HOW RELIABLE IS EMERGENT VEGETATION FOR ENGINEERING WITH NATURE?

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Abstract: To increase the use of natural and nature-based features (NNBF) as engineering solutions for flood risk mitigation, design methodologies consistent with conventional coastal infrastructure design are needed. This paper describes a performance-based design methodology for emergent vegetation, which is able to incorporate the inherent uncertainties in an emergent vegetation system into the engineered design. Using performance-based design of conventional (gray) infrastructure, this methodology for NNBF incorporates how emergent vegetation changes over its design lifetime, whether in response to natural growth or decay both during and post-storm. Future needs to reduce the uncertainty in estimates and comparison with conventional infrastructure are discussed.

Introduction

Natural and nature-based features (NNBF) are flood risk mitigation measures that incorporate or are inspired by "landscape features" (Bridges et al. 2021). These systems include emergent vegetation, beach nourishment, coastal reefs, and dunes (Bridges et al. 2021). In addition to flood risk management, NNBF systems also have the benefits of increased economic activity, ecological restoration, and recreational uses (van Zanten et al. 2021). While interest in these systems has risen, there remains a need to develop design tools and methodologies consistent with engineering practice for conventional structures to increase implementation of NNBF systems (Close et al. 2017; Cherry et al. 2018; Ostrow et al. 2022).

Consider the case of evaluating the design of a conventional rock revetment versus a designed mangrove shoreline (Figure 1) to minimize overtopping and protect an upland area. The design of a rock revetment typically involves the specification of stone size, slope, and crest elevation. There are design tradeoffs between initial and maintenance repair costs when selecting stone size, which can lead to some uncertainties in performance over the design life of the structure. However, the expected damage and deterioration of the structure due to storms can be predicted, and therefore the performance and maintenance costs can be evaluated. Moreover, immediately after construction, the condition of the revetment provides the desired performance level. In contrast, specifications for vegetation are highly constrained by the ecology in the project area. Similar to the stone revetment, the forest is susceptible to storm damage over the lifetime of the project, as well as other types of damage specific to vegetation (e.g., disease, invasive species). Yet, engineering practice cannot readily quantify the uncertainties associated with these processes that are unique to NNBF. Furthermore, a newly planted mangrove forest will take time to establish, grow, and provide the design performance level. Tools to quantify the added risk due to the initial growth phase are not readily available (see Ostrow et al. 2022 for a more complete discussion).

Fig, 1. Example mangrove system used for flood protection in Stuart, FL. Photo credit: E. Biondi.

While NNBF systems have a higher level of uncertainty than conventional infrastructure, nearly all engineered designs contend with uncertainty, and techniques have been developed to account for these. Performance-based design, for example, can be used to estimate the probability of failure of an engineered system over its design life. In this methodology, engineers define a failure criterion and use Monte Carlo simulations of the system's design life to determine the probability that this failure criterion will be exceeded. Performance-based design guidelines exist for wind (American Society of Civil Engineers 2019) and seismic (Vamvatsikos et al. 2016) design.

Performance-based design has also been used for conventional coastal infrastructure. Shimosako and Takahashi (1998) developed a performance-based design methodology, modified and translated into English by Goda (2010), to calculate the expected sliding distance for breakwaters. Significant wave heights, periods, friction factors, and other important design parameters were treated as probabilistic and sampled from underlying distributions. The calculations were repeated over the design life, and the design life was itself repeated for many Monte Carlo simulations (Goda 2010). Suh et al. (2012) expanded this framework, including nonstationary wave and mean sea level parameters to account for climate change and calculating the probability of failure over the design lifetime, rather than just at the end. The nonstationary framework has also been expanded to using overtopping rate as the failure mode rather than expected sliding distance (Pillai et al. 2019).

In this paper, we show a conceptual framework for performance-based design for NNBF, following these earlier examples for conventional structures. We use the example of emergent vegetation to minimize overtopping to protect an upland area, but the methodology could be extended to other uses of NNBF. In this framework, we emphasize key processes that are unique to NNBF design.

Performance-Based Design and Natural Infrastructure

An example engineering project might look like the one in Figure 2. This idealized example consists of a project site on the landward side of a coastal embayment, inspired by Southern Florida, USA. Fetch-limited wind waves may be a threat to infrastructure behind the project site. A hybrid system consisting of a mangrove forest and bulkhead revetment is employed to attenuate the wave energy. The incident wind waves with associated significant wave height $H_{s,i}$ travel through the mangrove forest, resulting in a lower transmitted significant wave height, $H_{s,t}$. The hybrid system would fail with too much overtopping of the revetment, q. Therefore, the output or performance variable of interest for this project may be the overtopping rate or volume.

With the output variable of interest established, a failure criterion for this infrastructure can be determined. The *Coastal Engineering Manual* (USACE 2002) and *EuroTop* (Pullen et al. 2007) are two common sources for determining thresholds of overtopping rate or volume that may not be exceeded if the primary interest are threats to human safety or use of coastal highways, for example. Other exceedance criteria may be based on ecological functions of the upland area. With these failure criteria, performance-based design calculations can be completed to determine the expected value of the performance variables and the probability of failure over the design life.

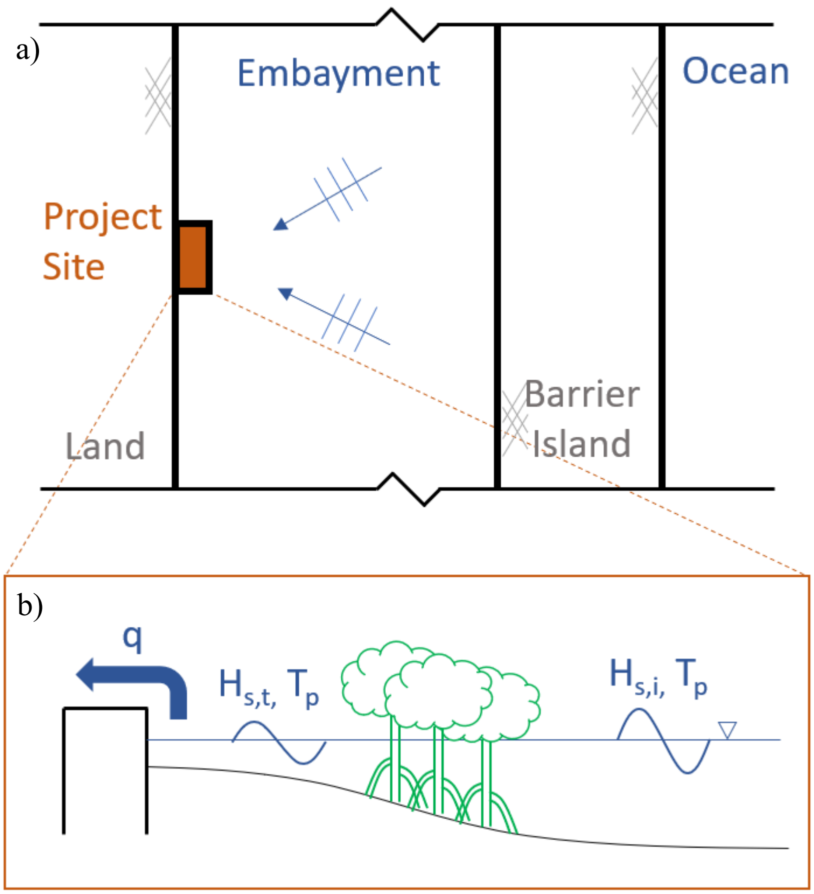

Fig. 2. Conceptual diagram of a NNBF project to attenuate waves, inspired by a coastal embayment in Florida, USA. a) location of project site. b) elevation view of project site.

Figure 3 shows an example of what the accumulated design variable, such as the cumulative overtopping volume, would look like. The x-axis is the time over the design life of the infrastructure (typically measured in decades), and the y-axis is the overtopping (output) variable. When the overtopping volume exceeds the threshold in a given year, this volume is added to the sum of the volumes from the previous years. In Figure 3a, each blue line represents the output from one design lifetime. Calculations from one design lifetime are repeated for many Monte Carlo simulations, resulting in many blue lines. The simulations are averaged to create an expected value of the output variable, shown as the black line in Figure 3a. A certain number of the Monte Carlo simulations will exceed the failure criterion, and the percentage of failed simulations is the probability of failure (Figure 3b). Figure 3 contains 10 Monte Carlo simulations for illustration purposes, but the actual number should be much larger, resulting in smooth curves for the expected value and probability of failure.

a) b)

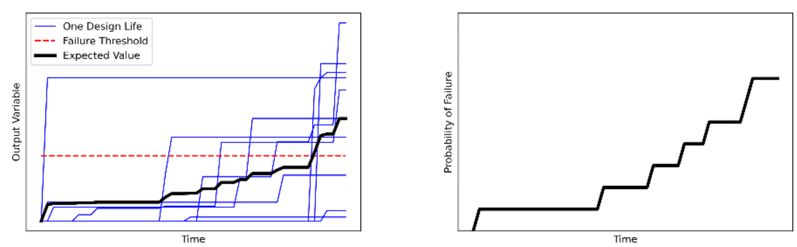

Fig. 3. Example performance-based design outputs for a 50 year design life and 10 Monte Carlo simulations. a) failure criterion over time. b) exceedance probability of failure over time.

a) b)

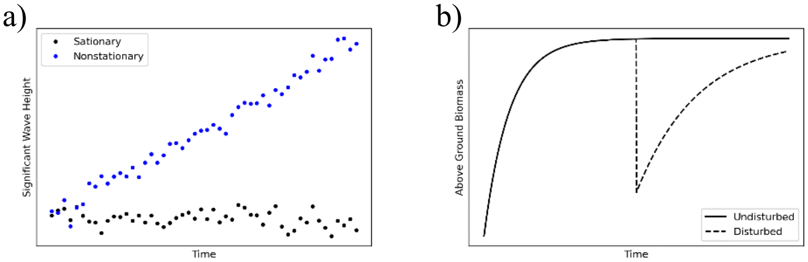

Fig. 4. Example inputs into the performance-based design of NNBF system. a) stationary and nonstationary significant wave heights. b) undisturbed and disturbed above ground biomass.

To estimate the probability of failure of an uncertain system that can change in time, it is important to test a wide range of conditions that may occur. This probabilistic approach results in the various blue lines in Figure 3, and comes from inputs as in Figure 4. The hydrodynamic conditions are sampled probabilistically, resulting in, for example, wave heights that change from year to year. These stochastic processes can be stationary or nonstationary if climate change is considered (Figure 4a). For emergent vegetation, the amount of wave attenuation is in part determined by the above ground biomass. The above ground biomass will change over the course of the design lifetime, as the vegetation can grow undisturbed or be reduced by a storm or other impact before recovering, for example (Figure 4b). As the storm conditions are random, damage and growth cycles for mangroves will occur at different times during the design life for different Monte Carlo simulations.

Framework for the Performance-Based Design of Engineering with Nature

Figure 5 shows a framework that uses the inputs in Figure 4 to calculate the outputs in Figure 3. The framework is adapted from methodologies by Goda (2010), Suh et al. (2012), and Pillai et al. (2019). While many of the same calculations are taken, there are multiple steps that are added to the framework for emergent vegetation systems.

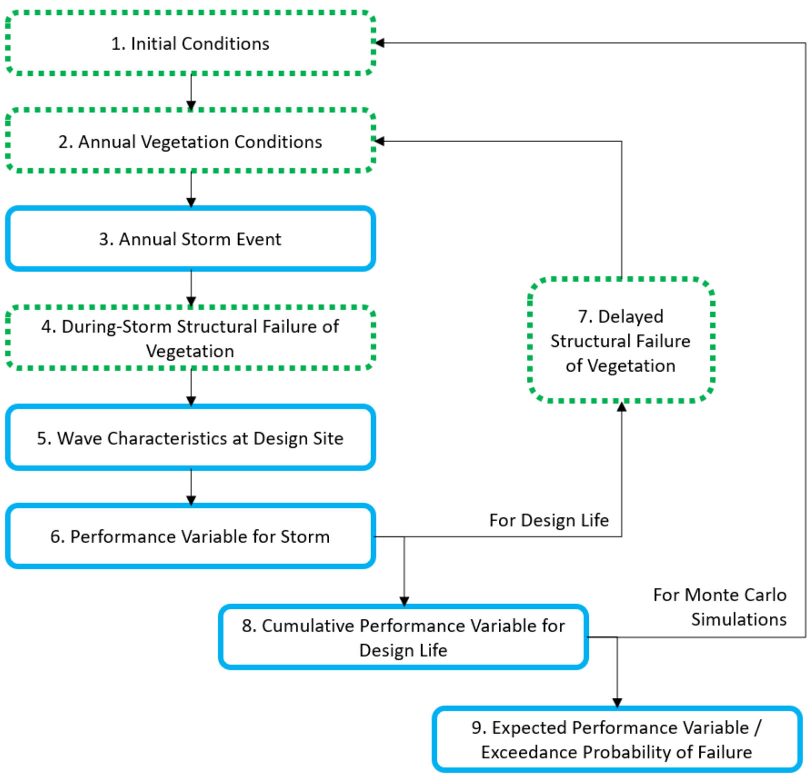

Fig. 5. Conceptual framework for performance-based design of NNBF systems. Blue solid lines indicate steps used for conventional infrastructure, and green dotted lines indicate added steps for vegetation.

Steps 2-7 are repeated in an inner loop over the design lifetime, and one iteration results in one blue line seen in Figure 3a. Steps 1-8 are repeated for many Monte

Carlo simulations, corresponding to the multiple blue lines in Figure 3a. Step 9 is calculated from the results of all of the Monte Carlo simulations, shown as the black line in Figure 3a.

Step 1: Initial Conditions

The initial conditions at the time of construction are required and consist of (a) the overall conditions of the site (*e.g.,* depth, astronomical tides, fetch length), (b) antecedent shoreline configuration such as an existing bulkhead revetment, and (c) the initial treatment of the NNBF. For the case of the mangrove forest, this would include planting specifications for vegetation, including the initial area of planting, vegetation density, species composition, and age of propagules. A failure criterion, such as a critical overtopping rate from the *Coastal Engineering Manual*, must be set.

Step 2: Annual Vegetation Conditions

The vegetation will change over time (Figure 4b), so each year will have vegetation conditions that depend on what occurred in the prior year. Examples of changes between years include mangrove growth or damage from previous storms. Allometric relations between age, diameter at breast height (DBH), and other morphologic parameters can be used to update the required vegetation parameters (Alongi 2008; Mori et al. 2022). The exception is the first year of the design life, which runs with the initial conditions set in Step 1.

Step 3: Annual Storm Event

In Goda (2010), an annual storm was randomly selected from an extreme probability distribution, resulting in three components: wind, wave, and surge. The relevant wave parameters were offshore significant wave height, significant period, and wave direction, and Goda (2010) suggested setting the storm duration to two hours for simplicity. Climate change may be incorporated by changing the hydrodynamic inputs over time (Suh et al. 2012). The total water depth as a function of distance is calculated by considering the bathymetry, astronomical tide, storm surge, and sea level rise if included. For the example case shown in Figure 2, we simplify the storm event by drawing the wind speed from an extreme distribution and estimating the fetch-limited wave height following design equations in the *Coastal Engineering Manual* (USACE 2002).

Step 4: During-Storm Structural Failure of Vegetation

Extreme storm conditions may cause mangroves to be damaged. Therefore, not all of the mangroves will be able to attenuate waves in their full capacity, and should be removed from the model for a conservative estimate of the performance variable. Damaged mangroves can be predicted with a fragility function, which describes the probability that a mangrove is damaged as a function of hazard intensity.

Step 5: Wave Characteristics at Design Site

For an open coast project, the waves can be transformed from offshore to the project site using conventional wave transformation equations (*e.g.,* USACE 2002). At the site in the example in Figure 2, the waves should be further transformed to the revetment location to obtain the transmitted wave height, $H_{s,t}$. The wave attenuation can be calculated with an empirical equation, such as Mendez and Losada (2004). Alternatively, the entire process (offshore to onshore, wave attenuation through vegetation) could be calculated by a numerical model, such as XBeach (Roelvink et al. 2009; van Rooijen et al. 2016).

Step 6: Performance Variable for Storm

With the conditions at the area of interest known, the output variable, such as the overtopping rate or volume, can be calculated for that year's storm. As in Step 5, the value of interest can be calculated from empirical formulas or a numerical model like XBeach. If the output variable exceeds the threshold set in Step 1, the system has failed in that year. Step 6 concludes the calculations for one year in the design life.

Step 7: Delayed Structural Failure of Vegetation

Storm conditions do not harm mangroves only during the storm event. Delayed mortality of mangroves may occur after the storm has ended, due loss of leaves or saltwater (*e.g.,* Craighead and Gilbert 1962). Therefore, mangroves that experience delayed mortality will not be able to attenuate waves effectively in future storms, and should be removed from the model. After Step 7, the model returns to Step 2 for the next year of the design life, and the next iteration of Step 2 considers the mortality of mangroves from Steps 4 and 7, as well as mangrove growth.

Step 8: Cumulative Performance Variable for Design Life

After the completion of the inner loop, the output variables for each year of the design life have been calculated. If necessitated by the variable of interest, the cumulative performance variable can also be calculated. For the example in Figure 2, Step 8 could involve calculating the cumulative overtopping volume. Step 8 completes the calculation over one design life of the structure, corresponding to one realization of the model (i.e., one blue line in Figure 3a).

Step 9: Expected Performance Variable / Exceedance Probability of Failure

Steps 1-8 should be completed for many Monte Carlo simulations, so that model uncertainties can be evaluated over the design life. Stochastic variables include, for example, wind, wave, and surge conditions, as well as the ecological parameters of the NNBF system, and parameters used to model the wave attenuation (*e.g.,* Kelty et al. 2022).

Summary statistics can then be obtained in Step 9; for example, taking the average of the cumulative overtopping volume for each year of the design life would result in the expected cumulative overtopping volume. This is the black line in Figure 3a. Also of interest is the probability of failure as a function of the design life. This can be calculated by determining the number of failed simulations for each year of the design life and dividing by the total number of simulations (Figure 3b).

Discussion

This performance-based design methodology is used for NNBF due to the inherent uncertainty in NNBF systems. Therefore, the choice of empirical relations for morphologic parameters and the quantification of the uncertainty of those relations is important for the success of the model.

While the methodology incorporates mangrove mortality driven by storms, there are many other ways that a mangrove system's flood protection capacity can be affected. For example, people can harvest mangroves and diseases can spread, which would take out trees from the system. Conservation efforts and engineered solutions may increase the number or health of vegetation in a system. These factors, and others, can be added into the methodology by changing the vegetation parameters assigned in Step 2, that is, adding additional parts to Step 7.

This methodology can also be extended to look at other failure modes for hybrid infrastructure, such as the sliding distance of a caisson breakwater as in Goda (2010). While damage to the revetment is not currently included in order to isolate the effect of the mangrove forest, the probability of structural failure of the revetment should be included for a full performance-based design of a hybrid system.

A model sensitivity study will be carried out to complete verification of the model. This verification step will also help determine areas of future research, as the parameters that have the largest effect on the model outcomes should be studied with the goal of reducing the uncertainties of the inputs. More research is needed to validate the model. This would involve refining the allometric relations that generate vegetation parameters and fragility functions for vegetation, as well as analyzing case studies over a long enough design lifetime.

Summary

This paper shows how performance-based design methodologies can be extended from conventional infrastructure to NNBF systems. Unlike conventional infrastructure, changes in emergent vegetation parameters are not fully in the engineer's control. Therefore, steps to calculate the morphologic parameters and survivability of emergent vegetation are required. With this methodology, engineers can quantify the probability of failure when using NNBF.

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References

Alongi, D. M. (2008), "Mangrove forests: Resilience, protection from tsunamis, and responses to global climate change," *Estuarine, Coastal and Shelf Science*, 76(1), 1–13. https://doi.org/10.1016/j.ecss.2007.08.024.

American Society of Civil Engineers (2019), *Prestandard for Performance-Based Wind Design*, American Society of Civil Engineers.

Cherry, C., Dix, B., Asam, S., Webb, B., and Douglass, S. (2018), *Peer Exchange Summary Report: Nature-Based Solutions for Coastal Highway Resilience*, Washington, DC: Federal Highway Administration.

Close, S. L., Montalto, F., Orton, P., Antoine, A., Peters, D., Jones, H., Parris, A., and Blumberg, A. (2017), "Achieving sustainability goals for urban coasts in the US Northeast: research needs and challenges," *Local*

Environment, Routledge, 22(4), 508–522. https://doi.org/10.1080/13549839.2016.1233526.

Craighead, F. C., and Gilbert, V. C. (1962), “The Effects of Hurricane Donna on the Vegetation of Southern Florida,” *Quarterly Journal of the Florida Academy of Sciences*, 25(1), 1–28.

Goda, Y. (2010), *Random Seas and Design of Maritime Structures*, Advanced Series on Ocean Engineering, World Scientific. https://doi.org/10.1142/7425.

Kelty, K., Tomiczek, T., Cox, D. T., Lomonaco, P., and Mitchell, W. (2022), “Prototype-Scale Physical Model of Wave Attenuation Through a Mangrove Forest of Moderate Cross-Shore Thickness: LiDAR-Based Characterization and Reynolds Scaling for Engineering With Nature,” *Frontiers in Marine Science*, 8. https://doi.org/10.3389/fmars.2021.780946.

Mendez, F. J., and Losada, I. J. (2004), “An empirical model to estimate the propagation of random breaking and nonbreaking waves over vegetation fields,” *Coastal Engineering*, 51(2), 103–118. https://doi.org/10.1016/j.coastaleng.2003.11.003.

Mori, N., Chang, C.-W., Inoue, T., Akaji, Y., Hinokidani, K., Baba, S., Takagi, M., Mori, S., Koike, H., Miyauchi, M., Suganuma, R., Sabunas, A., Miyashita, T., and Shimura, T. (2022), “Parameterization of Mangrove Root Structure of Rhizophora stylosa in Coastal Hydrodynamic Model,” *Frontiers in Built Environment*, 7, 782219. https://doi.org/10.3389/fbuil.2021.782219.

Ostrow, K., Guannel, G., Biondi, E. L., Cox, D. T., and Tomiczek, T. (2022), “State of the practice and engineering framework for using emergent vegetation in coastal infrastructure,” *Frontiers in Built Environment*, 8.

Pillai, K., Lemckert, C., Etemad-Shahidi, A., Cappietti, L., and Sigurdarson, S. (2019), “Effect of Sea Level Rise on the Wave Overtopping Rate at Berm Breakwater,” *Journal of Waterway, Port, Coastal, and Ocean Engineering*, American Society of Civil Engineers, 145(5), 04019019. https://doi.org/10.1061/(ASCE)WW.1943-5460.0000522.

Pullen, T., Allsop, N. W. H., Bruce, T., Kortenhaus, A., Schüttrumpf, H., and van der Meer, J. W. (2007), *EurOtop wave overtopping of sea defences and related structures: assessment manual*.

Roelvink, D., Reniers, A., van Dongeren, A., van Thiel de Vries, J., McCall, R., and Lescinski, J. (2009), "Modelling storm impacts on beaches, dunes and barrier islands," *Coastal Engineering*, 56(11-12), 1133–1152. https://doi.org/10.1016/j.coastaleng.2009.08.006.

van Rooijen, A. A., McCall, R. T., van Thiel de Vries, J. S. M., van Dongeren, A. R., Reniers, A. J. H. M., and Roelvink, J. A. (2016), "Modeling the effect of wave-vegetation interaction on wave setup: Wave Setup Damping by Vegetation," *Journal of Geophysical Research: Oceans*, 121(6), 4341–4359. https://doi.org/10.1002/2015JC011392.

Shimosako, K., and Takahashi, S. (1998), "Reliability Design Method of Composite Breakwaters Using Expected Sliding Distance," *Rept. Port and Harbor Res. Inst.*, 37(3), 3–30.

Suh, K.-D., Kim, S.-W., Mori, N., and Mase, H. (2012), "Effect of Climate Change on Performance-Based Design of Caisson Breakwaters," *Journal of Waterway, Port, Coastal, and Ocean Engineering*, American Society of Civil Engineers, 138(3), 215–225. https://doi.org/10.1061/(ASCE)WW.1943-5460.0000126.

USACE (2002), *Coastal Engineering Manual*, Washington, DC: USACE.

Vamvatsikos, D., Kazantzi, A. K., and Aschheim, M. A. (2016), "Performance-Based Seismic Design: Avant-Garde and Code-Compatible Approaches," *ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part A: Civil Engineering*, American Society of Civil Engineers, 2, C4015008. https://doi.org/10.1061/AJRUA6.0000853.

van Zanten, B., Arkema, K., Swannack, T., Griffin, R., Narayan, S., Penn, K., Reguero, B. G., Samonte, G., Scyphers, S., Codner-Smith, E., IJff, S., Kress, M., and Lemay, M. (2021), "Chapter 6: Benefits and Costs of NNBF," in *International Guidelines on Natural and Nature-Based Features for Flood Risk Management*, eds. T. S. Bridges, J. K. King, J. D. Simm, M. W. Beck, G. Collins, Q. Lodder, and R. K. Mohan, Vicksburg, MS: U.S. Army Engineer Research and Development Center.