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Discussion

Engineering coastal structures to centrally embrace biodiversity☆

Burton C. Suedel[a,h], Jon Calabria[b,h,*], Matthew V. Bilskie[c,h], James E. Byers[d,h], Kelsey Broich[e,h], S. Kyle McKay[f,h], Amanda S. Tritinger[a,h], C. Brock Woodson[g,h], Emily Dolatowski[b,h]

[a] Engineer Research and Development Center, US Army Corps of Engineers, 3909 Halls Ferry Road, Vicksburg, MS, USA
[b] College Environment and Design, University of Georgia, 152 Jackson Street Building, Athens, GA, USA
[c] College of Engineering, University of Georgia, 0712C Boyd Graduate Research Building, 200 D.W. Brooks Drive, Athens, GA, USA
[d] Odum School of Ecology, University of Georgia, Ecology Building, Rm. 194B, 140 E Green St, Athens, GA, USA
[e] Carl Vinson Institute of Government, University of Georgia, 201 North Milledge Avenue, Athens, GA, USA
[f] Engineer Research and Development Center, US Army Corps of Engineers, 26 Federal Plaza, New York, NY, 10278, USA
[g] College of Engineering, University of Georgia, 708C Boyd Graduate Research Center 200 D.W. Brooks Drive, Athens, GA, USA
[h] The Institute for Resilient Infrastructure Systems (IRIS), University of Georgia, Athens, GA, USA

ABSTRACT

Global environmental factors (e.g., extreme weather, climate action failure, natural disasters, human environmental damage) increasingly threaten coastal communities. Shorelines are often hardened (seawalls, bulkheads) to prevent flooding and erosion and protect coastal communities. However, hardened shorelines lead to environmental degradation and biodiversity loss. Developmental pressures that are growing in scale, scope, and complexity necessitate the development of sustainable solutions to work with, rather than against, nature. Such nature-based solutions (NBS) provide protection and improve environmental quality and enhance biodiversity. To further this pressing need into action, the US Army Corps of Engineers (USACE) began the Engineering With Nature (EWN) initiative to balance economic, environmental, and social benefits through collaboration with partners and stakeholders. This work shows how engineering practice can be advanced through structured decision-making and landscape architecture renderings that include ecological sciences and NBS into an integrated approach for enhancing biodiversity in coastal marine environments. This integrated approach can be applied when designing new infrastructure projects or modifying or repairing existing infrastructure. To help communicate designs incorporating NBS, drawings, and renderings showcasing EWN concepts can aid decision-making. Our experiences with implementing EWN in practice have revealed that involving landscape architects can play a crucial role in successful collaboration and lead to solutions that protect coastal communities while preserving or enhancing biodiversity.

1. Introduction

Global environmental risks (e.g., extreme weather, climate action failure, natural disasters, human environmental damage) that threaten human communities top the rankings in the annual Global Risks Report (Schwab and Zahidi, 2021). Coastal communities often take the brunt of these threats due to rising sea levels, hurricanes and storm surge. The impacts of these threats are also growing in scale, scope, and complexity due to increased competition and conflicts from population growth and climate change (e.g., Hurricane Harvey in 2017). We posit in this Perspective Article how these pressures require novel solutions that adapt to changing environmental and human needs through improved design to enhance biodiversity goals.

At present, many coastal areas are protected using coastline armoring or hardened (gray) infrastructure (e.g., structures such as levees, seawalls, floodwalls, breakwaters, dikes, groins, tide gates, and storm-surge barriers designed for coastal flood protection). However, the common global practice of shoreline hardening or armoring can actually accelerate erosion and loss of beaches and tidal wetlands (Gittman et al., 2016a). Hardened shorelines also contribute to a second global environmental crisis, biodiversity loss (Gittman et al., 2016a). For example, sea walls lead to lower biodiversity than natural shorelines, although project type variability may mask differences when similarly evaluating riprap and breakwater structures (Gittman et al., 2016a). In contrast, natural and nature-based features (salt marshes, mangroves, living shorelines) in conjunction with hard infrastructure (i.e., hybrid, a

☆ Financial support was provided by U S Army Corps of Engineers.
* Corresponding author. College Environment and Design, University of Georgia, 152 Jackson Street Building, Athens, GA, USA.
E-mail addresses: burton.suedel@usace.army.mil (B.C. Suedel), jcalabr@uga.edu (J. Calabria), mbilskie@uga.edu (M.V. Bilskie), jebyers@uga.edu (J.E. Byers), kbroich@uga.edu (K. Broich), Kyle.McKay@usace.army.mil (S.K. McKay), Amanda.S.Tritinger@usace.army.mil (A.S. Tritinger), bwoodson@uga.edu (C.B. Woodson), edolatow@uga.edu (E. Dolatowski).

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combination of built and restored or created natural infrastructure) can increase economic and social (e.g., recreation) value, provide flood and storm protection, reduce coastal structure costs, enhance coastal and community resilience, adapt to climate change, and enhance biodiversity (Firth et al., 2014a; Sutton-Grier et al., 2015; Browne and Chapman, 2011; Narayan et al., 2016; Morris et al., 2018; Bouw and van Eekelen, 2020; Castellari and M, 2021).

By necessity, successful coastal infrastructure projects that provide multiple benefits should integrate processes and components that support flood risk management, ecosystem restoration and biodiversity objectives (Table 1). A promising avenue to meet these objectives is the development of sustainable solutions to work with, rather than against, nature. Nature-based solutions (NBS, such as natural or hybrid infrastructure) offer an opportunity to deliver multiple benefits when considered as interconnected systems. A successful systems approach to NbS considers relevant physical, biological, and social processes and their interactions to include the immediate project footprint and the surrounding watershed or coastal zone (Nelson et al., 2020). Such approaches enable evaluating and identifying ways to reduce conflict and maximize synergies to produce sustainable solutions.

A systems-based approach necessarily involves identifying a range of NBS that could leverage existing physical systems, ecosystems, and socioeconomic systems in the project area. Such features can help reduce impacts and life cycle costs, provide multiple benefits, buy time for future adaptation, and improve biodiversity. For example, by strengthening sand dunes, building up salt marshes and barriers islands, constructing new offshore reefs, among various techniques, planners and engineers can protect coastal communities. The protection also enhances amenities for people and provides habitat for fish and wildlife, thus supporting local economies and minimizing the negative impacts of hard infrastructure (Nelson et al., 2020; Bridges et al., 2018, 2021a). To bring forth this pressing need into action, the US Army Corps of Engineers (USACE) 2011 Civil Works Strategic Plan (USACE, 2011) sought to balance economic, environmental, and social objectives while increasing stakeholder engagement and active partnering through innovative and environmentally sustainable solutions to the Nation's water resources challenges. Goal #4 focuses on restoring, protecting, and managing aquatic ecosystems that have become degraded, a key component of which is biodiversity.

The Convention on Biodiversity's (CBD) 2050 Vision for Biodiversity specifies protecting and restoring marine and coastal ecosystems to ensure sustainability, deploying NbS within built landscapes and using spatial planning to reduce the negative impacts on biodiversity from urban infrastructure, and enabling adaptation through resilient ecosystems while avoiding negative impacts on biodiversity (CBD, 2020). Similarly, three United Nations Sustainable Development Goals (SDGs) of the 2030 Agenda for Sustainable Development speak to biodiversity loss. SDG #13 on climate action addresses the drivers of biodiversity loss, SDG #14 promotes conserving and sustainably using the oceans, seas, and marine resources, and SDG #15 promotes sustainably managing forests, halting and reversing land degradation, and halting biodiversity loss. Collectively, the 2050 Vison for Biodiversity and the UN SDGs promote the use of NbS as a means for addressing biodiversity challenges interdependent with climate change and enhancing synergy between climate change adaptation and disaster risk reduction (Castellari and M, 2021; Cohen-Shacham et al., 2019).

Coastal infrastructure has been enhanced via NBS at various scales and geographies (Chapman and Blockley, 2009; Bulleri and Chapman, 2010; Coombes et al., 2015; Strain et al., 2018; Suedel et al., 2021a; Perkol-Finkel and Sella, 2015) In the Netherlands, the EcoShape consortium, through the Building with Nature (BwN) initiative, has developed detailed design renderings to communicate to practitioners implementing coastal biodiversity enhancements using NBS (Bouw and van Eekelen, 2020). More broadly, Milner-Gulland, Addison (Milner--Gulland et al., 2021) present a four-step (avoid, minimize, restore, and offset) framework for mitigating and compensating the biodiversity

Table 1
Conventional versus NBS approach to implementing biodiversity objectives into coastal infrastructure project planning.

Project Question	Conventional Approach to Coastal Engineering	Approach Embracing Biodiversity in Coastal Engineering
What are the biodiversity objectives for the project?	Focused on single (or few) engineering objectives to reduce erosion or storm impacts; environmental impacts are compliance only	Along with engineering, ecological/biodiversity, economic, and societal objectives are central to the project goal
What are the project constraints?	Funder satisfaction, cost, environmental compliance, spatial footprint	Funder satisfaction, cost, environmental compliance may be more flexible given the enhanced design as a mitigation option, intervention is an option
Are there opportunities to intervene or take actions?	Intervention is pre-assumed, binary Action vs. No Action process (i.e., dirt will be moved); construction window well defined; narrow window of intervening "solutions"	Structured decision-making process provides intervention options. Action may not be taken or may be taken in a different project phase (e.g., social process of land use planning). Actions consider nature-based features and hybrid designs to achieve multiple objectives; feedback embraced; implementation flexible (phased or incremental)
What level of protection should be designed for?	Based on associated risk and frequency of events. Protection is static based on design choice	Protection is also based on risk and event frequency, but initial design requirements may be lower as features may evolve in time to increase protection and enhance biodiversity based on lessons learned.
What materials will be used to construct the project?	Concrete, steel	Concrete, steel, natural materials, bio-enhanced materials and mixtures to attract desired biota; hybrid designs that include both conventional and green elements, bioprotective species to enhance material resistance to weathering (e.g., oysters); enhanced surface complexity to mimic natural habitat
What are the temporal impacts of project?	Assumed short with construction emphasis, often not monitored beyond initial compliance unless there is a clear structural problem	Short-term (weeks, months) as well as long-term (months, years)
What are the spatial impacts of the project?	Restricted to the site "footprint," biodiversity contributions incidental	More consideration of cumulative, ecological connectivity, and adjacent food web interactions
What are the unintended consequences of the project?	Direct and indirect effects are addressed through permitting and compliance; mitigation for bad outcomes	Indirect costs are included qualitatively and quantitatively in a structured decision-making process
What will be the products of the implemented design process?	Engineering solutions	Innovative engineering, ecological, economic, and social solutions; monitoring as education opportunity for students; community relationships and lessons learned applicable to other sites

(*continued on next page*)

Table 1 (*continued*)

Project Question	Conventional Approach to Coastal Engineering	Approach Embracing Biodiversity in Coastal Engineering
What are the outcomes and benefits to be achieved by building the project?	Project is built; only benefit considered is the initial engineering objective, although co-benefits may exist incidentally	Project is built; engineering, ecological, economic, and social benefits are all specifically integrated into the design; long-term benefits may far-outweigh both short-term costs and benefits

impacts of human developments. Díaz et al. (2020) advocated three main points that can reverse biodiversity loss using NBS: set multiple goals to address nature's complexity; develop goals that are holistic and minimize tradeoffs; and integrate the goals with a high level of ambition (set lofty goals), which include using NBS to reduce climate risk and foster more resilient natural and managed ecosystems. (Firth et al., 2014b). Firth et al. (2014b) developed guidelines for increasing biodiversity via the creation of desired habitat types and proposed simple methods to enhance hardened coastal structures during three project phases: during quarrying and concrete casting, during construction, and retrospectively. In the U.S., the USACE began the Engineering With Nature® (EWN®, www.engineeringwithnature.org) initiative in 2010 focused on using NBS to balance economic, environmental, and social benefits through collaboration (King et al., 2020).

Drawings and renderings showcasing EWN concepts can be used to aid decision-making that help communicate designs incorporating NBS within a structured decision-making process (Holmes et al., 2021a). Our experiences with implementing EWN in practice have revealed that successful collaboration focused on identifying and selecting NBS includes involving landscape architects (LAs) that can play a key role in accomplishing collaborative NbS project success. There are recent precedents for LAs to collaborate alongside engineers and scientists. For example, the Rebuild By Design (New York and New Jersey, 2013–19) and Resilient By Design Bay Area (California, 2017–18) design competitions involved multidisciplinary teams working together with a broad range of expert and community voices to develop NBS to address coastal resilience challenges (Ovink and Boeijenga, 2018; Brown-Stevens, 2019). In the Netherlands, LAs have played meaningful roles in creating, implementing, and upscaling NBS for water-related infrastructure through BwN (Bouw and van Eekelen, 2020). Relative to these examples, work of multidisciplinary project teams charged with implementing EWN that includes LA capabilities have been useful in building support for proposed NBS. For instance, abstract concepts, such as a desire to create a particular habitat feature, become linked to concrete imagery (King et al., 2021).

Here we build on USACE guidance to show how innovative designs incorporating EWN concepts can enhance biodiversity associated with coastal projects. We illustrate how coastal infrastructure can be designed to minimize the impact on, and maximize benefit from, biodiversity through a structured decision-making process. Our focus is on design, as other publications (e.g. (Bridges et al., 2021b),) address construction and management components of coastal projects. We show how engineering practice can be advanced by integrating structured decision-making. This process combines landscape architecture, engineering, ecological sciences, and NBS into an integrated, broadly applicable approach for enhancing biodiversity across conventional infrastructure during modifications, repairs, or replacement and when designing new infrastructure projects. We also pose that successful projects treat biodiversity as assets rather than liabilities, and ecological and other benefits should be considered central to project objectives.

2. Methodological application of an existing framework

2.1. Description of the approach

Projects that utilize NBS are not inherently different from gray infrastructure, so existing frameworks that foster coastal infrastructure planning and engineering projects can be used to incorporate NBS and biodiversity features into the project design. Yet, practitioners integrating NBS into coastal strategies need guidance on how natural and nature-based features (NNBF; a type of NBS application that reduces flood risks) fit within the broader project development process. The "International Guidelines on Natural and Nature-Based Features for Flood Risk Management" (Bridges et al., 2021a) is one such approach that can be broadly applied and was used as the basis for the approach described herein (Fig. 1). The NNBF Guidelines are based on two existing complementary frameworks: the US Army Corps of Engineers (USACE) NNBF framework in pursuit of coastal resilience (Bridges et al., 2015) and the World Bank (2017) framework, which focused on the implementation of nature-based flood protection measures (Sayers et al., 2013). These approaches provide a roadmap for future NBS applications that aim to incorporate features that enhance coastal biodiversity. NBS are inherently sustainable, intrinsically providing biodiversity benefits that enhance ecosystem services (provision, regulating, habitat, and cultural services) (Mace et al., 2012) and provide other environmental, social, and economic benefits (Dumitru and Wendling, 2021). This approach considers biodiversity as an asset in the coastal project development process (Fig. 1).

The approach is divided into five phases: Scoping, Planning, Decision-Making, Implementation, and Operations. These phases highlight a general progression and although depicted sequentially, the framework is designed to be iterative, so new information revealed during later phases can be incorporated. The order and sequencing of the phases are illustrative rather than obligatory as some activities are interconnected and may coincide.

2.1.1. Scoping

In Scoping, an initial assessment of the need and objectives is performed, and stakeholders and partners are identified, organized, and meaningfully engaged in integrating their knowledge about local coastal ecology and hydrodynamics into the project design. The problem is also identified and defined, and biodiversity goals (with biodiversity as an asset) are set based on identified project objectives and local knowledge (to include, for example, microhabitats in the structure; Table 1) (Aguilera et al., 2014, 2019). One means of increasing sustainability is to prioritize appropriate habitat creation/restoration to enhance biodiversity; projects that are linked to other existing projects can improve habitat connectivity.

Opportunities to enhance structures can occur at any stage during the design life, including during new construction, repair, maintenance, or modification. Projects that are likely candidates for enhancement include deteriorating existing structures that need repair, modification, or replacement (Fig. 2). Other candidates are new projects in areas with a large construction footprint where biodiversity is impaired or declining. In this instance, connections can be made to adjacent, more biodiverse areas. The objective is to include ecological principles beginning in planning and then through design and construction rather than mitigating short-term ecologically adverse impacts. Such designs offer applications to apply biomimetic technologies that mimic nature's forms and functions to improve structural and ecological performance.

While scoping infrastructure projects, it should be noted that coastal infrastructure is subject to harsh environmental conditions and must comply with applicable building codes and standards. This applies to the materials used (e.g., concrete mix), construction methods, and phasing or sequencing (Perkol-Finkel and Sella, 2015; Firth et al., 2014b). Enhancing structures for biodiversity can take multiple forms, serving as a continuum of measures over broad scales and structure types in coastal

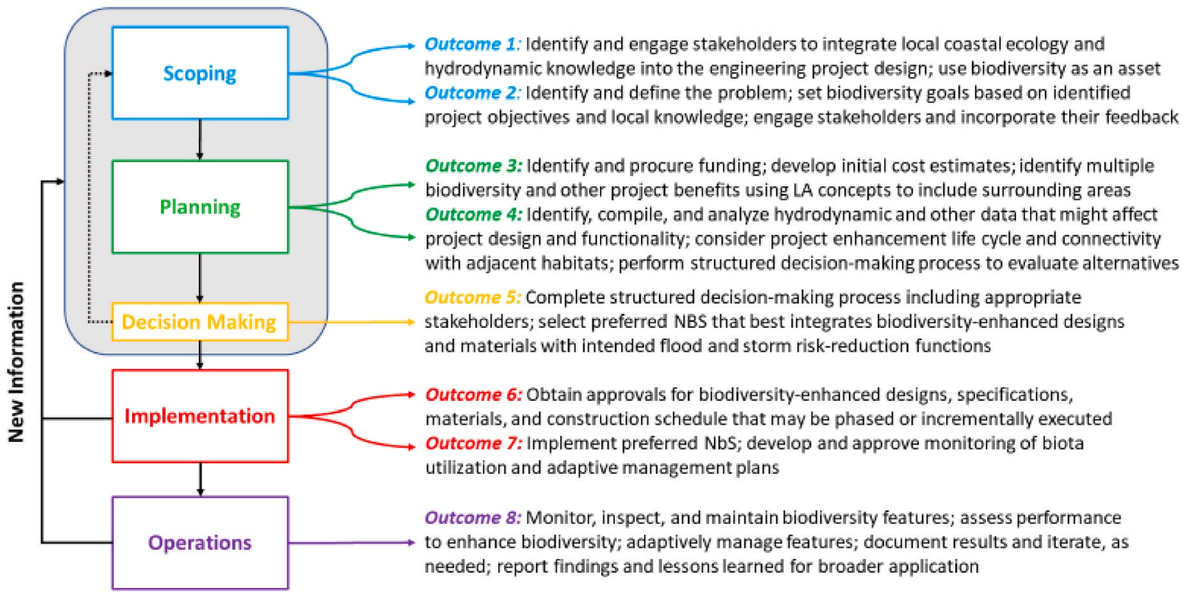

Fig. 1. Approach for designing coastal infrastructure that centrally embraces biodiversity.

Fig. 2. Deteriorating riprap revetment (right) near a culvert along FL-20 in Freeport, FL that is cause of concern for a deteriorating section of FL-20. Such conventional infrastructure is a prime candidate for enhancement during repair to restore its primary engineering function while broadening the biodiversity and other benefits associated with the structure (Photo Credit: M. Bilskie).

and fluvial environments (Schoonees et al., 2019; Suedel et al., 2021b). These elements of design should be factored into the scoping phase of the project to help identify potential constraints and opportunities.

Given the multi-objective nature of many coastal infrastructure projects that incorporate features for enhancing biodiversity, funding sources may include federal, state, and local government, non-governmental organizations, and the private sector. Various funding mechanisms should be sought, including private-public partnerships. When considering funding for such coastal projects, both the cost and funding strategies for the actual studies, evaluations, and analyses that will be conducted as part of the alternative's design and construction should be considered along with funding life cycle costs associated with project monitoring and maintenance. While the funding strategy is initiated in Scoping, it is refined during Planning and Decision-Making and concludes during Implementation.

2.1.2. Planning

Planning offers the opportunity to understand better and characterize the existing system and explore alternatives that satisfy project biodiversity goals and objectives using a systems approach. Considerations during planning include the objectives of the structure to be enhanced (i.e., stop or slow the water; high energy vs. low energy environment), what native species reside in the system, and what types of features are viable to encourage a diverse assemblage of organisms while achieving the engineering objectives. Any challenges associated with including NBS for biodiversity into the design should be considered, including the ability to enhance biodiversity beyond conventional approaches (Nelson et al., 2020; Chapman and Underwood, 2011). These factors need to be considered during the initial problem definition phase to understand better the site-specific hydrodynamic conditions and the habitat features that can be included in the design (Strain et al., 2018).

As part of planning, the risk of the system to storms and flooding are evaluated along with the associated physical, biological, and social processes. Such evaluations may involve reviewing existing data and information and conducting associated hazard, vulnerability, and risk analyses; and modeling to understand changes in water levels, erosional forces, and sediment transport patterns under various conditions. Coastal and riverine modeling (e.g., Advanced Circulation [ADCIRC], Adaptive Hydraulics [AdH], etc.) may play an important role in understanding local conditions, which can inform the development of alternative designs. Modeling tools can help the project team engineer with nature [see examples in (Bridges et al., 2018, 2021a)]. Socioeconomic analysis can be conducted to evaluate the plausible economic, social, and ecological costs and benefits of the NBS and hybrid (i.e., the combination of coastal habitat [e.g., salt marshes] with hard solutions (Sutton-Grier et al., 2015); options. Modeling offers an opportunity to make the value case for biodiversity, and the potential environmental, economic, and social benefits that might be realized in addition to engineering benefits. Metrics should be identified appropriate for site-specific conditions, relate meaningfully to project goals and objectives, and can be easily and cost-effectively measured or qualitatively assessed. The outcome of planning is a transparent evaluation, including numerical rankings of the alternatives being considered. The alternative analysis results identify high-priority alternatives for final consideration during Decision-Making.

2.1.3. Decision-making

During Decision-making, the preferred alternative is selected from the list of high-priority alternatives developed during Planning. This alternative best meets project objectives and manages identified risks of storms and flooding to the system. Designs that achieve the intended engineering function, coastal resilience, and enhanced biodiversity may include a mix of NBS, structural, and non-structural measures. Features incorporated into the design (King et al., 2021; Suedel et al., 2021b; Holmes et al., 2021b) should retain the structure's full flood and storm risk reduction function. During this phase, the preferred alternative selected from the alternatives list developed in Planning is further differentiated in Decision-making amongst the other alternatives under consideration. Cost (e.g., construction, maintenance, and monitoring) and the diversity and magnitude of associated biodiversity and related social and economic benefits become deciding factors for selecting the preferred alternative. Other factors that may affect the results of this evaluation include investment contributions, land acquisition requirements, and regulatory, governance, or funding requirements (Milner-Gulland et al., 2021). Implementing a structured decision-making process is encouraged to help demonstrate how to implement such design features in practice, show how tradeoffs can and should be made, and engage stakeholders in the process (Gregory et al., 2012; Kiker et al., 2005). The ability to implement enhancements can be increased by identifying and quantifying the value biodiversity provides so that the associated costs and benefits can be made and compared effectively against conventional structural measures (Suedel et al., 2021b).

Successful decision-making includes meaningful engagement with knowledgeable community members, stakeholders, and decision-makers involved in the Scoping and Planning phases (e.g., floodplain managers, city or county planners, coastal planners, and resource agency representatives). Communicating with partners, stakeholders, and the public on the outcomes of decision-making and anticipated project benefits is a key element for a successful project. Effective communication can be promoted by Engineering With Nature Landscape Architecture (EWN-LA) drawings and renderings to show how alternative designs can be developed and selected to help drive the decision-making process. Renderings can then serve as communication tools so both stakeholders and decision-makers can visualize the final alternative design and its inherent benefits (Holmes et al., 2021a; King et al., 2021). An example includes the EWN-LA collaboration with the USACE Philadelphia District, in which an array of design renderings was developed and evaluated for implementation in the New Jersey Back Bay region. The report details those findings and includes strategies for pairing NBS with non-structural measures to obtain coastal storm risk management (CSRM) and ecological benefits (Holmes et al., 2021b).

2.1.4. Implementation

Once selected, the preferred alternative is further refined and finalized during Implementation, where construction is initiated and completed. This phase involves refining costs and finance strategy, pursuing final designs and permits, drafting the construction schedule, and obtaining regulatory authorizations. Once completed, the construction of the project can commence. Those involved with the project with biodiversity experience should provide oversight to ensure features are constructed as designed and that any engineering modifications needed do not interfere with features designed to enhance biodiversity. Project elements do not have to be constructed all at once, and care should be taken not to 'over-engineer' the system. That is, the exact goal of the engineering should be clearly stated since this goal determines which engineering options are available. Alternatives to enhance the design for biodiversity in phases over time should consider objectives (stop the water vs. slow the water; see for example (Dugan et al., 2018)) and local conditions (e.g., high energy vs. low energy; subtidal vs. supratidal, pulsed [see (Odum et al., 1995)], species the infrastructure is intended to attract such as fish (Ziegler et al., 2021), etc.). Some design features may be adapted or modified in the future in response to changing environmental conditions, such as changes in storm intensity or sea level rise. Environmental compliance may be more flexible given that enhanced designs that integrate biodiversity features may ameliorate some permitting and compliance issues by reducing the project's footprint.

2.1.5. Operations

The Operations Phase begins when the construction of the project is completed. To enable optimal performance of the project in the face of the dynamic nature of coastal environments and anticipated future system changes (e.g., natural, or man-made), a well-developed monitoring and maintenance plan that puts in place actions that will promote the long-term performance of the project is required. Such plans will inform adaptive management, and lessons learned offer an opportunity to provide valuable insights into future coastal infrastructure projects that incorporate biodiversity objectives. Reporting of monitoring and maintenance activities is also an important element of Operations because it continues the engagement of communities, stakeholders, and decision-makers. Monitoring should include metrics that can quantify (to the extent possible) biodiversity losses and gains. Metrics chosen during planning should reflect local conditions, species, and scales and relate meaningfully to project goals and objectives. Metrics allowing comparison of biodiversity gains and losses can be used to help calculate benefits.

3. Coastal infrastructure renderings

This section identifies ten (10) common coastal infrastructure types that can be enhanced to support a more biodiverse community using NBS through the methods previously described. For each structure type, we present ways in which each can be enhanced either alone or in combination with other structural features. And finally, we provide key examples of how these structural types can be rendered using EWN-LA techniques to support infrastructure decision-making.

Thin Layer Placement: Thin Layer Placement (TLP) is used to restore ecological function by placing sediment or dredged material to simulate natural accretion (Myszewski and Alber, 2017). Sediment is placed at various depths to accommodate project goals, commonly ranging from about 10 cm up to 36 cm maximum depth (Berkowitz et al., 2019). TLP is often used for marsh stabilization or nourishment and to elevate areas in shallow open water. TLP offers a more environmentally sensitive way to elevate areas with the goal of overall maintenance of established natural processes like supporting existing vegetation and promoting new vegetative growth and related habitat. Some coastal marshes, such as those in New England, are losing marsh area due to sea-level rise and are converting from high to low marsh. Such marsh loss reduces biodiversity and may impact the nesting success of bird species that rely on high marsh habitats. TLP can help prevent or delay high marsh loss, with no short-term adverse effects on the native high marsh vegetation (Payne et al., 2021). In addition, the application of TLP can help restore ecosystems starved of sediments and is consistent with EWN principles of keeping sediments in the system (Parson et al., 2015).

Living Shoreline: A living shoreline is defined as a sloped, erosion control technique built to protect an embankment which: mimics natural habitat; provides increased opportunities for species diversity and productivity; and can serve to improve water quality and the ecological integrity of the area (Resources, 2013). Living shorelines can provide a more natural alternative to 'hard' shoreline stabilization methods while enhancing long-term coastal resilience. Unlike conventional coastal erosion techniques that use hard infrastructure and materials, living shoreline projects use oyster shells to promote the recruitment and growth of oysters and other species. Stabilization of the living shoreline features can be enhanced by natural cements created by organisms as they adhere to each other and the underlying structures; roots of native vegetation such as marsh grasses can be used to stabilize soils and sediments and provide additional habitat (Gittman et al., 2016b). In this manner, living shorelines can enhance the ecological integrity of the coastal environment, promote biodiversity, and provide additional water filtration, habitat, recreational, commercial, and enhanced coastal resilience benefits (Resources, 2013; Smith et al., 2020).

Seawall: The USACE has defined seawalls as onshore structures built parallel to the shoreline. Their principal function is to reduce overtopping and consequent flooding of land and infrastructure due to storm surges and waves (USACE, 1995). Seawall and bulkhead terms are used interchangeably; however, seawalls are generally larger and have the primary purpose of intercepting waves to protect high-value property. Conventional materials used to build seawalls include concrete and stone, and various designs and materials are used to prevent undermining the structure. Yet the design of seawalls can be modified to increase the habitat value associated with these structures (Fig. 3). Seawalls can be designed, modified, or constructed to enhance biodiversity by planting native vegetation landward and seaward, creating a submerged reef in front of the seawall, using different construction materials, retrofitting habitat features (e.g., vertipools), and adding roughness to the face of the seawall to add habitat (Browne and Chapman, 2011; Suedel et al., 2021a; Wiecek, 2009; Cordell et al., 2017; Rasna et al., 2019).

Revetment: Revetments are sloped onshore structures with the principal function of protecting the shoreline from erosion by dissipating wave action, storm surge, and currents. Revetments are designed to reduce coastal erosion and not prevent flooding like other coastal structures. They can be exposed or buried and conventionally designed with rock, concrete, and other construction materials (Fig. 2) (USACE, 1995). To increase biodiversity in a revetment, rock or other natural and nature-based materials can be placed with enough spacing between to provide habitat for marine life and vegetation. Some habitat features can be designed to be dry and/or submerged during low tide to enhance habitat value and biodiversity. Rocks can be scored or textured to create microhabitats, and conventional materials such as concrete can be designed and fabricated to include shapes and textures that enhance habitat value (Bouw and van Eekelen, 2020; MacArthur et al., 2020).

Bulkhead: A bulkhead is primarily intended to retain or prevent land sliding while protecting the upland area against wave action is a secondary function (USACE, 1995). Conventionally, bulkheads are usually vertical walls built with concrete, rock, or other hard materials. Bulkheads constructed of conventional materials have been shown to be associated with decreased submerged aquatic vegetation abundance (Patrick et al., 2016) and other adverse impacts (Currin et al., 2010). Yet bulkheads can be combined with other coastal protection features to increase biodiversity while maintaining shoreline protection (Fig. 4). For example, living shoreline or dune features can be placed seaward of the bulkhead to prevent erosion of the area while greatly increasing habitat value (Nordstrom, 2019). Other investigators have developed alternative materials and designs to create bulkhead structures that

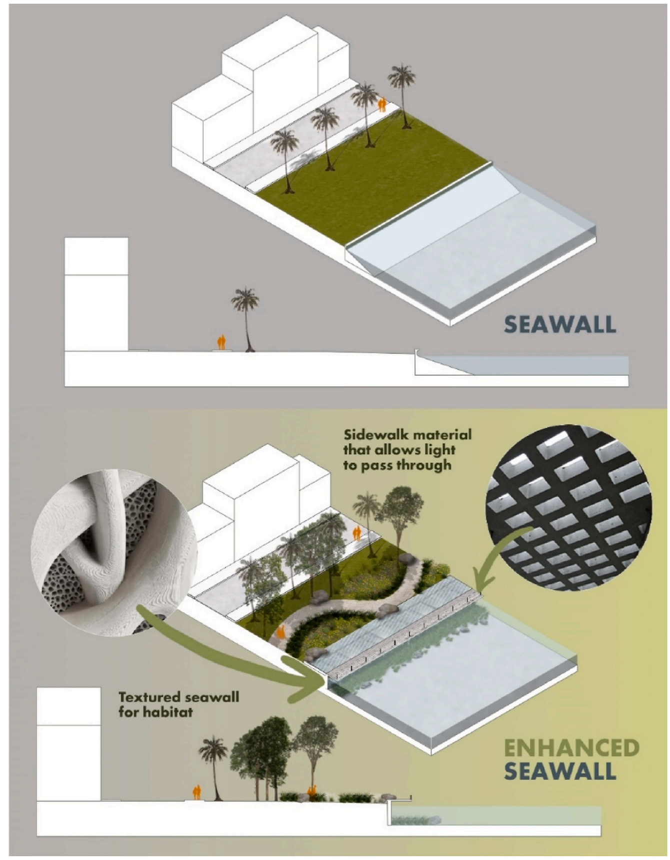

Fig. 3. Renderings of a conventional seawall design (top) and an enhanced seawall design (bottom) that includes various natural and nature-based features for improving habitat quality of the structure, thereby promoting biodiversity and other benefits.

enhance their habitat value while concomitantly meeting the underlying engineering objectives (e.g., see pages 128–130 in (Bridges et al., 2021b).

Detached Breakwaters and Jetties: Detached breakwaters are near-shore structures built parallel to the shore just seaward of the shoreline in shallow water depths. The principal function is to reduce beach erosion by reducing wave height and thus longshore and cross-shore sediment transport (USACE, 2008). Detached breakwaters can be used to create or stabilize coastal wetlands. They have been used in combination with sediment beneficial use for years (Chasten et al., 1993). There are several ways detached breakwaters can be designed or modified to increase biodiversity (e.g., (Geisthardt et al., 2021). Detached breakwaters can be submerged to help improve aesthetics or can be segmented to promote water circulation and improve habitat value. A detached breakwater can be made of many materials, but structures such as reef balls can stimulate reef habitats (Harris, 2009). Multi-purpose breakwaters that are designed to provide added environmental enhancement and/or social, as well as structural benefits, play an important role in harbor and coastal resiliency efforts (Fredette et al., 2016; Manson et al., 2018; Hardaway et al., 2020).

Jetties are another type of structure perpendicular to the shore and are placed adjacent to tidal inlets and harbors to control inlet migration and minimize sediment deposition within the inlet. Jetties are like breakwaters in design and materials yet differ in their function (USACE, 1989). Jetties may disrupt natural sediment regimes and cause erosion along the coastline. Jetties can be improved for biodiversity by using natural building materials and materials that promote habitat growth in the jetty (see Fig. 4 in (King et al., 2021).

Sill: A sill is a rock structure placed parallel to the shore to reduce

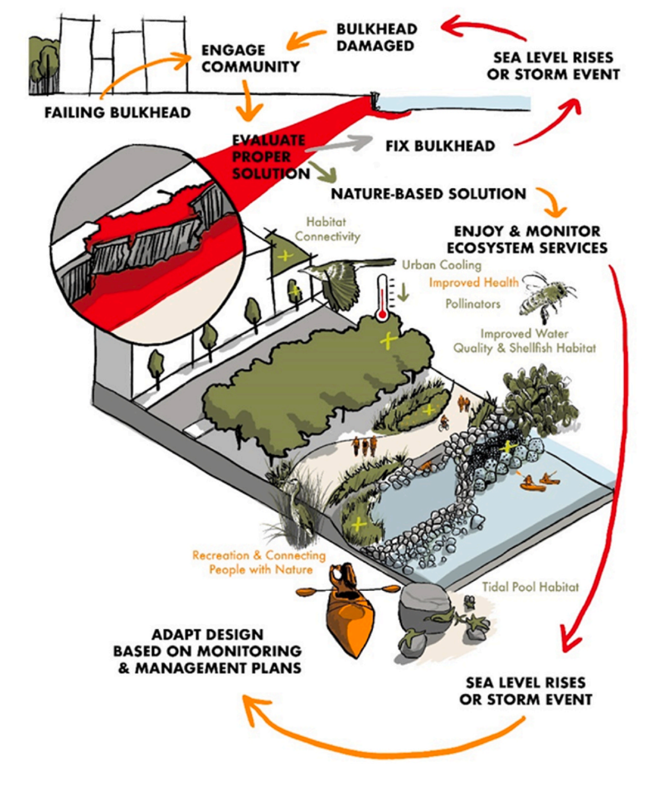

Fig. 4. Conceptual drawing of existing coastal infrastructure showing natural and nature-based features to be included in a design proposal using the structured decision-making approach (red and orange arrows) for repairing a failing bulkhead, along with the inter-relationships among the various components of the structure and related environmental, economic, and social benefits. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

wave energy. Sills are like breakwaters but are usually smaller and placed relatively close to the shore (Hardaway and Byrne, 1999). In many cases, fill is needed to supplement the backshore to help establish a marsh fringe in the lee of the sill. In higher wave energy environments, sills can be used to establish intertidal marsh grasses. As features in living shorelines, sills offer opportunities to enhance biodiversity through elements of their design and choices of backshore fill material. In this manner, sills help stabilize the shoreline while promoting the development of a marsh fringe landward of the sill to promote biodiversity (Bilkovic and Mitchell, 2017; Bilkovic et al., 2021).

Tidal Control Structure: Tidal control structures such as dikes and tide gates are used to drain wetlands in both estuaries and the lower sections of rivers influenced by tides. Tide control structures are built into levees and other structures, restricting incoming tides to reduce tidal influx. Structures remain open to drain into the receiving waters. Unfortunately, how these structures were designed, constructed, and operated resulted in adverse effects on the ecosystems (Giannico et al., 2005). Adverse effects include severing connectivity within tidal floodplains, thereby impacting water quality, fish passage, and biodiversity (Scott et al., 2016); this highlights the challenges of balancing flood protection and floodplain connectivity. Tidal and flood control structures have been recently designed and operated to be friendlier to native fish and coastal marsh habitats (Bridges et al., 2021a). For example, in the Tomago Wetlands of New South Wales, Australia, novel tidal control gates were designed and built to restore 450 ha of coastal marsh habitat, including supporting migrating avifauna. In another example, the Southern Flow Corridor project utilized an existing tide gate that was integrated with other measures, including the removal of levees and the addition of setback levees to restore nearly 180 ha of land and over 21 km of tidal channels for migratory salmonids (Bridges et al., 2021a).

Groin: Groins are designed and constructed to retain sand on a subaerial beach (Basco and Pope, 2004; USACE, 2002). Groins can cause an accretion of beach material on the updrift side and erosion of material on the downdrift side. Usually, this erosion extends from the structure down the coast, instigating more groins to be built, thus causing a ripple effect (USACE, 2013). Similar to how jetties can be improved, a groin can be retrofitted with the addition of plant material or be included as a component of a living shoreline or other nature-based solution (van der Spek et al., 2020; Conservancy, 2021).

The structured decision-making approach described in this paper can be used to design and develop multiple structural enhancement features for alternatives implementable within each of these coastal infrastructure types. Specifically, aspects of EWN-LA that promote biodiversity on coastal infrastructure can be applied in each of the five elements. Using an example of a failing bulkhead slated for repair, EWN-LA can play a meaningful role in each element. In Scoping, EWN-LA expertise should be identified and included on the project team to help define the nature and scope of the bulkhead repair. In Planning, drawings and renderings of various bulkhead designs are developed by LAs to help facilitate the transparent evaluation of the alternatives and help inform the analysis and identification of those with the highest priority (Fig. 4). In Decision-Making, effective communication can be promoted by EWN -LA drawings and renderings that can serve as communications tools so stakeholders and decision-makers can visualize the final alternative bulkhead design and its inherent benefits (Fig. 5). During Implementation, bulkhead design alternatives are developed by LAs that promote biodiversity while considering other project objectives, local hydrodynamic conditions, and the species the enhanced bulkhead is designed to support. Design features that are convertible or modifiable based on lessons learned or in response to changing environmental conditions can also be communicated by EWN-LA. And finally, in Operations, EWN-LA renderings could play a role in education, training, and technology transfer to document results, lessons learned, and development of webinars or workshops reporting the findings of the repaired bulkhead structure.

3.1. *Promoting best practices*

As with any coastal project, opportunities for success require consideration of risks and uncertainties associated with incorporating NBS and promoting biodiversity. Such risks and uncertainties include obtaining project approval (regarding costs, etc.), hampering future maintenance, compromising structural integrity, choice of project materials, timing, location, ecological connectivity, project scale, and aspects of a changing climate. Yet several actions can be taken to increase the likelihood of success.

The value NBS provides should be identified and quantified so that both benefits and costs and associated with the project can be made. Biodiversity enhancements should be framed in the context of both the short- and long-term benefits to prevailing risks and uncertainties; the enhancements should not degrade the structure or reduce access for maintenance or repairs. Sea level rise and increased storm intensity that can potentially impact NBS implementation should be considered during Planning. Consideration should be given to whether the objective is to “hold the line” or “move in” so that the NBS features meet project objectives. When considering a “hold the line” objective, structural measures can be designed to provide future accommodation space for intertidal species to reduce the risks associated with coastal squeeze (Perkol-Finkel and Sella, 2015; Perkol-Finkel et al., 2018; Naylor et al., 2017).

Coordination and education activities can offer solutions for reducing NBS risks and uncertainties. Education should be promoted because NBS may be a relatively new concept for some stakeholders. Introducing the concept may produce a change in how a risk manager

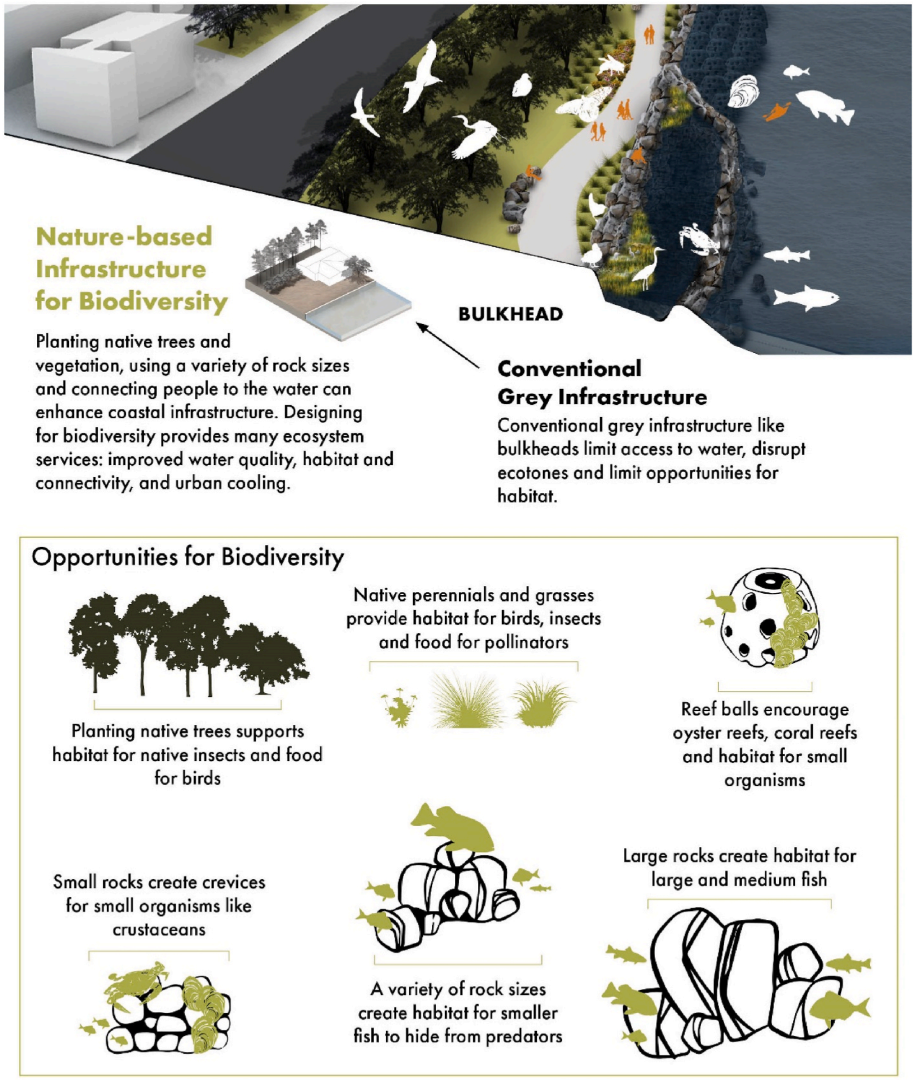

Fig. 5. Detailed rendering showing the various aspects of how a bulkhead structure can be enhanced, including the features that are designed specifically to enhance biodiversity. Such biodiversity enhancements can also provide related social and economic benefits associated with the infrastructure.

might perceive a proposed project. While the primary project objective may be to reduce coastal flood risk, NBS introduces the perspective of “what could be done creatively to promote biodiversity in addition to serving the engineering objective?” Education, training, and technology transfer can also include documentation of case studies, development of webinars or workshops, and site visits of successful coastal NBS projects. This approach has proven successful in the UK, where these activities have helped raise awareness and improve practitioners’ confidence who are keen to promote NBS (Naylor et al., 2017).

Effective communications both internally within the project team and externally with stakeholders are imperative so that the approach can be successfully applied elsewhere. Monitoring should include collecting data to improve understanding of the future value-added that applying such an approach in practice can achieve and how effectively the NBS can integrate into broader coastal risk reduction measures. Maintenance activities appropriate for enhanced structures may include engineering inspections adapted slightly too, for example, scraping off non-native biota (Perkol-Finkel and Sella, 2015) or using unmanned technologies in situations where access is limited due to safety concerns. Enhanced projects that relay lessons learned are more informative and valuable for applying these concepts elsewhere.

4. Conclusions

In this paper, we present a process whereby NBS can be used to enhance biodiversity in coastal infrastructure across various spatial and temporal scales. Scoping, Planning, Decision-making, Implementation, and Operations are structured decision-making elements for achieving enhanced biodiversity through collaboration with partners and stakeholders. Through this structured process, engineering practice can be advanced by landscape architecture renderings utilizing ecological sciences and NBS into an integrated approach for enhancing biodiversity in coastal marine environments. Opportunities for success when redesigning hardened shorelines require consideration of risks and uncertainties associated with incorporating NBS. Several actions can be taken to increase the likelihood of success for addressing risks and uncertainties such as obtaining project approval (with regards to costs, etc.), hampering future maintenance, compromising structural integrity, choice of project materials, timing, location, ecological connectivity, project scale, and a changing climate (Table 1). Promoting best NBS practices includes identifying and quantifying the short- and long-term value of NBS, coordination and education activities, and effective communications both internal and external to the project team. LA renderings can play a meaningful role in securing biodiversity project success. And finally, as knowledge is gained by the design, implementation, and operation of such enhanced structures, guidance documents such as the USACE Engineer and Coastal Manuals can be updated, thereby advancing NBS as standard practice.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests.

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