

Quantifying Wave Attenuation by Nature-based Solutions in the Galveston Bay

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Abstract: This study assessed the effectiveness of Nature-based Solutions in reducing flood risk in the Galveston Bay, Texas (USA), by means of wave attenuation. The energy-dissipating mechanisms of marsh vegetation, seagrass meadows, and oyster reefs were described and assessed quantitatively with a numerical model. The effectiveness and limitations of the Nature-based Solutions, as well as potential optimization strategies were investigated for the Galveston Bay. Marsh vegetation was found to be most effective in reducing the wave height at the northern shore of Galveston Island, but stem breakage may become a dominant mechanism during extreme storm condition. Oyster reefs are effective at reducing wave height in relatively shallow waters like the Galveston Bay, provided that their location is close to the intended area of wave height reduction. They are especially effective in moderate storm conditions. Seagrass meadows do not significantly attenuate storm waves.

Keywords: Nature-based Solutions, wave attenuation, numerical modeling, flood risk, Galveston Bay, marsh, seagrass, oyster reefs, hurricanes

1 Introduction

1.1 Flood risk reduction by Nature-based Solutions

Flooding is one of the largest hazards in coastal areas. Approximately 40% of the world population lives within a range of 100 km of a coast. In addition, the increase in population in coastal areas is higher than the overall increase in world population (Nicholls & Small, 2002). Significant drivers for coastal flood risk are storms, such as hurricanes. They are accompanied by heavy precipitation and strong wind. The latter generates storm surge and extreme waves in coastal waters, which form a threat in various ways. Hydrodynamic wave loads can inflict considerable damage on coastal constructions such as houses, levees and bridges. Especially breaking waves, that release large amounts of concentrated wave energy at once, can be hazardous (Jin et al., 2010).

Flood protection measures often rely on water retaining structures such as levees and barriers. Apart from using structural protection to reduce flood risk, natural mitigation measures have gained relevance in recent years. Nature-based Solutions (NbS) address a variety of environmental and societal challenges with a sustainable approach. They consist of natural or nature-inspired processes and actions (Temmerman et al., 2013). Such natural measures can contribute in meeting a wide range of challenges, from resilience to climate change to flood risk reduction.

Although the mitigating effects of Nature-based Solutions on flood risk is widely acknowledged, many have not been measured and documented thoroughly. One of the challenges of NbS is the difficulty of quantifying their effects. This certainly holds for their behavior under extreme conditions (e.g. large wave heights and storm surge). This is nevertheless highly relevant, as design requirements for flood risk protection are based on extremely high water levels and low-probability behavior in general.

1.2 Flood risk in the Galveston Bay

The Houston-Galveston Bay Region (HGBR), Texas, U.S.A., is prone to flooding and situated in a complex coastal environment, due to the variety of land use (heavy industry in the vicinity of nature reserves), and a densely populated area. Further, the situation is complicated by a combination of stakeholders with contradicting interests and the large investments needed for flood risk reduction. Hurricane Harvey in 2017 and Hurricane Ike in 2008 made clear that the current protection of the region is substandard. Both led to dozens of fatalities and billions of damages, even though both events were not worst-case scenarios.

In the US, the Federal Emergency Management Agency (FEMA) is responsible for disaster response and pre-disaster mitigation programs. They have been mapping the flood risk in the HGBR and found that, in addition to storm surge and extreme rainfall, large parts of the HGBR are threatened by wave action during a storm or hurricane (FEMA, 2017).

Although a range of possible flood risk reduction measures are available for the area, selecting an optimal strategy is complicated. This is largely due to the size of the area at risk: a single mitigation measure is not enough to reduce the flood risk significantly in the entire area. Multiple measures have been suggested and investigated independently and each measure favors a different zone and different stakeholders. To investigate the optimal risk reduction strategy, van Berchum et al. (2018) developed a model that optimizes a combination of flood risk mitigation measures. It calculates the economic impact of a strategy in terms of investment costs and expected damage. Non-economic performance indicators can also be included. In order to assess the feasibility of NbS in a flood risk reduction strategy in the Galveston Bay, their ability to contribute to flood risk reduction should be quantified.

1.3 Research objective

The mechanisms of NbS that contribute to flood risk reduction due to wave attenuation are not yet fully understood. Although implementation of NbS to reduce wave-related risks has been acknowledged, their effectiveness has not been studied thoroughly and quantitatively. As a result, it is unknown if NbS will be effective in the Galveston Bay and, in case they are, how they can best be implemented.

Considering the above, there is a need for quantitative assessment of the wave-height-reducing capacities of Nature-based Solutions. This contributes to the effective implementation of NbS in flood prone areas, such as the Galveston Bay. Quantitative assessment can contribute to design guidelines for Nature-based Solutions. In short, the research objective for this study is as follows:

Assess the effectiveness of Nature-based Solutions in reducing flood risk in the Galveston Bay by means of wave attenuation.

2 Methods

In order to assess the effectiveness of Nature-based Solutions in the Galveston bay, the wave height reduction by NbS should be described quantitatively. Both literature review and numerical modeling were used to analyze the wave attenuating mechanisms of Nature-based Solutions and to quantify wave height reduction in the Galveston Bay. Literature of previous research was used to select promising NbS for wave height reduction. As the case study of this research will focus on the Galveston Bay, the selection of NbS also links to the environmental and climatic conditions of that region.

Next, the wave height reducing processes that can be recognized in the selected Nature-based Solutions were schematized and included in a 1D numerical wave propagation model. Section 2.2 discusses the details of the model. The use of a numerical model makes sense, as it can simulate the behavior of Nature-based Solutions beyond that of the field measurements. Further, the numerical model can be used as a tool to gain insight into wave energy dissipation by Nature-based Solutions.

An analysis of wind and water conditions in the Galveston Bay was made with observations from the NOAA¹ to derive realistic input for the model for the Galveston Bay case study. For various return periods, the model input parameters for the wave climate were derived (i.e. wind speed, water depth, wave height, wave period) with use of extreme value analyses of historic observations. This is done

¹ The U.S. governmental scientific agency that focuses on meteorological, climatic, and oceanographic conditions.

because flood risk is often explained in terms of return periods (e.g. 'a 100-year water level'). Next, the numerical model was used to simulate and assess the wave behavior under influence of NbS at two normative locations in the Bay. The characteristics of the simulated NbS are hypothetical but realistic, as they are based on previous field observations.

The results of the simulations can be used to assess the potential wave reduction in the Bay due to NbS. As the simulations were conducted for various return periods, the resulting wave reduction rates indicate potential flood risk reduction in the Galveston Bay. Subsequently, the results were further refined through optimization of the configuration of the NbS. The limitation of applicability of the NbS were investigated, which helps to indicate promising locations for NbS in the Bay.

2.1 Wave height reduction by nature-based solutions

When considering coastal protection, three often heard functions of Nature-based Solutions are their potential for surge reduction, wave attenuation, and sediment trapping. Narayan et al. (2016) and Scyphers et al. (2011) show that vegetation and reefs are promising natural structures to attenuate waves. Because many types of NbS show potential to attenuate waves (e.g. mangroves, kelp, wetland vegetation, coral reefs, oysters), the (historically) natural occurrence of reef and vegetation species in coastal zone in the Galveston Bay was investigated, based on Gonzalez and Lester (2011); Pulich et al. (1996); GalvestonBayFoundation (2016); Laffoley and Grimsditch (2009) and HoustonWilderness (2007). It was found that marsh vegetation (fig. 1), seagrass meadows (fig. 2), and oyster reefs (fig. 3) are promising NbS with the capability to attenuate waves and can prevail in the Houston-Galveston Bay Region. These three NbS were selected for further research and quantification.

Next, wave energy dissipating mechanisms will be matched with the selected Nature-based Solutions. The mechanisms that closely resembles the hydrodynamic behavior of each NbS, will be used to simulate the effect of the NbS on the wave height.

2.1.1 Wave energy dissipation by selected Nature-based Solutions



Fig. 1. Marsh vegetation. Source: Texas CWP



Fig. 2. Seagrass meadow. Source: New Scientist



Fig. 3. Oyster reef. Source: The Nature Conservancy

2.1.2 Wave energy dissipation mechanisms

In order to quantify wave height reduction by NbS, wave energy dissipation mechanisms were analyzed. As adopted from Vuik et al. (2018) the wave energy balance (1) can be used to quantify wave height reduction, as wave height is directly related to wave energy (2). In this case, the dissipation of wave energy in the coastal zone is effectively obtained by three processes: depth-induced breaking, bottom friction, and vegetation induced drag. Subsequently, the wave energy balance is composed as follows:

$$\frac{\delta(Ec_g)}{\delta x} = S_{in} + S_{ds,br} + S_{ds,bf} + S_{ds,veg} \quad (1)$$

with total wave energy:

$$E = \frac{1}{8} \rho g H_{rms}^2 \quad (2)$$

and wave group celerity c_g [m/s], root-mean-square wave height H_{rms} [m], water density ρ [kg/m³], gravitational acceleration g [m²/s], distance x [m], energy source wind S_{in} [J/m²], energy sink depth-induced breaking $S_{ds,br}$ [J/m²], energy sink bottom friction $S_{ds,bf}$ [J/m²] and energy sink vegetation induced drag $S_{ds,veg}$ [J/m²].

Depth-induced breaking is the effect that waves become too steep in shallow water and start to break (Battjes and Stive, 1985). Bottom friction is caused by bottom elements that slow down the wave motion if a wave passes over the bed, expressed through bottom roughness K_s and a friction coefficient f_w (Swart, 1974, Johnsson, 1966). Vegetation-induced drag is caused by rigid submerged vegetation. When a wave motion passes vegetation, it causes turbulence, which dissipates wave energy. An important parameter is the drag coefficient C_D , that needs to be calibrated when applying this method (Mendez and Losada, 2004).

The numerical modeling to simulate wave height reduction in this study was conducted with a Matlab-based model for 1D wave propagation in coastal waters. It is entirely based on the principles of SWAN (Simulating WAVes Nearshore). The configuration of Vuik et al. (2016) was used to explore the possibilities of Nature-based Solutions in attenuating storm waves in the Galveston Bay.

2.1.3 Marsh vegetation

Typical marsh vegetation consists of different types of bulrush and marsh grasses (both reed-like plant types), with upright, stiff stems. Marsh vegetation is usually uniform in diameter and height, which supports the selection of the vegetation-induced drag approach. Several authors found that typical marsh vegetation is effective in reducing wave height (Jadhav and Chen, 2012; Ysebaert et al., 2011). Vuik et al. (2016) shows that even if the vegetation is deeply submerged, it can still attenuate waves significantly.

The method of Mendez and Losada (2004) considers each plant as an individual cylindrical element and takes into account vegetation-specific properties, such as the number of stems per m² and the height of the vegetation. The method assumes all energy dissipation by vegetation is a result of drag. A species and site-specific calibration of the bulk drag coefficient C_D is necessary. This approach represents the physical mechanisms that occur in the vegetation field more accurately than an approach where vegetation is accounted for via bottom friction.

Vuik et al. (2016) also looked into vegetation under storm conditions. Apart from their own measurements, they reanalyzed the data set of Yang et al. (2011), in which smooth cordgrass (*Spartina Alterniflora*) was the principal species. After calibrating their model with the observations, they proposed a drag coefficient of 0.4 for smooth cordgrass under high-energetic conditions ($Re > 1000$).

2.1.4 Seagrass meadows

Little research has been done on the effect of seagrass meadows on wave attenuation under storm conditions. However, Infantes et al. (2012) investigated the behavior of waves over deeply submerged seagrass meadows (less than 20% of the water column occupied) and found that the wave reduction was significant. They adopted the formula of Mendez and Losada (2004) and used their measurements to calibrate the drag coefficient C_D .

Paul and Amos (2011) observed a larger water depth and larger waves. They also calibrated the C_D in their study and compared it with several other calibrations. Their study leads to more conservative results for C_D in comparison to Infantes et al. (2012).

In this study, a drag coefficient of 0.13 is adopted, which is reasonable for storm conditions (Vuik et al., 2016). This assumption is further supported by the fact that for high Reynolds numbers ($Re > 1000$), the C_D converges to a constant value.

2.1.5 Oyster reefs

Oyster reefs thrive in salt and shallow water in the tidal zone. They hatch on hard substrate such as rock and old shells, and are able to form columns. Reefs can occupy vast stretches of a bay if the conditions are favorable and can act as a natural breakwater. Scyphers et al. (2011) investigated oyster reefs and confirmed their wave attenuating capacities. Additionally, they found that the reefs trap sediment and thus could prevent shoreline erosion locally.

Styles (2015) researched the impact of oysters on hydrodynamic processes and found that the main effect of an oyster reef is an increased bottom roughness and a change in bathymetry. He accounts for

a flat oyster bed by empirically adapting the Nikuradse roughness K_s of the bottom. He found that a value of 5 times the length of an average oyster gives an acceptable fit for the Nikuradse roughness for the bottom friction. He further mentions that an oyster reef only affects waves if the waves can 'feel' the reef. Consequently, the effect of an oyster reef reduces when the water depth increases. This assumption was confirmed by Volp, van Prooijen, Ysebeart, and Dijkstra (2012), who found a linear maximum for the influence of an oyster reef, depending on the height of the reef and the water depth.

Subsequently, in this study oyster reefs are accounted for by bottom roughness and an increased bed level. It is assumed that a bottom roughness of 0.3 m for an average oyster bed gives an acceptable estimate to account for the bottom roughness. Ecoshape (n.d.) also uses an increased bottom roughness for different types of shellfish in a roughness module that can be included in the numerical model Delft3D. They suggest a K_s of 0.15 m for mussels, which supports the assumption of 0.3 for oysters (being rougher and larger than mussels). A increased bed level of max. 0.5 m is used in this study to account for the bathymetry of the reef. This increased bed level can cause depth-induced wave breaking (Volp et al., 2012).

2.2 Model description

The SWAN model (Booij, Ris, & Holthuijsen, 1999) is widely used to simulate wave behavior in coastal areas. It is a numerical wave model that can predict wave parameters in near-shore and inland waters, given incoming wind, wave, and bathymetry conditions. The model is based on the wave action balance and includes several hydrodynamic processes that influence the wave energy (sources and sinks). Here, the effect of vegetation on waves can also be included. Suzuki et al. (2012) validated the performance of a vegetation module in SWAN. Vuik et al. (2016) calibrated and validated the vegetation module of SWAN with new field data and used it to compute the reduction of the incident wave height on a dike under storm conditions.

The model simulates 1D wave propagation by evaluating the wave energy balance, for each grid point. It uses characteristic wave parameters (H_s and T_p) that represent a wave spectrum. This implies that certain frequency dependent processes are not captured in the model. Although the model is very well capable of simulating the effect of vegetation on wave energy, the model was slightly altered in this study to also account for oyster reefs. The model is a representation of an idealized situation and includes simplifications and assumptions. An overview of the input parameters, hydrodynamic processes and output parameters is given below.

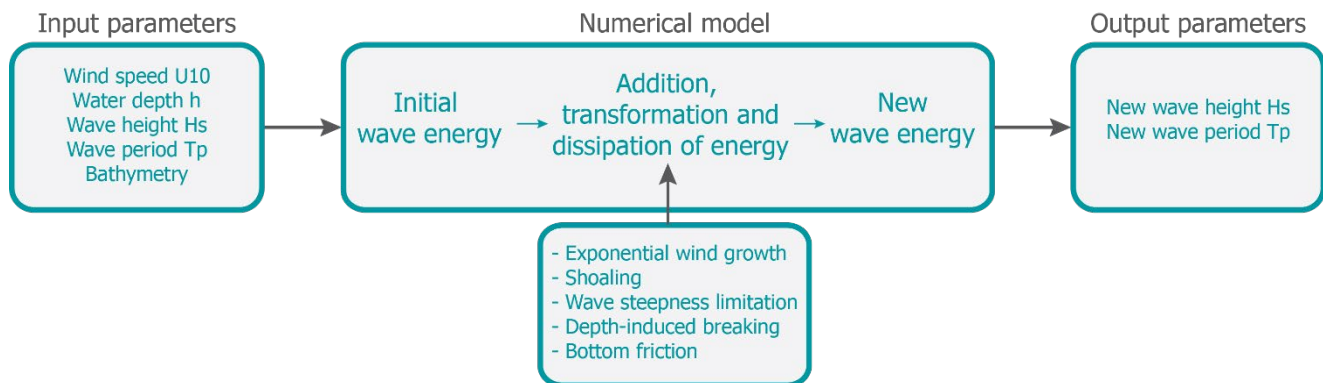


Fig. 4. An overview of the input parameters, hydrodynamic processes and output parameters that were used in the model.

2.3 Model validation

The formula of Mendez and Losada (2004) for vegetation-related energy dissipation was included in SWAN and validated by Suzuki et al. (2012). Vuik et al. (2016) used measurements of stormy conditions to validate the model for the influence of vegetation for a large water depth and wave height. They chose the bulk drag coefficient C_D as main calibration parameter and used three data sets with field observations. One of their calibration results was a C_D of 0.4 for high Reynolds numbers (e.g. stormy conditions).

The implementation of an oyster reef in the model, although based on existing mechanisms, should be tested, as it has not been applied this way before. However, published data of experiments on wave attenuation by oyster reefs are scarce. Two sets of published measurements were found and used to

validate the method (Borsje et al., 2011 and Manis et al., 2014). Both are laboratory observations, made in a flume. Unfortunately, no published observations of wave attenuation over oyster reefs for stormy conditions are available. The model was configured to match the conditions in the studies as closely as possible and it was found that the observed reduction of Manis et al. (45% wave height reduction) could be modeled accurately (49% wave height reduction). The valuation with the observations of Borsje et al. (2011) was less accurate (50% vs. 26% wave height reduction). However, in absolute terms, the difference was less than 0,01 m.

In spite of the limited validation data, the model is assumed to be reasonably accurate, because both model simulations follow the general behavior of a gradually reducing wave height and a significant total reduction.

3 Case study: Galveston Bay

The model assesses the effectiveness of the selected NbS in the Galveston Bay at two locations that are prone to wave action during storm conditions. For both locations, a schematized cross-shore section and hydrodynamic boundary conditions were derived, namely water level, wave height, wave period and wind speed, for return periods varying from 10 to 500 years.



Fig. 5. Overview of the Houston-Galveston Bay Region. Location of case study at northern shore of Galveston Island.

In order to assess the effect of the NbS, a characteristic location was selected, where the wave height with and without influence of Nature-based Solutions are compared (i.e. the first line of houses at the coast). Although two locations near the Galveston Bay (San Leon and Galveston Island) were researched, only the results of Galveston Island will be presented because it was found that the results for San Leon give limited insight in the effect of the NbS. This is because the wave height reduction was largely due to the bathymetry of the location at San Leon, and NbS had little additional effect. Both San Leon and the site at the northern coastline of Galveston Island is shown in Fig. 5.

3.1 Numerical simulations for the Galveston Bay

Galveston Island is largely protected from extreme surge and waves at the Gulf-side by the Galveston Seawall. However, the northern side is vulnerable to both surge and waves. This is especially the case when a hurricane crosses the area, due to its rotating character. Both waves and surge can be piled up against the northern side of the island by the wind. Note that in this case study the waves are locally

generated wind waves. Also, the bathymetry at this location is very suitable, due to its gradual slope. This enables better assessment of the effect of the Nature-based Solutions, as the abrupt change in bathymetry that causes strong wave breaking, is absent. Fig. 6 shows the cross section and set-up used in the model.

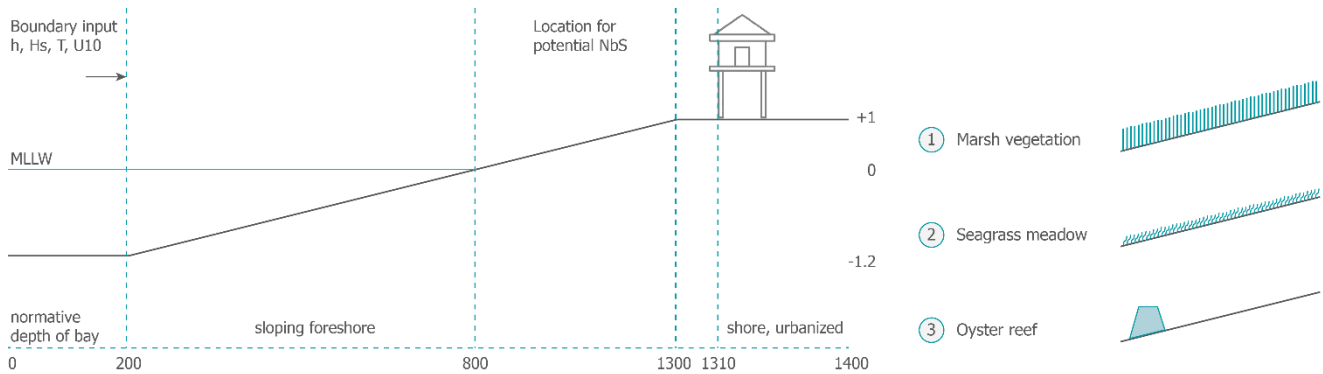


Fig. 6. Schematized cross section of Galveston Island location. Point [1310] is the location of reference, where the effect of NbS is compared.

3.1.1 Hydraulic parameters

An overview of the input parameters for the numerical model is given in tab. 1. The values were derived by applying extreme value analysis on the historical observations in the Galveston Bay (FEMA, 2012).

Tab. 1. Simulated significant wave height and significant wave period near Galveston Island.

	Galveston Island				
Return period	h	U_{10}	H_s	T_s	H_s/h_{abs}
[years]	[m]	[m/s]	[m]	[s]	[-]
10	2.59	18.9	0.81	3.14	0.21
50	3.17	24.7	1.08	3.55	0.25
100	4.09	28.0	1.27	3.76	0.24
500	5.34	37.8	1.76	4.32	0.27

3.1.2 Nature-based Solution parameters

In the Galveston Bay region, salt marshes dominate the areas close to the water line. Smooth cord grass (*Spartina alterniflora*) is the dominant shoreline species and was used as the reference species in this study. A hypothetical marsh is incorporated in the model to investigate the effect of marsh vegetation on the wave height (see fig. 6). Values for marsh characteristics from reference studies with field measurements were used in the model as input for calculation of the vegetation-induced drag (Keefer, 2017; Vuik et al., 2016; Yang et al., 2011; Jadhav & Chen, 2012). These values are shown in tab. 2 and represent averages of values from the aforementioned reference studies.

Tab. 2. Characteristics of *Spartina alterniflora* as used in the numerical model. N_v is density in stems per m^2 , b_v is the stem diameter in m , h_v is the vegetation height in m .

Density N_v	Stem diameter b_v	Vegetation height h_v	Drag coefficient C_D
[m^{-2}]	[m]	[m]	[-]
491	0.006	0.58	0.4

Similar to marsh vegetation, a hypothetical -but realistic- seagrass meadow is incorporated in the model. The dominant species in the Galveston Bay is *Thalassia testudinum* (turtle grass). Specific characteristics of the vegetation that stem from observations from reference studies were used (Bradley & Houser, 2009; Fonseca & Cahalan, 1992; Congdon & Dunton, 2016; Medina-Gómez, 2016; Vidal & Basurto, 2003). The applied values are given in tab 3.

Tab. 3. Characteristics of *Thalassia testudinum* as used in the numerical model. N_v is density in stems per m^2 , b_v is the stem diameter in m , h_v is the vegetation height in m .

Density N_v	Stem diameter b_v	Vegetation height h_v	Drag coefficient C_D
$[m^{-2}]$	$[m]$	$[m]$	$[-]$
941	0.0035	0.21	0.13

The third Nature-based Solution that was incorporated in the numerical model is an oyster reef. Several reference studies were used to compose a realistic oyster reef, to include in the numerical model (Styles, 2015). In view of wave reduction, relevant characteristics of an oyster reef are its location, dimensions and roughness. The location of the reef is mostly determined by the tidal range at the location: oysters need to be alternately emerged and submerged on a daily base. The used values are given in tab 4.

Tab. 4. Oyster reef parameters used in the numerical model.

Height top h_{top}	Width b	Nikuradse roughness of reef k
$[m]$	$[m]$	$[m]$
0.5	30	0.30

4 Results

The wave height at the first line of houses on shore was compared for the situation with and without placement of Nature-based Solutions.

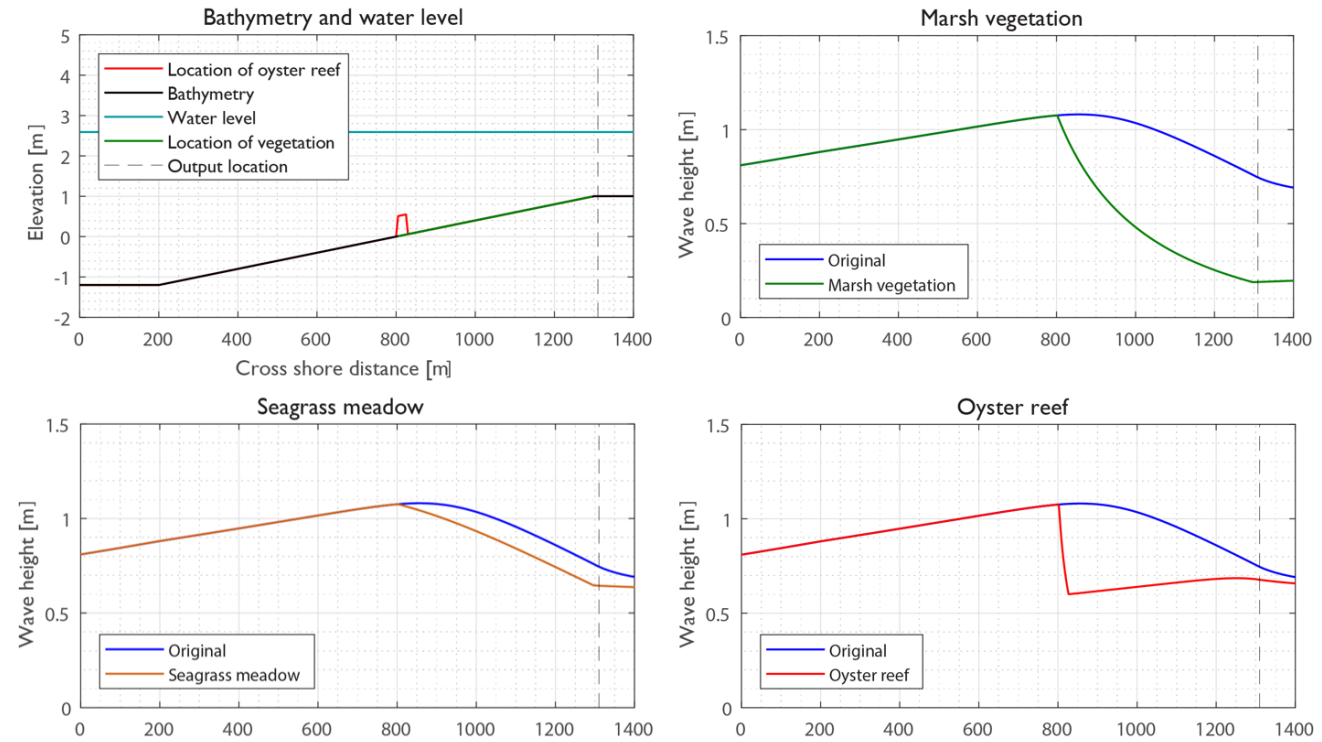


Fig. 7. Upper left: schematized cross-section of the Galveston Island location, as included in the numerical model. The characteristic location, which is ten meters from the shoreline, is visualized as the dotted line (i.e. the first line of houses). The cross shore distance in meters corresponds to the numerical model grid. The figure shows the resulting wave heights in a 1 in 10 years situation. The x-axis shows the cross shore distance in all four panels. Three configurations of Nature-based Solutions are used (panel 2 upper right: marsh vegetation, panel 3 down left: seagrass meadow, panel 4 down right: oyster reef).

The results at Galveston Island for a 100-year return period are shown in fig. 7. The grid points in cross shore direction in these graphs correspond to the cross shore distance shown in fig. 6. An overview of the results is given in tab. 5.

Tab. 5. Summary of results: residual significant wave height at output location for Galveston Island location and the reduction rate w.r.t. the wave height without NbS.

Return period	Without NbS	Marsh vegetation	Seagrass meadows	Oyster reef
[years]	[m]	[m]	[m]	[m]
10	0.75	0.19 (-75%)	0.64 (-14%)	0.68 (-9%)
50	1.05	0.32 (-70%)	0.93 (-11%)	1.00 (-4%)
100	1.53	0.61 (-60%)	1.40 (-8%)	1.50 (-2%)
500	2.19	1.06 (-52%)	2.06 (-6%)	2.19 (-0%)

Marsh vegetation makes the largest difference at the output location for all return periods, with a reduction in wave height between 52% and 75%. The reduction is strongest in small water depth, but remains significant as the return periods, and thus water depth and wave height, increase. Fig. 7, panel 4, clearly shows the effect of an oyster reef; it locally induces a significant reduction in wave height. Whereas the marsh vegetation and the seagrass meadow stretch for hundreds of meters, the length of the oyster reef is only 30 m. If the waves have passed the reef, there are no additional wave-reducing mechanisms in action and the wave height increases again due to wind input. At the first line of houses on shore (output location [1310]), the effect of the oyster reef is almost completely canceled out. Additionally, the effect of oyster reefs varies considerably for a varying water depth. The larger the water column above the reef, the smaller the reduction. The initial reduction, directly behind the reef (around grid point [830]) is 44% for the 1 in 10 year situation and 5% for the 1 in 500 year situation.

Even in very large water depth with high waves (i.e. 500-year conditions), the marsh vegetation is able to reduce the wave height significantly. This can be explained by the fact that vegetation is able to dissipate wave energy if it 'feels' the waves. That means that the H/h ratio is important: for the same water depth, vegetation will have more effect on large waves than on small waves. As long as the marsh vegetation 'feels' the waves, it is effective in dissipating energy, due to its upright stems and its dense above-ground biomass. The results further suggest that marsh vegetation has a range of applicability that is, hydraulically spoken, very wide. Its impact on wave height exceeds that of oyster reefs and seagrass meadows for all simulated conditions.

However, it was assumed that the stems withstand the force of the waves and do not break. This might not be an realistic assumption. Large-scale breakage of stems could dwindle the reduction rate, especially for marsh vegetation, and overestimate its effectiveness. To assess the reliability of the assumption, the effect was further investigated (see section 5.1.2.).

If the oyster reef is at a large distance from the output location, its attenuating effect at the output location is canceled out in comparison to the original wave height propagation (visible in fig. 7, panel 4). This suggests that an optimal location could be found to maximize its effect. The results further suggest that oyster reefs are, more than the other two measures, sensitive to the water depth. This may be caused by the fact that its main reducing mechanism is in this case increased bottom friction, which is more sensitive to the H/h ratio than vegetation-induced drag.

A seagrass meadow seems to have little effect on wave height under storm conditions. The seagrass meadow reduces the wave height slightly. Its effect decreases with increasing water depth and wave height. This can be explained by the characteristics of seagrass: it is not as high and dense as marsh vegetation. Both factors influence the energy dissipation rate, so seagrass is less effective in attenuating waves. The effect of the H/h ratio on the effectiveness of seagrass to reduce wave height was not investigated.

5 Discussion

5.1 Limitations and optimizations

Several limiting factors and optimization strategies for the application of Nature-based Solutions were investigated. It was found that the wave attenuating effect of NbS can improve significantly if their location is close to the shore, because the wave height reduction is strongest directly behind the NbS.

Furthermore, the tidal range is important for the distribution pattern of the selected NbS. Marsh vegetation grows in the middle and upper tidal zone. Seagrass meadows thrive in shallow water and constant submergence although certain species are known to be able to survive in shallow tidal pools or

on dry ground during ebb tide for several hours (Pedersen, Colmer, Borum, Zavala-Perez, & Kendrick, 2016). Also, the growth range of oyster reefs is primarily determined by the tidal range, because the growth of oyster reefs benefits from daily alternation of submergence and emergence. The spatial growth range of all three species increases with a larger tidal range. These natural factors illustrate the limited influence that engineers and policy makers have on whether or not NbS thrive at a chosen location.

5.1.1 Location of oyster reefs

It was found that a shift in location towards the output location increases the effectiveness of the oyster reef in attenuating waves: the reduction percentage for 10-year storm conditions increases from 9% to 64% if the reef is directly in front of the output location. This effect can also be found for more extreme conditions (e.g. higher waves and water levels, corresponding with 50, 100 or 500 year return periods). A major uncertainty is the growth ceiling of the reef, i.e. the top of the reef needs to be submerged on a daily base in order to sustain the reef. This suggests that oyster reefs could be more effective at other locations, for instance near the toe of a dike, on steep slopes or at locations with a larger tidal range.

Detailed knowledge on hydrodynamic processes tailored for oyster reefs is limited. Let alone availability of observations of their behavior during storm conditions. Their incorporation in the used numerical model is unprecedented and, although supported by findings from academic papers, should be calibrated and validated with observations during extreme hydrodynamic conditions. Since there is no measured wave data for the Galveston Bay or for oyster reefs in storm conditions, the results should be interpreted with care.

5.1.2 Stem breakage of marsh vegetation

Vuik et al. (2018) investigated stem breakage and their results indicate that stem breakage significantly influences the capacity of marsh vegetation to reduce storm waves. This is caused by the strong orbital wave velocity of storm waves that exert a force exceeding the strength of the stems. For the case of the Galveston Bay with the currently applied marsh configuration, stem breakage will probably occur during hydrodynamic conditions with a return period of 100 years or more. Particularly for 500 year conditions and with a vegetation height of 0.58, stem breakage will likely occur over the total length of the vegetation field.

The residual attenuating capacity of the vegetation field (i.e., after stem breakage) is not investigated in this study. Vuik et al. (2018) includes the stem breakage model in a numerical model that calculates the wave energy development at every grid point in a cross section, this should be done for the Galveston Bay as well.

6 Conclusion

Marsh vegetation and oyster reefs can reduce wave height significantly. Particularly marsh vegetation has potential to contribute to the protection of coastal infrastructure during extreme conditions. Since flood risk is mainly defined by low probability events, this study focused on storm conditions. However, because these conditions rarely occur, there is a lack of field observations on the effect of Nature-based Solutions on wave height during such conditions. Therefore, measurements of mild to moderate hydrodynamic conditions are extrapolated to simulate the mechanisms. But by doing so, non-linear effects or unexpected behavior that only occur during extreme conditions, are not captured. These effects include, for instance, stem breakage of vegetation, or extreme erosion during a storm event that destabilizes a Nature-based Solution.

In summary, this research shows that Nature-based Solutions have potential to contribute to flood risk reduction in the Galveston Bay due to their capability to contribute to wave height reduction during storm conditions. However, it is emphasized that the limitations and optimizations with respect to their location, strength and biological requirements must be taken into account in order to maximize their effectiveness.

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