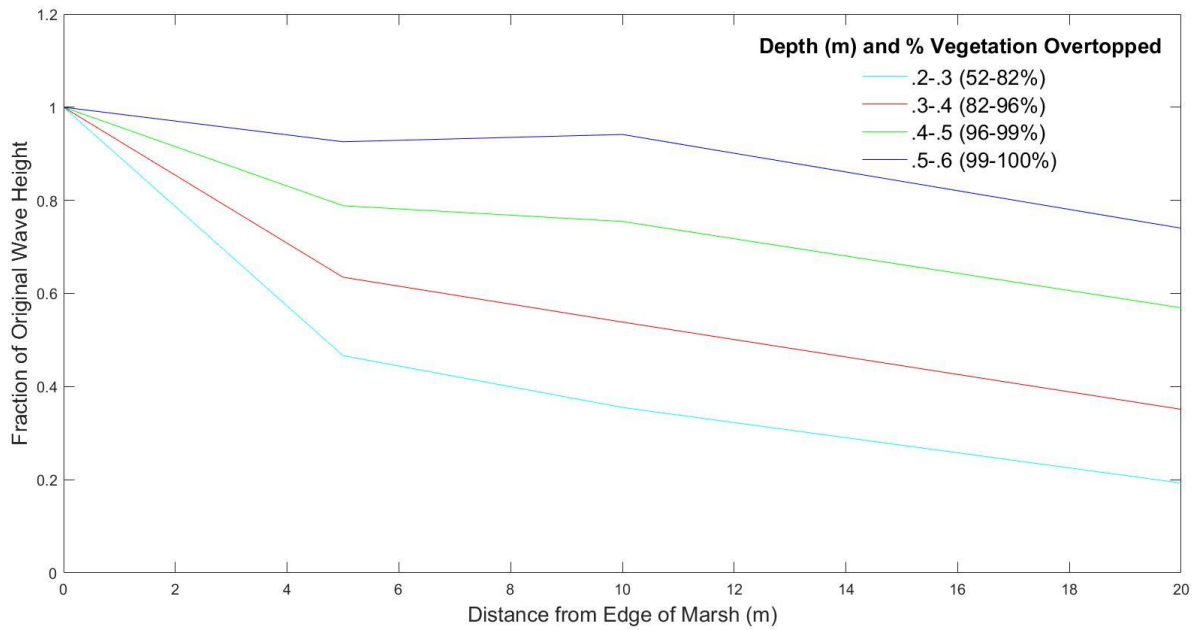
at those water depths.

Figure 10. Wave height reductions (y-axis) at different distances from the marsh edge (x-axis) at Crab Point during the first deployment (normal conditions). Each colored line represents a different water depth range. The numbers in parentheses in the legend show the percentage of vegetation overtopped (completely submerged) at those water depths.

Figure 11. Wave height reductions (y-axis) at different distances from the marsh edge (x-axis) at

Bogue Watch. Each colored line represents a different water depth range. The numbers in

parentheses in the legend show the percentage of vegetation overtopped (completely submerged)
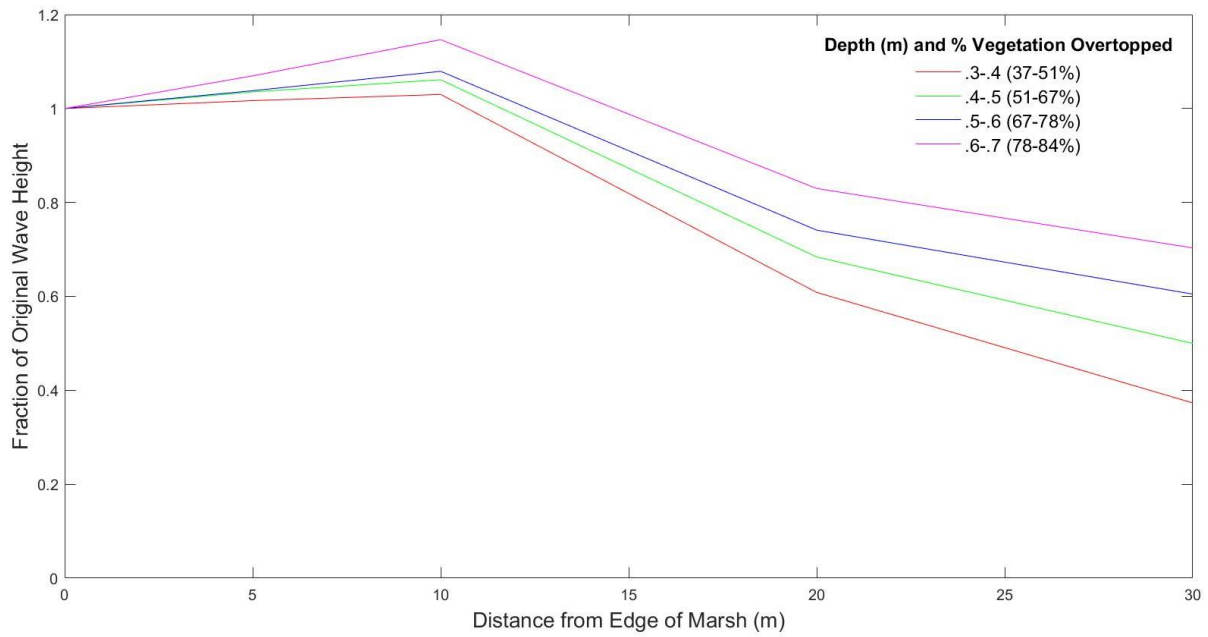
at those water depths.

Figure 12. Wave height reductions (y-axis) at different distances from the marsh edge (x-axis) at Pine Knoll Shores. Each colored line represents a different water depth range. The numbers in parentheses in the legend show the percentage of vegetation overtopped (completely submerged) at those water depths.
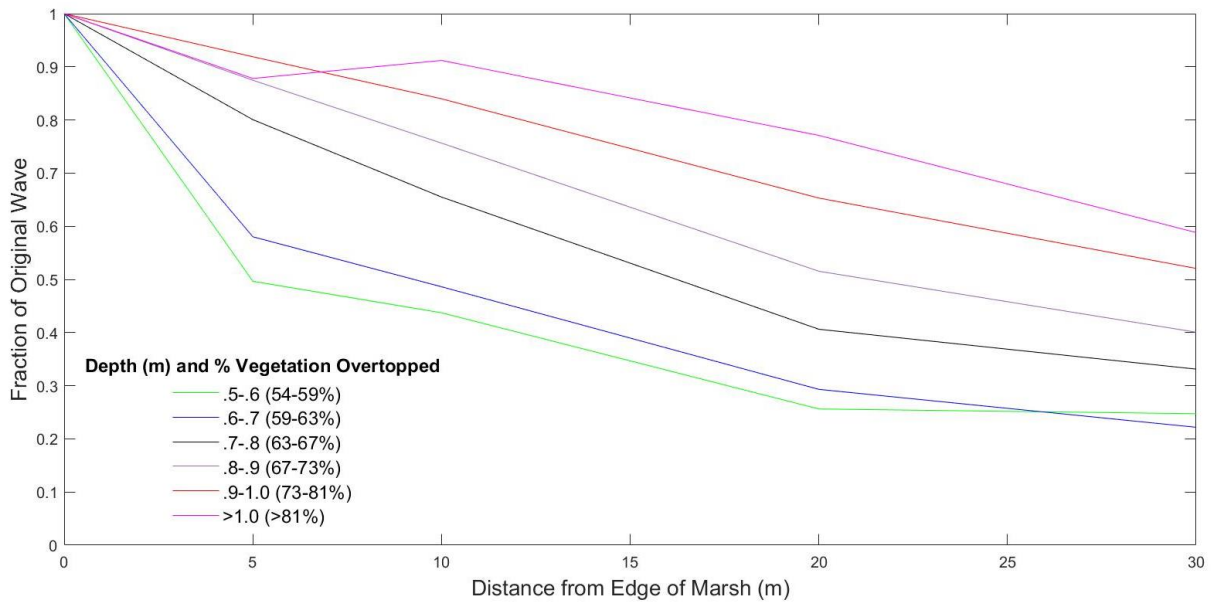
Figure 13. Wave height reductions (y-axis) at different distances from the marsh edge (x-axis) at

Crab Point during the second deployment, which included the passage of Hurricane Matthew.

Each colored line represents a different water depth range. The numbers in parentheses in the

legend show the percentage of vegetation overtopped (completely submerged) at those water
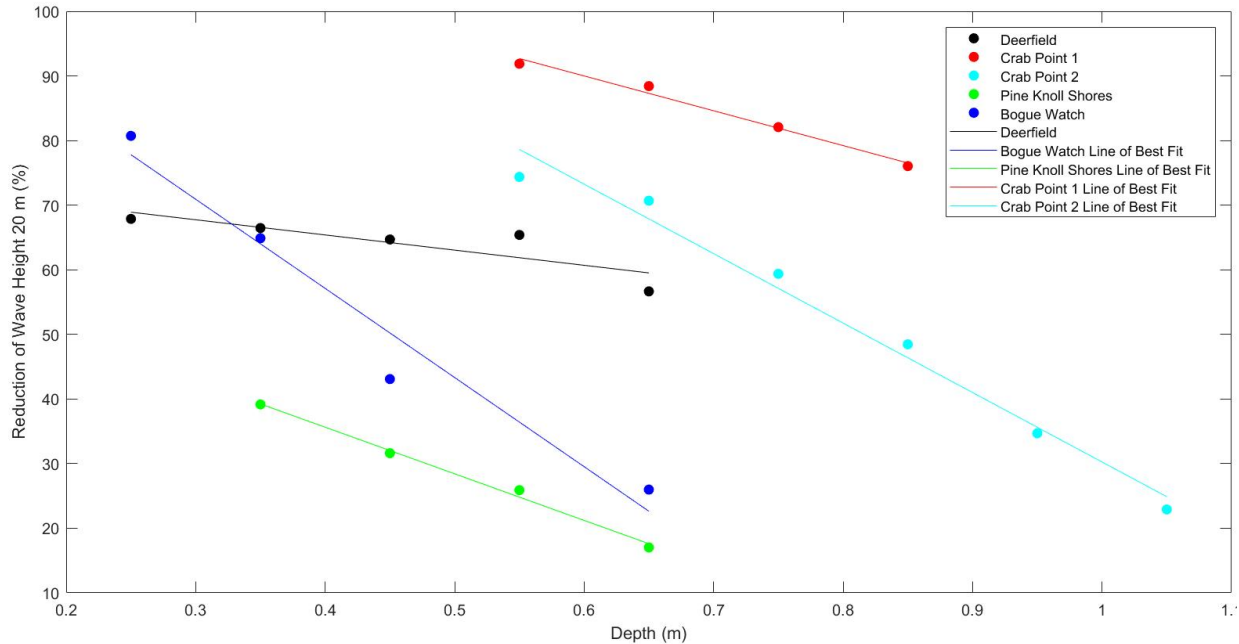
depths.

Figure 14. Reduction of wave height at 20 m into the marsh versus water depth for all deployments. The color of the dots indicates different deployments. The lines are lines of best fit for each of the deployments and are also colored to indicate the deployment.

Table 4. Equations and r-squared values of lines of best fit for the relationship between wave height decline and water depth in Figure 13. For equations in the middle column, y is the percentage of wave height decline by 20 m from the marsh edge and x is the depth of the water on the marsh platform, according to the 10-m sensor.

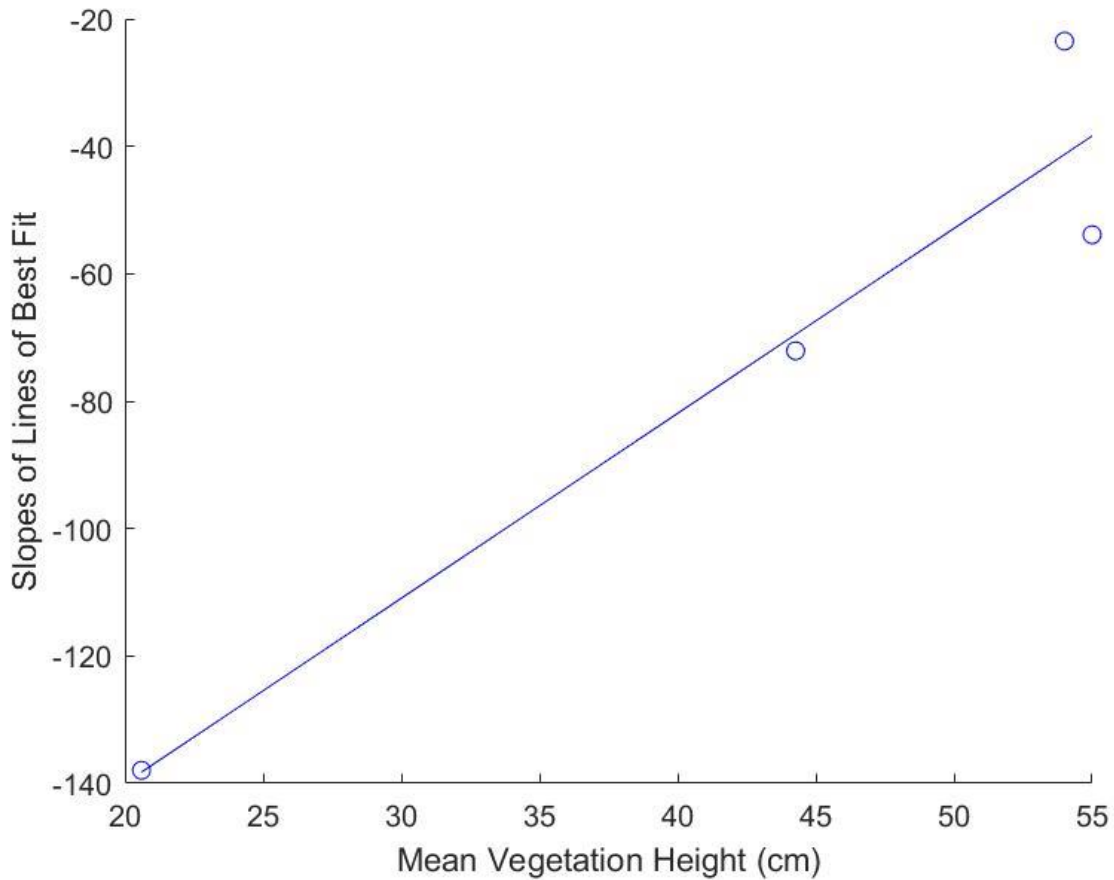| Deployment	Line of Best Fit	R-squared value
Bogue Watch	y=-137.9x+112.3	0.96
Deerfield	y=-23.5x+74.8	0.72
Pine Knoll Shores	y=-72.1x+62.5	0.99
Crab Point – 1st Deployment	y=-53.9x+122.3	0.99
Crab Point- 2nd Deployment	y=-107.5x+137.8	0.98

Figure 15. Slopes of relationships between water depth and wave height reduction from Figure 13, plotted against mean vegetation height.

C. Wave Period

Figures 16-20 display histograms of mean wave periods during each of the deployments at different distances from the marsh edge. There was a general trend of waves with longer periods being damped less than waves with shorter periods, which shifts the distribution of wave periods

to the left, towards the longer periods. This trend is most prominent during the deployment at Pine Knoll Shores (Figure 18) and during the first deployment at Crab Point (Figure 19). The trend is present at Bogue Watch. It is much less prominent at Deerfield (Figure 17) and during the second deployment at Crab Point (Figure 20).

There are differences in the periods of incident waves between sites. The incident waves at Deerfield (Figure 17) and at Crab Point (Figure 20) during the second deployment have a much greater range of periods than during the other deployments. This difference of wave period range may be why there is a difference in the attenuation rates between the first and second deployment at Crab Point (Figures 11 and 12). Since there are more long period waves during the second deployment at Crab Point, and waves with longer periods are attenuated less, this could explain the smaller rate of attenuation during the second deployment.
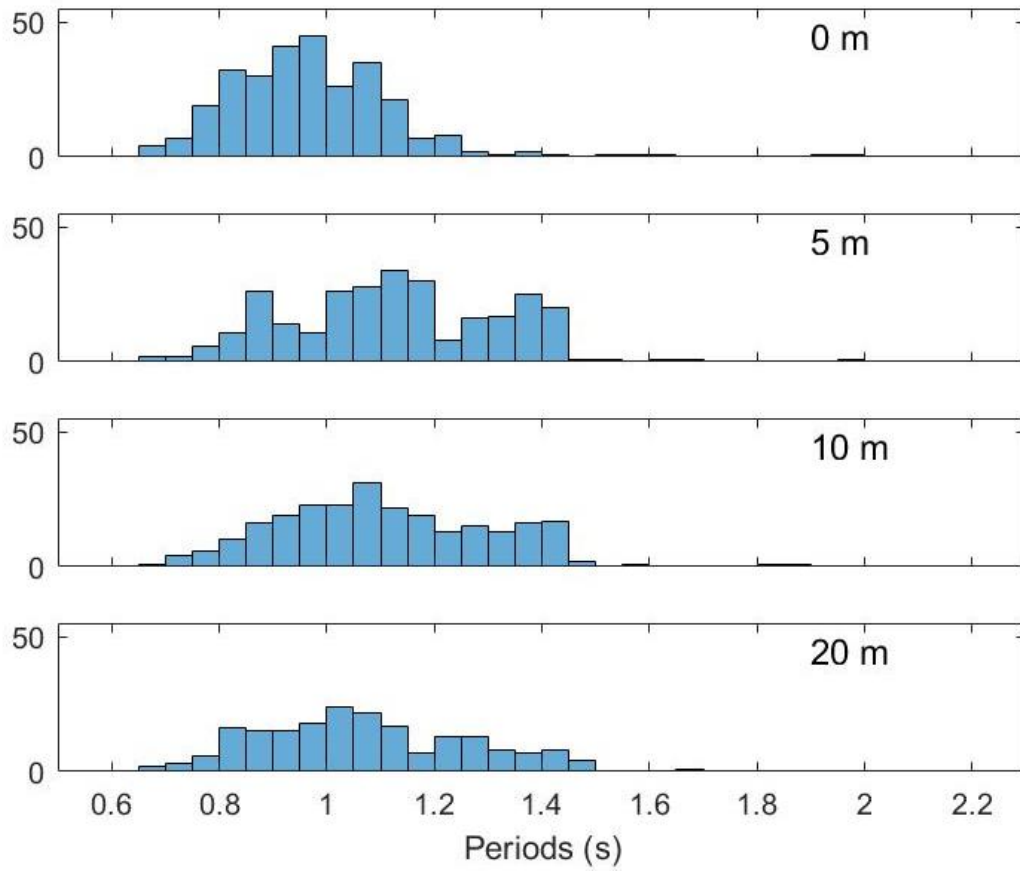
Figure 16. Histograms of the wave periods at different distances into the marsh at Bogue Watch.

The wave periods are on the x axis and the numbers of 5-minute intervals with a mean wave

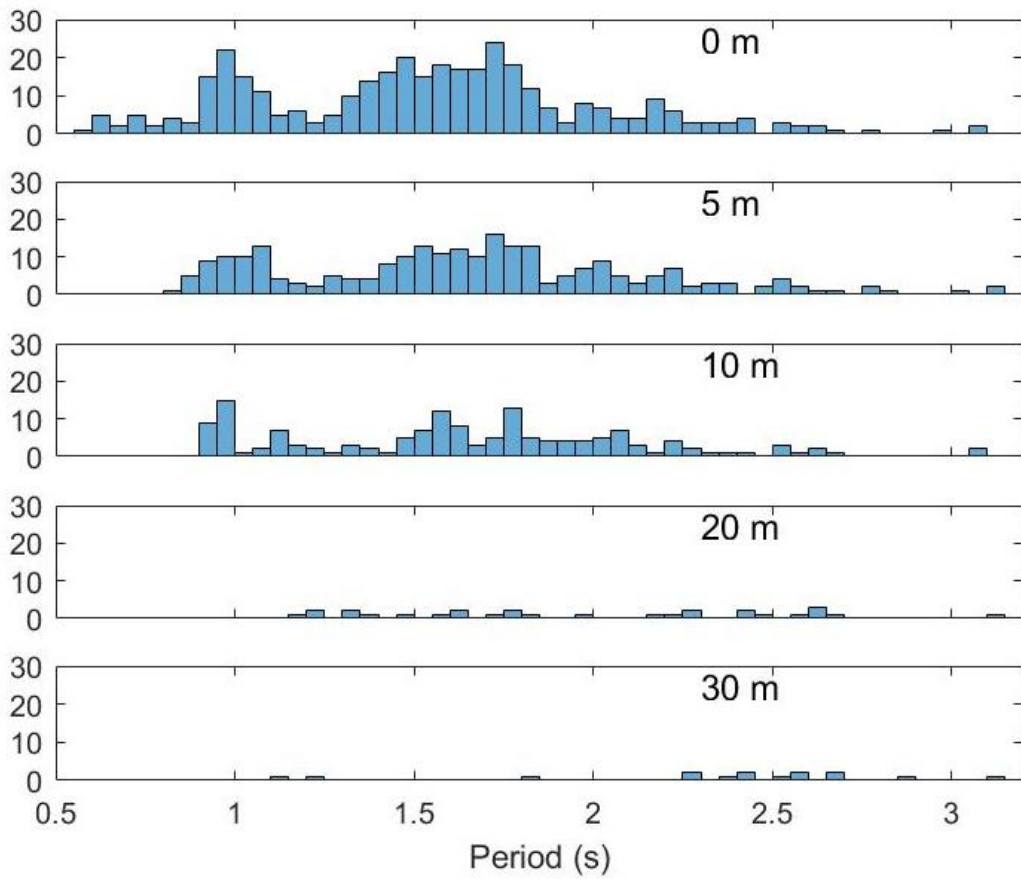period in each range are on the y axis.

Figure 17. Histograms of the wave periods at different distances into the marsh at Deerfield. The wave periods are on the x axis and the number of waves are on the y axis. Each histogram shows the wave periods at a different distance from the marsh edge, as indicated in the upper right corner of each graph.
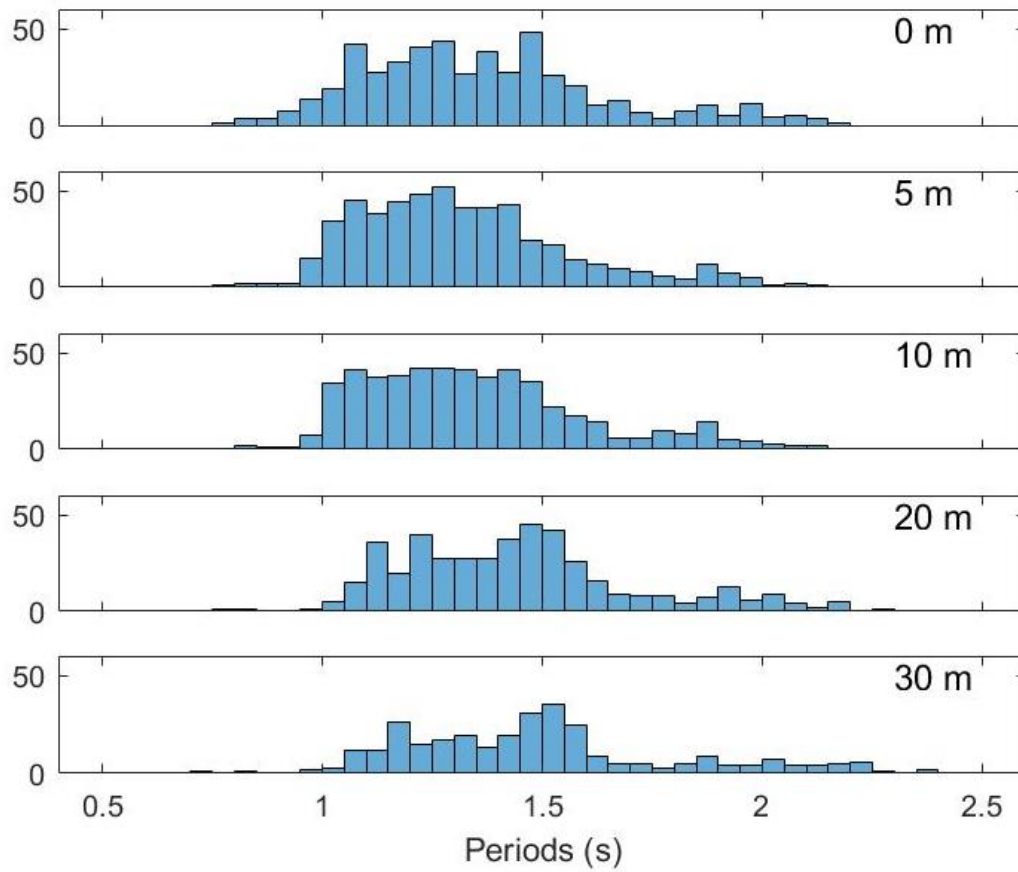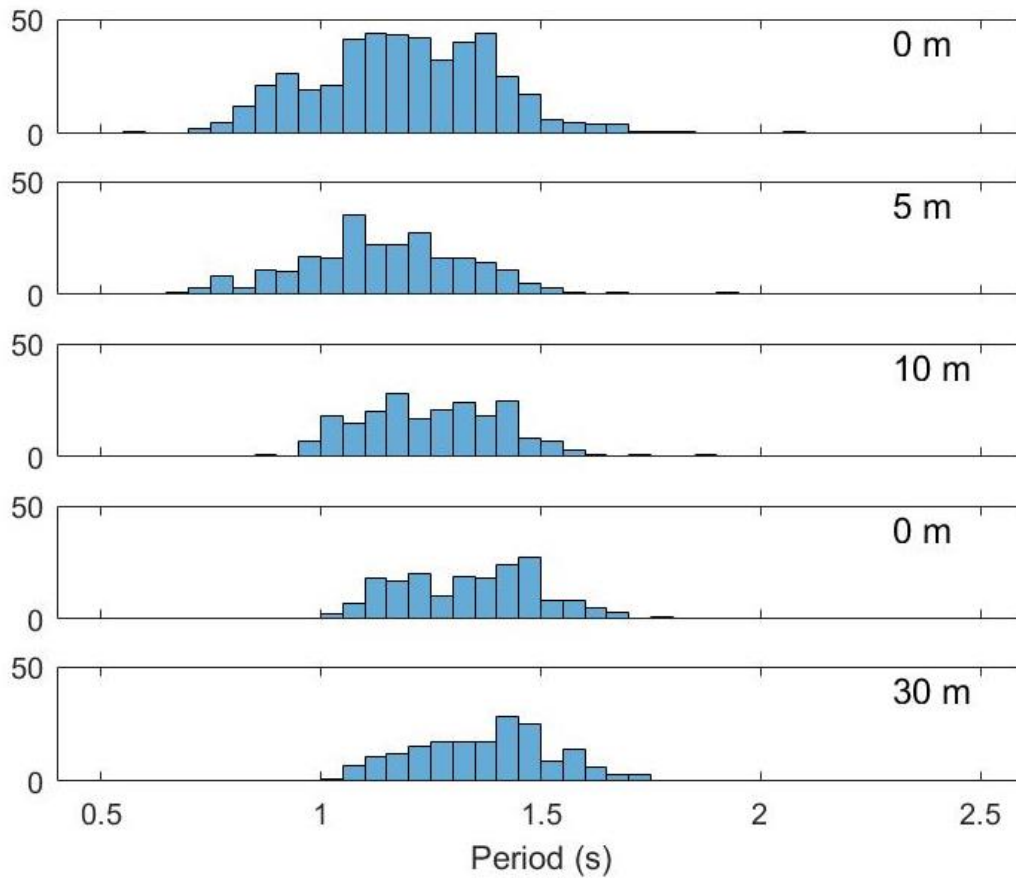
Figure 18. Histograms of the wave periods at different distances into the marsh at Pine Knoll Shores. The wave periods are on the x axis and the number of waves are on the y axis. Each histogram shows the wave periods at a different distance from the marsh edge, as indicated in the upper right corner of each graph.

Figure 19. Histograms of the wave periods at different distances into the marsh at Crab Point during the first deployment. The wave periods are on the x axis and the number of waves are on the y axis. Each histogram shows the wave periods at a different distance from the marsh edge, as indicated in the upper right corner of each graph.
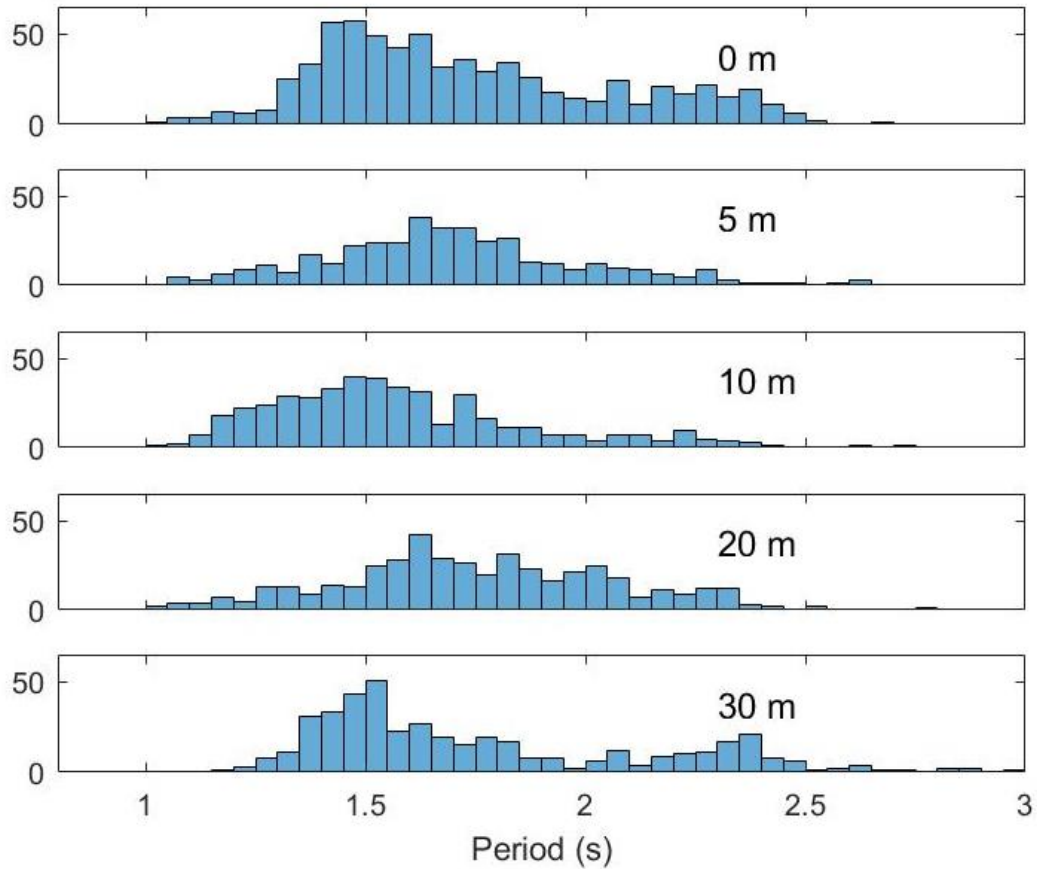
Figure 20. Histograms of the wave periods at different distances into the marsh at Crap Point during the second deployment. The wave periods are on the x axis and the number of waves are on the y axis. Each histogram shows the wave periods at a different distance from the marsh edge, as indicated in the upper right corner of each graph.

4. Discussion

This study examined five factors that affect wave attenuation rates in salt marshes: water depth, vegetation density, vegetation height, marsh topography, and wave period. Overall, the rate of wave attenuation was observed to decrease with greater depth. This was observed during

all deployments. Marshes with taller vegetation had more wave attenuation and the wave attenuation varied less with water depth, when compared to marshes with shorter vegetation. This trend is most likely due to the tall vegetation's ability to occupy the top portion of the water column where the orbital velocity is greatest for a larger range of water depths. It has been previously observed that emergent vegetation is more effective at damping waves than fully submerged vegetation (Augustin et al., 2009). If the vegetation in a marsh is short, then it is more likely to be fully submerged, and less effective at damping waves, at shallower water depths. Additionally, if vegetation is short, then the fraction of the water column occupied by vegetation will vary more as water depth varies than if vegetation is tall.

Greater vegetation density and surface area was also associated with higher rates of wave attenuation. This is most likely due to the greater surface area opposing the wave energy, a combination of greater stem diameter, more plants, and or taller plants. All three of these factors varied from site to site and within sites. At one of the sites, Deerfield, there was a steep drop in wave height after a particularly dense area of vegetation.

Additionally, the steep upward slope of one of the marsh bottoms at Deerfield may have induced wave shoaling. Shoaling initially increases wave height, but when the waves break energy is dissipated. This could be another one of the reasons why wave height did not significantly decrease initially at this site, but then decreased rapidly after the marsh bottom stopped sloping upwards and became flatter. Another marsh bottom feature may have induced energy dissipation Crab Point. There was an oyster berm there which could have acted as a breakwater and dissipated the wave energy. Crab Point had a large drop in wave height around the oyster berm, and the magnitude of this drop in wave height was a strong function of water depth.

Wave period also appeared to have an effect on wave attenuation. Waves of higher frequencies (shorter periods) were typically attenuated more than waves of lower frequencies (longer periods). This trend was stronger at some sites than others. This period-dependent attenuation rate has been observed in another study examining wave attenuation in seagrass where it was attributed to the motion of the grass (Bradley and Houser, 2009). Seagrass moved in phase with the lower frequency waves, but out of phase with the higher frequency waves, effectively acting as a filter for the higher frequency waves. Grass motion could also affect attenuation in marsh grass causing similar effects. Frequency dependent attenuation may also have to do with Keulegan Carpenter number. The Keulegan Carpenter increases with increasing period, and in models of wave damping, a bigger Keulegan Carpenter means a reduced drag coefficient and thus less resistance acting on the wave motion (Mendez and Losada, 2004).

There was also a large difference between the patterns of wave attenuation observed during a storm and those observed during everyday conditions. Attenuation during the storm was smaller overall than normal conditions, despite water depths being similar. The incident wave periods were longer during the storm conditions and, as previously explained, waves with longer periods are attenuated less than waves with shorter periods.

Within this study it is difficult to separate out the causes of wave attenuation to determine which has the largest effect on the variance between the rates during the different deployments. In order to do this, one would need to develop a process based model, such as the model developed explained in Mendez and Losada, 2004.

The attenuation rates during normal conditions in this study are most similar to those found in Knutson et al. 1984 and Yang et al., 2012. During the second deployment at Crab Point, the wave attenuation rates resemble Jadhav et al., 2013, which was also during storm conditions.

Overall, the rates observed in this study are within the range of attenuation rates found by other studies in *Spartina alterniflora* marshes.

5. Conclusion

This study examined various factors affecting wave attenuation in salt marshes. Taller and denser vegetation was associated with higher rates of wave attenuation. Marsh topography played a role in reducing wave energy. A raised area near the front of the marsh acted as a breakwater, which dissipate and refract wave energy, and a steep slope at the front edge of another marsh was thought to cause wave shoaling. Finally, waves with longer periods were attenuated less than waves with shorter periods, though the strength of this trend varied from site to site. Under storm conditions, waves periods were longer, which may be what caused smaller rates of wave attenuation during storm conditions than during regular conditions.

These findings have implications for using salt marshes in living shorelines to attenuate wave energy. When constructing marshes, tall and dense vegetation should be used and one might consider installing features like oyster berms to act as a breakwater. Also, marshes are more likely to be effective at protecting shorelines in areas with short fetches, where wave periods are shorter.

More study is needed on why wave attenuation varies more strongly with wave period on some marshes than others. Additionally, future studies should look at the differences in wave attenuation at *Spartina alterniflora* dominated versus *Juncus roemerianus* dominated marshes. Those plants have different morphologies, with Spartina being a cord grass with leaves and Juncus being needle like, and may have different attenuation abilities. Both species are common to North Carolina marshes.

In conclusion, salt marshes are capable of attenuating waves to protect shorelines, though the rates of attenuation vary with vegetation, morphological, wave period, and depth.

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