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Coastal Natural and Nature-Based Features: International Guidelines for Flood Risk Management

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Natural and nature-based features (NNBF) have been used for more than 100 years as coastal protection infrastructure (e.g., beach nourishment projects). The application of NNBF has grown steadily in recent years with the goal of realizing both coastal engineering and environment and social co-benefits through projects that have the potential to adapt to the changing climate. Technical advancements in support of NNBF are increasingly the subject of peer-reviewed literature, and guidance has been published by numerous organizations to inform technical practice for specific types of nature-based solutions. The International Guidelines on Natural and Nature-Based Features for Flood Risk Management was recently published to provide a comprehensive guide that draws directly on the growing body of knowledge and practitioner experience from around the world to inform the process of conceptualizing, planning, designing, engineering, and operating NNBF. These Guidelines focus on the role of nature-based solutions and natural infrastructure (beaches, dunes, wetlands and plant systems, islands, reefs) as a part of coastal and riverine flood risk management. In addition to describing each of the NNBF types, their use, design, implementation, and maintenance, the guidelines describe general principles for employing NNBF, stakeholder engagement, monitoring, costs and benefits, and adaptive management. An overall systems approach is taken to planning and implementation of NNBF. The guidelines were developed to support decision-makers, project managers, and practitioners in conceptualizing, planning, designing, engineering, implementing, and maintaining sustainable systems for nature-based flood risk management. This paper summarizes key concepts and highlights challenges and areas of future research.

Keywords: natural and nature-based features, flood risk management, reefs, islands, vegetation, wetlands, beaches, dunes

INTRODUCTION

Coastal flood risk management (FRM) reduces future flood damages and erosion by constructing structural measures (seawalls, breakwaters, and revetments), applying natural and nature-based features (NNBF) (beaches, dunes, islands, wetlands, and reefs), and using non-structural measures (coastal retreat). Natural landscapes and features have always contributed to coastal flood resilience. Keen interest in NNBF approaches is driven by the desire for long-term risk mitigation, increased resilience of coastal communities and ecosystems, reduced maintenance, and increased value of FRM investments (Bridges et al., 2015). NNBF use landscape features to reduce flood risk while providing additional economic, social, and environmental co-benefits. NNBF can be used alone, in combination, or with conventional coastal protection infrastructure to reduce flood risk. The use of NNBF in an FRM system depends on the FRM goals, geographic setting, temporal/spatial scales, and other factors. This paper reviews the coastal NNBF content of the recently published International Guidelines on Natural and Nature-Based Features for Flood Risk Management (Bridges et al., 2021). **Figure 1** provides an overview of the content and concepts of the guidelines within a system context. This unique, comprehensive guide draws on the international growing body of knowledge and experience, consolidating and expanding to provide a systems approach as well as descriptions of fundamental processes and engineering tools. The guide is not a step-by-step design manual, but instead informs the process of conceptualizing, planning, designing, engineering, and operating NNBF based FRM systems.

Climate change is a major challenge of our time (IPCC, 2021). To address this challenge, NNBF provide flexibility, adaptability, and co-benefits that hard infrastructures alone lack. Innovation is required to expand the knowledge and application of NNBF for practical application, and policies are needed to guide and expand the use of NNBF. NNBF research and application is multidisciplinary, requiring collaboration, coordination, and partnerships across disciplines and stakeholders for success. This paper summarizes NNBF principles; systems approach; performance, benefits, and costs; coastal NNBF systems; enhancing structural measures; and knowledge gaps and research needs.

PRINCIPLES

Applying NNBF to FRM projects is similar to standard engineering approaches, but emphasizes a multidisciplinary, systems approach. Key NNBF principles are (Bridges et al., 2021):

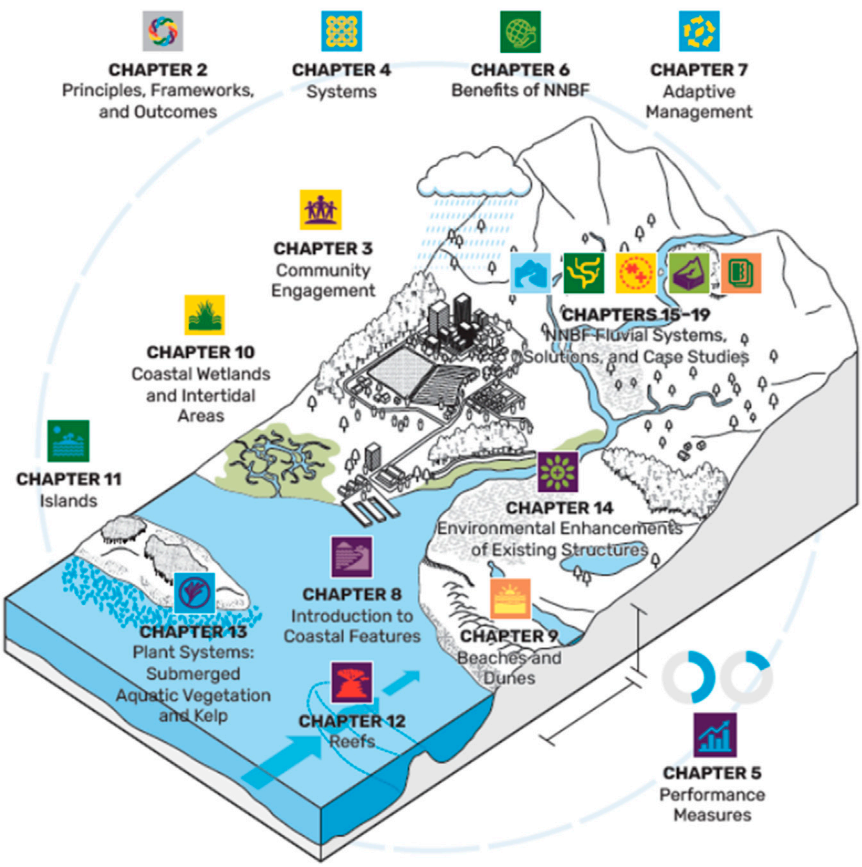

FIGURE 1 | Contents and concepts of NNBF guidelines within a systems context (Bridges et al., 2021).

- Expect change and manage adaptively
- Identify resilient solutions that produce multiple benefits
- Use a systems approach to leverage existing components and projects and their interconnectivity
- Engage communities, partners, and multidisciplinary team members to develop innovative solutions and monitor social, economic, and environmental outcomes
- Anticipate, evaluate, and manage risk in project or system performance

The International Guidelines includes a project framework for NNBF applications (King et al., 2021). The design process is iterative and may require revisiting previous phases based on new data or information. Desirable outcomes are identified at each phase: scoping (stakeholder engagement/commitment), planning (funding, benefits), decision making (option selection), implementation (approvals, optimization), and operations (monitoring/adaption).

NNBF projects require a deeper commitment to engagement than other types of projects (Dillard et al., 2021). The engagement process should be iterative, flexible, and feed into all phases of the project (defining the problem, developing/evaluating alternatives, maintenance, monitoring, and evaluation). Engagement should include all who are interested in, have influence over, or are impacted by the project, and these stakeholders should be involved early and kept informed throughout. Strong engagement increases the likelihood of multiple benefits and beneficiaries. NNBF projects should include an engagement plan (focused on project objectives) with resources to carry it out. NNBF projects generally evolve in different ways and rates than conventional, hard infrastructure, so communication with stakeholders about expectations is key (e.g., features may erode during storms and need maintenance; and protection may be subaqueous and not easily visible). Engagements should be planned (objectives, context, resources, methods), documented, and evaluated, but also flexible and adaptive. Stakeholders can assist in successfully involving press, politics, and the broader community.

SYSTEMS APPROACH TO PLANNING AND IMPLEMENTING NATURAL AND NATURE-BASED FEATURES

A systems approach is needed to define, characterize, and manage multifunctional and sustainable NNBF solutions (de Vries et al., 2021). The interplay of ecology, geomorphology, and hydrodynamics with communities and engineering infrastructure provides the context of the system. Evaluating FRM solutions requires assessing physical, biological, and social processes and their interaction and synergies. Holistic, system-wide solutions can be explored through collaboration of people with different perspectives and disciplines to accelerate identification and implementation of suitable, resilient, and well-functioning solutions. Systems thinking is needed to evaluate the variety of ecosystem benefits, multiple potential outcomes, multifunctional design, and direct engagement with stakeholders. NNBF solutions evolve and develop over time and space (e.g., accretion of sediment and growth and succession of vegetation). A systems perspective is used to implement a large-scale system or integrate effects of small or standalone projects as part of a larger FRM effort. Since some aspects and applications of NNBF are new, there are limited examples of mature projects. It is important to document case studies to help mainstream the application of NNBF and highlight the potential for wide-ranging benefits.

NATURAL AND NATURE-BASED FEATURES PERFORMANCE, BENEFITS, AND COSTS

Performance of NNBF projects can be challenging to document because the system is dynamic and some benefits accrue slowly (e.g., beach fill adjustments, colonization of flora and fauna) (Piercy et al., 2021b). Performance of an NNBF project is the ability to meet desired outcomes as measured by a set of metrics. Metrics are specific parameters or properties of the NNBF that are quantifiable and associated with desired aspects of performance. Metrics include direct and indirect measurements and are assessed based on predetermined performance criteria. Sources of uncertainty in NNBF performance are similar to structural measures, although natural variability in NNBF is greater. Monitoring metrics should be chosen to capture the most critical project aspects. Periodic assessment at a frequency commensurate with nature dynamism are required over the project life cycle. Both NNBF and structural measures need better assessment of long-term failure rates (fragility) and maintenance costs. FRM and ecological, social, and economic performance of NNBF are interrelated, and proper ecological function of NNBF is critical to FRM, social, and economic functions. There are several interrelated categories of performance related to NNBF:

- FRM—reduction of physical forces that produce flooding and damages for the full range of possible events (system and structural performance).
- Ecological—production of desired ecological function (ecosystem goods and services).
- Social—social co-benefits include health, well-being, and equity, as well as recreational, cultural, and educational benefits.
- Economic—reduction in economic damages and value (ecological, social, and FRM) produced by the NNBF.

NNBF project performance should be considered over the entire project life cycle, including present and future conditions. NNBF performance may deteriorate with time and require maintenance to preserve function (e.g., beach/dune renourishment). Unlike structural measures, NNBF may naturally adapt to future conditions (e.g., through marsh sedimentation or vertical growth of oyster or coral reefs), and performance may improve over time. Performance concepts also apply to natural features existing within projects. Performance measurement/monitoring is key to adaptive management (de Loof et al. 2021).

The goal of protecting, restoring, and advancing NNBF is to reduce flood risk and erosion, adapt to climate change, and build coastal resilience (van Zanten et al., 2021). Additionally, NNBF produces ecological, social, and economic co-benefits that vary with local conditions and stakeholder values. Evaluating NNBF alongside structural alternatives requires evaluating relative costs and benefits, including both flood risk reduction and co-benefits. Flood and erosion risk reduction is achieved via different processes depending on the type of NNBF, including trapping sediment, wave damping, and water storage. Advances in numerical modeling have increased the capacity to value NNBF risk reduction benefits. Co-benefits include habitat for fisheries, opportunities for tourism and recreation, carbon sequestration, and human health benefits (Barbier et al., 2011). Agencies and stakeholders define shared objectives and develop performance standards that capture economic, social, and ecological benefits of implementing NNBF. Guidance is needed to better incorporate co-benefits into assessment of alternatives and monitoring of outcomes. Multiple valuation approaches and metrics can be used to assess benefits and social vulnerability outcomes qualitatively and quantitatively, and different metrics and decision-support tools are suitable for different audiences. Societal benefits can be assessed by combining hazard analysis with maps of social indicators to estimate the number of people and critical infrastructure at risk and compare risk reduction benefits from NNBF. Co-benefits may expand funding and financing options. The costs in the total lifecycle of NNBF projects include: planning; design and permitting; land acquisition; creation, protection or restoration; and monitoring and maintenance.

NATURAL AND NATURE-BASED FEATURES IN COASTAL SYSTEMS

Coastal NNBF creates or recreates natural habitats, enhances existing habitats, uses more-organic materials, and enhances existing hard infrastructure (Simm, 2021). The coastal landscape provides risk mitigation and is the foundation that supports structural measures. FRM systems may be single lines or multilayer, multizone cross-shore systems with both structural and NNBF elements. The coastal environment is in continual change, both cyclical and continuous, e.g., nonstationary waves (varying energy, frequency, and direction) and water levels (tides, surge, sea level rise (SLR)), evolving cross-shore profile and shoreline, and growing population and development. Coastal NNBF includes beaches and dunes, wetlands and plant systems, islands, and reefs. The maturity of knowledge about application of different features varies significantly. The international NNBF guidelines describe these features in detail, including a conceptual understanding; objectives and metrics; design; implementation; monitoring, maintenance, and adaption; and gaps and future directions. Extensive case studies, examples, and references are provided.

Beaches and Dunes

Beaches are dynamic coastal landforms, constitute a natural transition between land and sea, are an amenity and economic resource, and provide habitat for diverse species (Lodder et al., 2021). They reduce land loss and flooding while providing recreational and environmental benefits. Beaches are acted on by wind and hydrodynamic processes (waves, currents, and water levels). Dunes accumulate wind-blown sand and are stabilized by vegetation or control structures and naturally buffer against flooding during extreme events. The shape and size of beaches and dunes are a function of geology, geomorphology, wind and wave regime, and tidal range. A sustainable beach and dune system requires sufficient sediment sources (longshore and cross-shore) and appropriate flora and fauna.

Beach and dune design typically aligns with the natural system, particularly regarding grain size, to reduce maintenance. Design should allow for beach profile dynamism, focusing design on elevation, volume, slope, and width. Sediment budgets and modeling of hydrodynamic and sediment processes aid understanding of the physical system dynamics to determine scale and feasibility of projects. Designs must consider past and future scenarios, including socioeconomic development and climate change impacts (SLR, storm frequency and intensity). Management requirements, strategies, and monitoring must be part of the design. Innovative sand placement techniques tap nature to enhance coastal resilience (e.g., nearshore placement to winnow fines, sand fencing to build dunes). Beaches and dunes can gradually adapt to climate change when supplied with enough sediment and space to adjust. Maintenance can be adapted over time to respond to system nonstationary.

Coastal Wetlands and Plant Systems

Wetlands and intertidal areas dampen waves and surge and trap sediments (Piercy et al., 2021a). Wetlands provide tens of thousands to millions of US dollars in flood damage reduction/km^2/yr, depending on location and configuration (Sun and Carson, 2020). These features provide co-benefits including fish production, filtration of pollutants, water-quality mediation, recreation, and carbon sequestration. Coastal wetlands and tidal flats reduce coastal flood and erosion risk with raised bed levels and frictional resistance to attenuate waves and surge. NNBF projects include conservation of existing wetlands, restoration of degraded wetlands, or construction of new wetlands and may be combined with other structural or NNBF measures. Wetland performance is controlled by location, coastline geometry, and storm characteristics. Significant wave reduction can occur within relatively narrow feature widths (10's of meters), while reduction of surge requires greater cross-shore extents (100–1,000's of meters) (Piercy et al., 2021a). In some configurations, coastal wetlands may serve as flood storage areas to reduce water levels in estuarine environments. Coastal wetland NNBF projects draw on extensive experience in restoration of marshes and mangroves which has created thousands of hectares worldwide over recent decades. The performance of wetland and tidal flat NNBF projects may vary over time as vegetation establishes and develops. Designs should consider storm damage, recovery, and maintenance requirements. Wetlands have the potential to be self-sustaining under climate change if there is sufficient sediment for accretion and space to adapt.

Submerged aquatic vegetation (SAV), kelp, dune grass, wetland vegetation, mangroves, and maritime forests are examples of coastal plant systems that provide both above and below ground benefits (Altman et al., 2021). These systems reduce wind, wave, and current energy and stabilize sediments. The magnitude of wave attenuation depends on the height of the canopy relative to the total water depth; stem diameter, rigidity, and density; and plant morphology, as well as hydrodynamic conditions (waves, currents, water levels). The protective value is maximized when canopy height is equal or greater than the water depth. Plants provide ecological benefits, nursery habitat for fish and shellfish, and water quality improvement. Plant systems complement other NNBF techniques and should be considered for use in larger NNBF projects that incorporate multiple features or small-scale projects in low-energy environments. It is critical to match the plant system to the site. Vegetation habitats are spatially dynamic, and thus robust monitoring is required to understand their condition and health trajectory. SAV benefits are optimized in low-energy environments or in conjunction with other techniques to reduce wave and current energy. The protective role of coastal dune vegetation is widely acknowledged, but not extensively quantified. Through their natural ability to protect shorelines against erosion and flood risk and adjust to SLR, vegetated systems play an important role in sustainable coastal FRM strategies. Plant systems are subject to natural habitat succession, so it is critical to understand that functional plant-based NNBF may not persist as a particular habitat type in perpetuity. Changing ocean temperatures and SLR must be considered in planning for species succession.

Islands

Island in estuaries, river deltas, and open-coast environments reduce the severity of coastal hazards, including erosion and flooding from waves and extreme water levels (Gailani et al., 2021). They can provide multiple benefits: storm surge reduction, wave dissipation, erosion control, dredged material management, safe navigation/harbor, ecosystem diversity (critical ecosystem function for threatened and endangered species), recreation, and commercial opportunities. Islands can be newly constructed or restorations of islands degrading due to SLR, subsidence, or inadequate sediment input. Islands deliver resilience benefits, especially as part of multiple-lines-of-defense strategies and may be effective where other NNBF methods are not feasible (urban or high energy areas). The regional influence of islands thus must be considered (circulation, water quality, sediment transport, and habitat). Islands are multihabitat features (beach/dune, wetlands, and upland), and habitat trade-offs are inevitable. Short-term impacts must be considered within the context of long-term ecosystem co-benefits and SLR. Uncertainties and risk exist in island construction due to the complex physical processes. Design and maintenance of resilient islands requires consideration of the evolving, dynamic conditions.

Reefs

Coral, rock, and shellfish reefs reduce flooding and erosion in coastal areas by reducing wave energy. For example, coral reefs in the United States provide more than USD$1.8 billion/yr in flood risk benefits (Reguero et al., 2021). Many reef-lined coasts act as the first line of defense against flooding, storm damage, and erosion (Lowe et al., 2021). Reefs also provide numerous co-benefits, including fisheries, habitat and biodiversity, recreation and tourism, and improved water quality. Reef organisms in a healthy system produce calcium carbonate that is a source of sand nourishment to adjacent beaches. Design and construction of a NNBF reef should mimic the natural geomorphology of a pre-existing or existing reef platform to favor biological growth, and materials should be compatible with those in the surrounding environment. Adaptive management is needed to support reef resilience in the context of global environmental change. Natural and engineered reefs can be self-sustaining ecosystems, continuing to grow and maintain a structure to keep pace with SLR, if the reef accretion rate exceeds the rate of SLR. Understanding the coastal protection services of reefs and quantifying how they reduce risk are required to effectively use reefs in coastal climate adaptation and hazard mitigation strategies.

Reefs provide coastal risk reduction by dissipating waves as they propagate over shallow, rough reef structures, thus reducing wave-driven coastal flooding. The effectiveness of reefs depends on their size, orientation, elevation, and location relative to shore. The reef crest elevation relative to sea level is a key parameter. Reef degradation also decreases wave attenuation as the elevation and roughness reduce over time. Reefs promote shoreline stability and play critical roles in protecting and establishing other coastal habitats (seagrass beds in protected lagoons, mangrove forests, beach/dune systems). For example, by reducing wave energy and improving water quality, shellfish reefs can provide suitable conditions for salt marshes and seagrass beds. These multiple layers of protection may be the most effective strategy when habitats are interconnected and functioning together.

ENHANCING STRUCTURAL MEASURES

Conventional FRM includes structures such as bulkheads, seawalls, sheet piling, and floodwalls, in addition to levees and dikes that may combine earthen, rock, and concrete structures. The environmental value of these conventional structures may be enhanced through inclusion of nature-based elements that expand their ecological value by enhancing habitat or social benefits (Suedel et al., 2021). Enhancements through NNBF take multiple forms and span broad scales and structure types, from applying small-scale features to create habitat to large structures to dissipate waves and surge. Ecological enhancements can offer multiple benefits, e.g., increased engineering design life and flood risk reduction, habitat enhancement, improved water quality, and societal benefits (Naylor et al. 2017). Opportunities to enhance structures occur at any stage in the design life of a project (new construction, repair, maintenance, or structure modification). Identifying and quantifying the value of NNBF enhancement allows costs and benefits to be compared alongside conventional structures (Naylor et al. 2018). Engaging stakeholders in the process of identifying opportunities to enhance value and benefits broadens the base of support for infrastructure projects and aids in complying with environmental laws and regulations. The best opportunity to enhance structures is often during maintenance, repairs, and modifications to existing structures.

TABLE 1 | Knowledge gaps and research needs.

NNBF category	Knowledge gaps
Planning and implementing NNBF using a systems approach	• Comprehensive systems-thinking lessons learned and case studies, including mature projects • Evidence base to mainstream systems thinking and NNBF. • Best practices to account for expansive consideration of co-benefits • Incorporation of multiple spatial and temporal scales and their feedback to support NNBF design and operation
NNBF performance measurement	• Methods/tools to characterize the dynamic nature of NNBF performance • Performance metrics that describe how individual measures and the FRM system as a whole serve to reduce inherent and residual risks associated with flood hazards • Methods to better capture risk evaluation across project life cycles in nonstationary systems • Holistic quantification and consideration of benefits and co-benefits of NNBF performance and sustainability
Benefits and costs	• Quantitative methods to account for fragility of NNBF to coastal hazards (fragility curves) • Better alignment between financing models for NNBF and benefit assessment methodologies to unlock funding sources • New methodologies to accurately reflect risk reduction and co-benefits of NNBF projects • Combined field and modeling studies to monitor the long-term social and economic outcomes of NNBF. • Advanced Earth observation technology to assess and monitor NNBF benefits
Adaptive management	• Community Adaptive-Management definitions and frameworks • Efforts to improve leadership and stakeholder acceptance of the concept of Adaptive Management • Flexibility in laws and policy to account for shifting baselines to capture future conditions • Flexibility in funding to facilitate data collection, analysis, and active adaptive management
Beaches and dunes	• Document evidence base on the long-term performance of beach and dune NNBF for coastal resilience under a wide range of conditions and environmental settings • Enhance understanding, uptake and upscaling, and improved implementation of beach and dune NNBF in coastal resilience projects • Develop and implement long-term strategies for sustainable coastlines in relation to long-term processes such as climate change and socioeconomic developments • Quantify dune vegetation impacts on dune growth, erosion, and long-term sustainability • Enhance existing beach evolution models for combined hard and soft structures under complex loading (nonstationary wind, wave, and water level forcing)
Wetlands	• More field and modeling studies to address long-term wetland stability to compare with effectiveness of other nonstructural and structural measures • Consistent cost-benefit framework that accounts for full array of benefits, co-benefits, and life-cycle costs • Expand knowledge base of wetland NNBF performance under different conditions (extreme storms, high water levels, and SLR) • Methods/tools to quantify system-scale benefits and co-benefits of wetland NNBF and linkage between wetland NNBF and other measures • Improvements to coastal wetland hydrodynamic and sediment models to include wetland NNBF more accurately and efficiently in modeling scenarios • Quantify parameters to determine sustainability of marshes
Islands	• Research on combined, complementary effect of multiple habitat types from offshore to onshore in terms of both short- and long-term benefits to justify larger NNBF island projects • Quantitative studies of island areas of influences to address habitat switching and potential impacts of island restoration • Innovative practices and field experimentation (living labs) to improve understand of island systems • Regional case studies to illustrate and optimize design, implementation, and maintenance approaches • Enhance models for long-term erosion and recovery of islands, spanning long and short time and space scales
Reefs	• Methods to optimize performance of reef NNBF to achieve ecological and coastal protection benefits at larger scales • Long-term monitoring to understand changes to sources and composition of coastal sediments and long-term evolution of shorelines protected by reefs • Advances to support increased survival and fitness of shellfish reared in hatcheries and selective breeding programs for disease resistance • Economic studies that account for the full suite of ecosystem benefits that natural reefs provide to incentivize protection and restoration of coral and shellfish reefs • Improve and ground truth predictions of reef effectiveness in reducing wave-drive flood risk across a range of different types of reefs (including wave breaking and friction associated with reef roughness) • Technical advancements to scale up reef restoration projects to support joint flood and coastal risk reduction with environmental conservation objectives • Additional studies to monitor and document the efficacy of materials used in reef construction • Innovative solutions to accelerate the broader application of reef NNBF, further increase the cost-effectiveness of designs that are appropriate for a range of local socioeconomic conditions

(Continued on following page)

TABLE 1 | (*Continued*) Knowledge gaps and research needs.

NNBF category	Knowledge gaps
Plant systems	• Collect baseline data on hazard reduction and plant system evolution and resiliency, especially in changing conditions • Develop metrics for baseline information such as beach erosion rate and beach profile change to quantify the contribution of SAV to coastal protection • Advance use of remote sensing to monitor and evaluate the efficacy of SAV in providing storm protection and integrate into models
Enhancing benefits	• Widely distributed documentation of existing projects and conduct pilot studies to establish proof of concepts • Education, training, and tech transfer of case studies and workshops to disseminate best practices and coordinate of site visits to observe implementation of innovations in practice • Demonstration projects to demonstrate and document successes in NNBF enhancements on multiple spatial and temporal scales • Consider emerging technologies to improve planning and practice: materials, observation methods for planning and monitoring (e.g., remote sensing), model advancements for evaluating design and project siting • Novel designs for creating habitat niches for a variety of species and replace conventional hard structures with hybrid structures • New materials to reduce carbon dioxide emissions during construction • Document and proliferate the most valuable advances

INNOVATION AND RESEARCH NEEDS

The understanding and acceptance of NNBF for FRM is increasing quickly, but many knowledge, experience, and policy gaps remain. NNBF technical research often focuses on specific features, feature elements, or specific sites; integrating across such approaches is needed to provide generalized, wide-ranging solutions. **Table 1** summarizes knowledge gaps and future research areas. Investment in research and development will inform and fuel future advancements in practice for both conventional and nature-based approaches to FRM.

CONCLUSION

The combination of aging infrastructure and climate change is prompting new thinking and practices regarding FRM strategies, viewed broadly to include long-term benefits and value, including economic damages avoided, co-benefits, and greater system resilience. NNBF solutions are an important part of future FRM strategies and require a multidisciplinary approach. Effective and timely implementation of NNBF to address FRM challenges depend on progress in three overarching areas: developing and delivering, communicating and collaborating, and elevating and educating. A systems approach is required to provide a comprehensive vision for process functions, relationships, and engineering interventions critical to successful outcomes.

Expanding the engineering application of NNBF for FRM requires continued advancement of the supporting interdisciplinary science as well as advancing policy and economic valuations. Integrative approaches to FRM that include NNBF measures require advancing models and modeling practice with respect to natural features, processes, systems, and uncertainty quantification in the dynamics of physical and natural systems. Advancement of environmental regulation and management to conserve and protect natural systems is also required. These advances build on the growing recognition of natural values and capital so that communities can fully leverage natural systems and functions to address the dynamic challenges posed by FRM and climate change. Engagement, communication, and collaboration that bridge the gaps between technical disciplines, organizations, and the public are fundamental to successful project development and implementation through purposeful investment in communications and engagement. Many environmental and social co-benefits are challenging to quantify but critical to establishing a project's value (e.g., biodiversity, social equity). Monitoring and adaptive management of NNBF is critical to the ultimate success of projects. The International Guidelines on Natural and Nature-Based Features for Flood Risk Management support developing and delivering FRM projects that incorporate NNBF to provide resilient solutions over the long term. Next steps include developing guiding policy and engineering manuals to support NNBF design, implementation, and operations.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

TB contributed to conception and design of the study. JaS wrote the first draft of the manuscript. TB, JaS, JK, JoS, MD, JV, DR, CP, BZ, KA, TS, HL, QL, CJ, NP, JG, PW, EM, RL, EM, SA, CC, BS, and LN contributed to sections of the manuscript. All authors contributed to manuscript revision, read and approved the submitted version.

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