NNBF

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

International Guidelines on Natural and Nature-Based Features for Flood Risk Management Overview

OVERVIEW

NNBF

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

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

Published 2021

Sponsoring Agency Headquarters, U.S. Army Corps of Engineers
441 G Street Northwest
Washington, District of Columbia 20314-1000

Publisher U.S. Army Engineer Research and Development Center
3909 Halls Ferry Road
Vicksburg, Mississippi 39180-6199

DOI http://dx.doi.org/10.21079/11681/41945

Report Number ERDR SR-21-5

Citation Bridges, T. S., J. K. King, J. D. Simm, M. W. Beck, G. Collins, Q. Lodder, and R. K. Mohan, eds. 2021. *Overview: International Guidelines on Natural and Nature-Based Features for Flood Risk Management.* Vicksburg, MS: U.S. Army Engineer Research and Development Center.

ISBN Hardcover: 978-1-7378868-0-8
Softcover: 978-1-7378868-1-5
Digital: 978-1-7378868-2-2

Cover Photo Georganna Collins

Refer to the NNBF Guidelines for a full listing of contributing organizations or agencies.

OVERVIEW

NNBF

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

EDITED BY:

Todd S. Bridges, *U.S. Army Corps of Engineers, United States*
Jeffrey K. King, *U.S. Army Corps of Engineers, United States*
Jonathan D. Simm, *HR Wallingford, United Kingdom*
Michael W. Beck, *University of California, Santa Cruz, United States*
Georganna Collins, *Aqua Strategies, United States*
Quirijn Lodder, *Rijkswaterstaat, the Netherlands*
Ram K. Mohan, *Anchor QEA and Texas A&M University, United States*

Final document assembled, technically reviewed, copyedited, and designed by Anchor QEA, LLC, under contract to U.S. Army Corps of Engineers. Jonathan Simm of HR Wallingford provided technical and quality reviews of the document, and Georganna Collins of Aqua Strategies provided consulting on graphics and layout, as subcontractors to Anchor QEA. Refer to the Acknowledgments section of this Overview for a full listing of the NNBF Guidelines' respective chapter lead authors and co-authors and collaborating organizations.

Foreword

The following are select excerpted quotations from the *International Guidelines on Natural and Nature-Based Features for Flood Risk Management*.

Advancing Twenty-First-Century Flood Risk Management

"Change takes courage, but as one starts down the path of innovation, what was once novel becomes more familiar, more established. The U.S. Army Corps of Engineers (USACE) is walking this path with our partners through the Engineering With Nature Initiative (EWN), integrating human engineering with natural systems."

LTG Scott A. Spellmon
55th Chief of Engineers, Commanding General, USACE (United States)

US Army Corps of Engineers.

Natural and Nature-Based Features to Deliver Value for People, Planet, and Prosperity

"For the Netherlands, a country of which about 30% is below sea level and about 60% of its surface is flood-prone, 'Engineering with Nature approaches' have become essential for improving our flood safety in an adaptive manner."

Michèle Blom
Director General, Rijkswaterstaat (the Netherlands)

Ministry of Infrastructure and Water Management of the Netherlands

Using Nature's Techniques to Deliver Adaptation and Resilience for the Future

"Natural and nature-based features (NNBF) are increasingly important to the Environment Agency and its partners in enabling flood risk management programs that create better places for people and wildlife."

Caroline Douglas
Executive Director, Flood and Coastal Risk Management, Environment Agency (United Kingdom)

Environment Agency

A Natural Approach to Our Future Infrastructure Needs

"National Oceanic and Atmospheric Administration (NOAA) recognizes that the scope of flood risk management challenges, worldwide, cannot be fully addressed solely through use of conventional infrastructure and is proud to be a contributor to the International Guidelines on Natural and Nature-Based Features for Flood Risk Management.*"*

Richard W. Spinrad
Under Secretary of Commerce for Oceans and Atmosphere and NOAA Administrator, National Oceanic and Atmospheric Administration (United States)

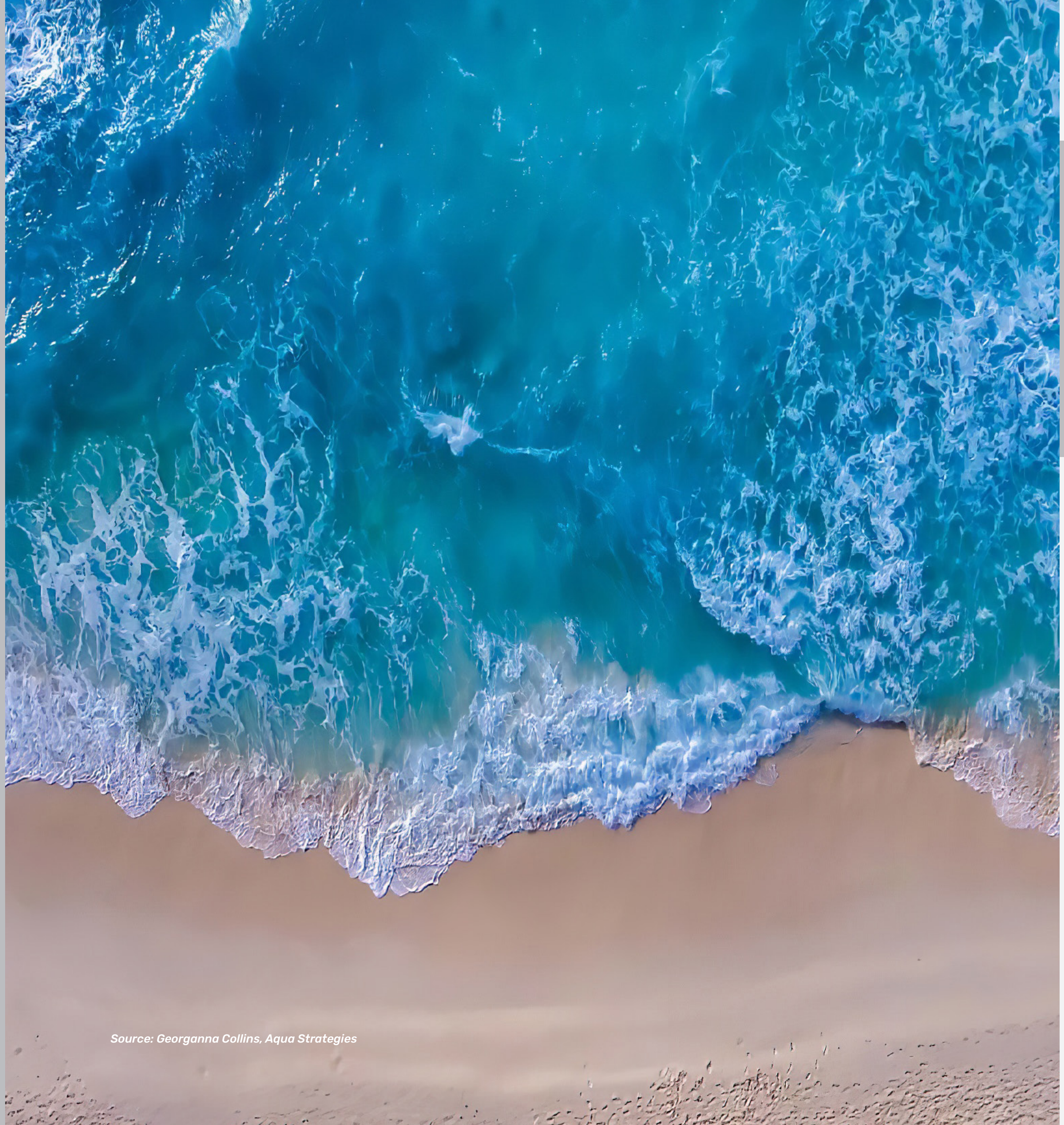
Mainstreaming Nature-Based Solutions for Resilient Development

"We hope these guidelines will provide a new baseline for the technical assessment and implementation of nature-based solutions (NBS) for our client countries and partners."

Sameh Naguib Wahba
Global Director, Urban, Disaster Risk Management, Resilience and Land, World Bank (United States)

WORLD BANK GROUP

NNBF
TABLE OF CONTENTS



Source: Georganna Collins, Aqua Strategies

CHAPTER 1

Introduction

The application of natural and nature-based features (NNBF) has grown steadily over the past 20 years, supported by calls for innovation in flood risk management (FRM) and nature-based solutions from many different perspectives and organizations. Technical advancements in support of NNBF are increasingly the subject of peer-reviewed and other technical literature. A variety of guidance has been published by numerous organizations to inform program-level action and technical practice for specific types of nature-based solutions. This effort to develop international guidelines on the use of NNBF was motivated by the need for a comprehensive guide that draws directly on the growing body of knowledge and experience from around the world to inform the process of conceptualizing, planning, designing, engineering, constructing, and operating NNBF.

This overview of the *International Guidelines on Natural and Nature-Based Features for Flood Risk Management* (NNBF Guidelines) provides a high-level review of each chapter of the guidance and outlines key principles, key messages, and data gaps requiring further study. It is meant to provide a quick read and, therefore, omits details that are found in the full document. The NNBF Guidelines is the product of a large-scale collaboration that included 5 years of working-level meetings and knowledge sharing involving key practice leaders from around the world. The project was initiated and led by the U.S. Army Corps of Engineers (USACE) as a part of its Engineering With Nature (EWN) Initiative. USACE in the United States, the Rijkswaterstaat Ministry of Infrastructure and Water Management in the Netherlands, and the Environment Agency in the United Kingdom were the three primary government institutions that organized and led the effort. Many other organizations also provided critical leadership and participation, including the National Oceanic and Atmospheric Administration, World Bank, National Institute of Standards and Technology, The Nature Conservancy, and the World Wildlife Fund.

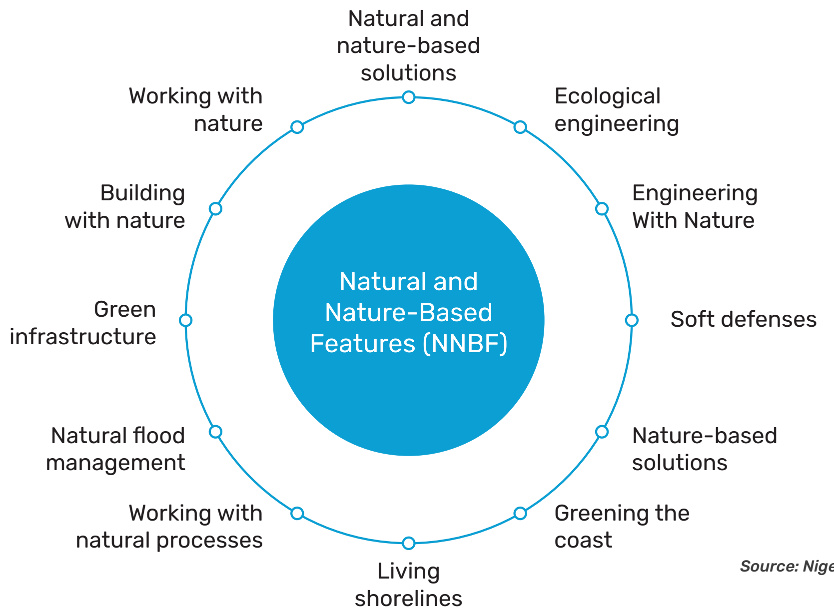
The NNBF Guidelines is a step forward in advancing twenty-first-century flood risk management concepts and practices. It is intended to inform the efforts of practitioners, organizations, and communities seeking to increase the performance of FRM systems and achieve long-term risk mitigation; increase water infrastructure resilience and sustainability; reduce infrastructure maintenance and repair costs; and, ultimately, increase the value produced by FRM infrastructure investments.

In these guidelines, FRM refers to actions taken to reduce future damage to people and property caused by flooding and erosion in coastal and fluvial systems, including actions to address the myriad biophysical processes that contribute to flooding and erosion (e.g., processes contributing to shoreline erosion and loss of land elevation that can increase flood risks over time). NNBF refers to the use of landscape features to produce FRM benefits. NNBF projects may also produce other economic, environmental, and social benefits known as co-benefits. These landscape features may be natural (produced purely by natural processes) or nature based (produced by a combination of natural processes and human engineering) and include such features as beaches, dunes, wetlands, reefs, and islands. Landscape features can be used alone, in combination with each other, and in combination with conventional engineering measures such as levees, floodwalls, and other structures. The type, number, size, and combinations of measures (NNBF or conventional structures) used in an FRM system depend on the context of the problem and on the geographic setting, the goals of the project, and a host of other factors.

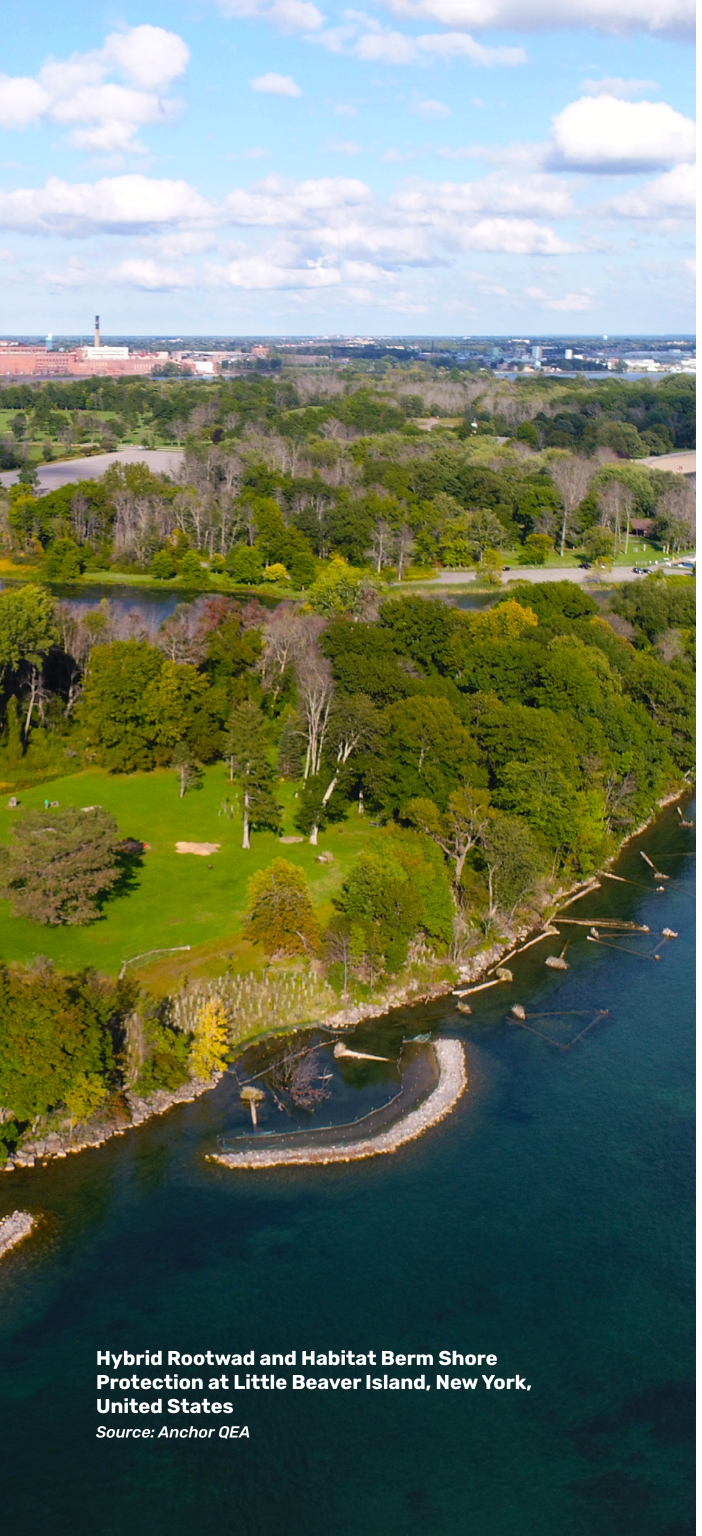
There is a need to address FRM at various, interlinked spatial and temporal scales. These scales are also related to project level (local and regional), program level (regional and national), and even policy or strategy level (national and international). The concept remains similar, but the specifics of implementation can vary.

As used in these guidelines, NNBF are a type of nature-based solution. Different definitions of nature-based solutions for risk reduction and adaptation are in use across the numerous and diverse organizations that are advancing and applying these approaches. The common element among all these definitions is the focus on conserving, restoring, and engineering natural systems for the benefit of people and the ecosystems we inhabit. Related terms, though not necessarily synonymous, include *building with nature, engineering with nature, nature-based solutions, natural flood management,* and *green infrastructure*. The pursuit and development of such approaches stretch across several decades. In the 1960s, ecologist Howard T. Odum and others developed a foundation for ecological engineering; and in 1969, the landscape architect Ian McHarg published his seminal book *Design with Nature* (McHarg 1969[1]). These efforts, and others, contributed to the development of what are now called nature-based solutions.

Terms Related to NNBF



Source: Nigel Pontee, Jacobs



Hybrid Rootwad and Habitat Berm Shore Protection at Little Beaver Island, New York, United States
Source: Anchor QEA

The use of NNBF in various forms has been growing and maturing for several decades, and NNBF projects have been built and are successfully operating around the world (see photograph of the Dutch Sand Motor). Collecting and sharing the international experience on NNBF was a primary motivation for developing the NNBF Guidelines. The length of this document (more than 1,000 pages) testifies to the significant amount of global experience and technical work on NNBF, which continues to grow. Hundreds of scientific papers and reports related to NNBF have been produced by organizations, researchers, and practitioners around the world during the 5 years this NNBF Guidelines was developed.

That said, the purpose of these guidelines is to inform and guide, not to provide an exhaustive summary or analysis of this growing body of technical literature. This guidance is not intended to be a “cookbook” with NNBF “recipes” to follow. We do not aim to provide the NNBF analog for calculating the size of rock to be used in conventional shoreline armoring projects. The goal of the NNBF Guidelines is to help inform the process of conceptualizing, planning, designing, engineering, and operating FRM systems that include NNBF. The escalating scale of flood risks and challenges calls for new ways of envisioning solutions, layering, and combining measures, and phasing the development of FRM systems that include the functions and values nature can provide.

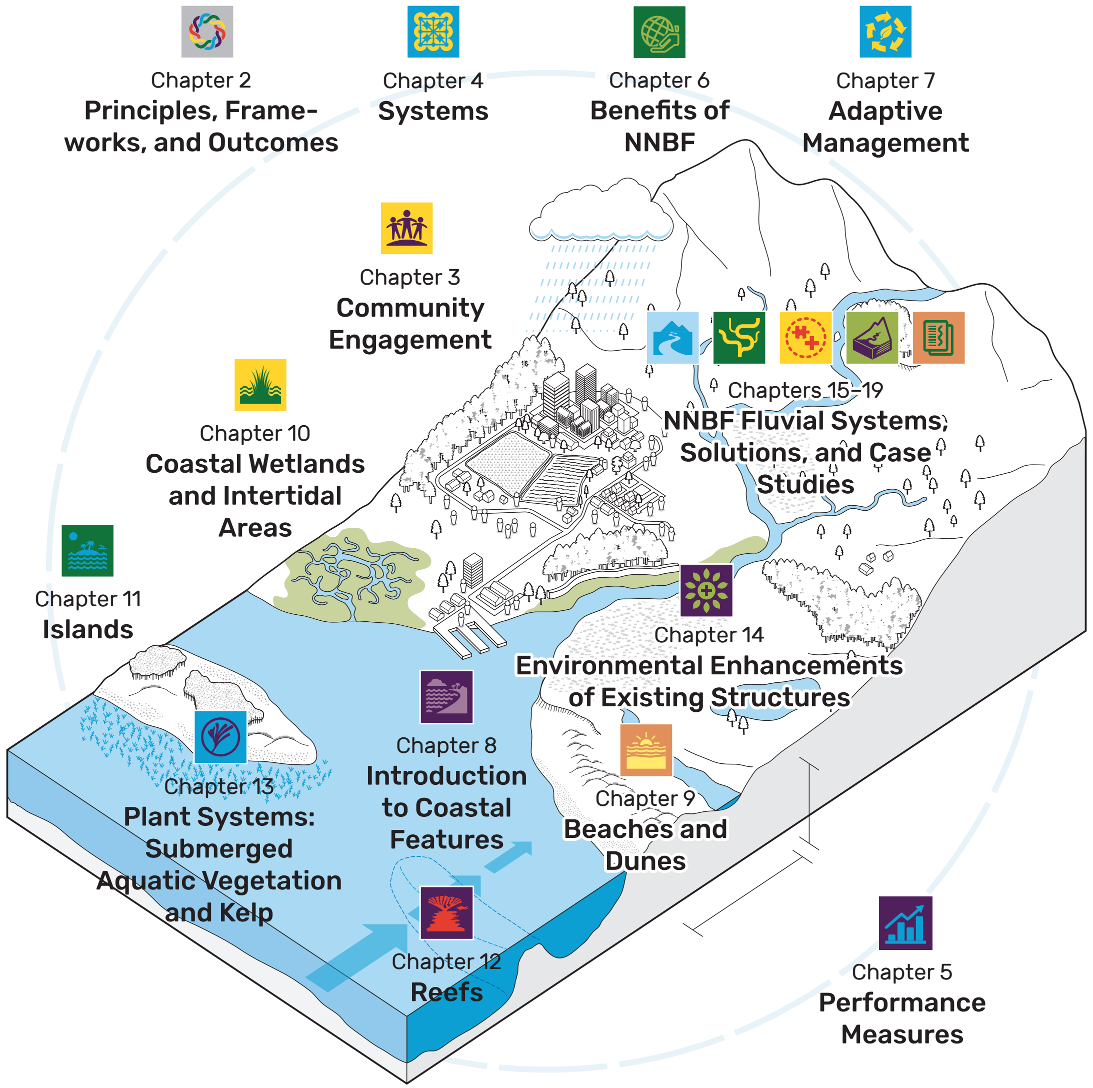
The Dutch Sand Motor, a Great Example of NNBF, The Hague, the Netherlands
Source: Rijkswaterstaat

Organization of the Guidelines

These guidelines are divided into three major sections. The first major section (Chapters 1 to 7) covers a set of common topics that are broadly applicable to NNBF. The second major section (Chapters 8 to 14) addresses coastal applications of NNBF, including open coast and estuarine environments. The third major section (Chapters 15 to 19) covers NNBF applications in fluvial or riverine environments. Throughout the document, examples and case studies illustrate the diverse contexts and progress being made in applying NNBF worldwide.

The guidelines are organized so that readers can begin where their interests lie. Given the conceptual connections and relationships among the topics covered in the chapters, the chapters were developed in a collaborative environment where there was communication and engagement across chapter teams. We wanted the chapters to be able to not only stand on their own but also be part of an integrated treatment of NNBF. Each chapter begins with a list of its key, high-level messages, includes references to other chapters, and uses icons and case studies to draw attention to key topics covered elsewhere in the NNBF Guidelines. The science and practice in this field are rapidly advancing, so we plan to update these guidelines in the future, when the timing seems appropriate to do so.

Contents and Concepts of NNBF Guidelines Linked to a Watershed Approach



Overarching Observations

In view of the breadth of material covered in these guidelines, it is useful to offer a few relevant observations and principles to inform our thinking about natural systems and FRM, our approach to implementing NNBF, and future needs.

- Natural features and landscapes have always contributed to flood resilience.
- The function and success of FRM measures and systems are related to scale.
- Sustainable FRM systems will include combinations of conventional, natural, and nature-based elements.
- The flexibility and adaptability of NNBF are useful for achieving flood resilience.
- NNBF can increase and diversify the value provided by infrastructure.
- Innovation in practice will be key to addressing future problems and opportunities.
- Policies need to be developed to guide and expand the use of NNBF.
- Coordination, collaboration, and partnership will fuel successful implementation of NNBF.

FengChuiSha in Kenting, Southern Taiwan
Source: Timo Volz

CHAPTER 2

Principles, Frameworks, and Outcomes

These guidelines assume that an initial evaluation of the "systems of interest" has revealed that NNBF should be considered as an element in the overall approach to flood risk reduction. A key step in the NNBF planning process is also the identification of uncertainties and data gaps, which naturally facilitates adaptive management of projects. These principles, framework steps, and desired outcomes are, therefore, offered to practitioners, along with recommendations for integrating NNBF into a broader, multidimensional approach for managing the system of interest.

Key NNBF Principles

The following five foundational principles are critical to the overall success of an NNBF project:

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

DEFINITIONS OF RISK AND UNCERTAINTY

For the purposes of this NNBF Guidelines, *risk* and *uncertainty* are defined as follows:

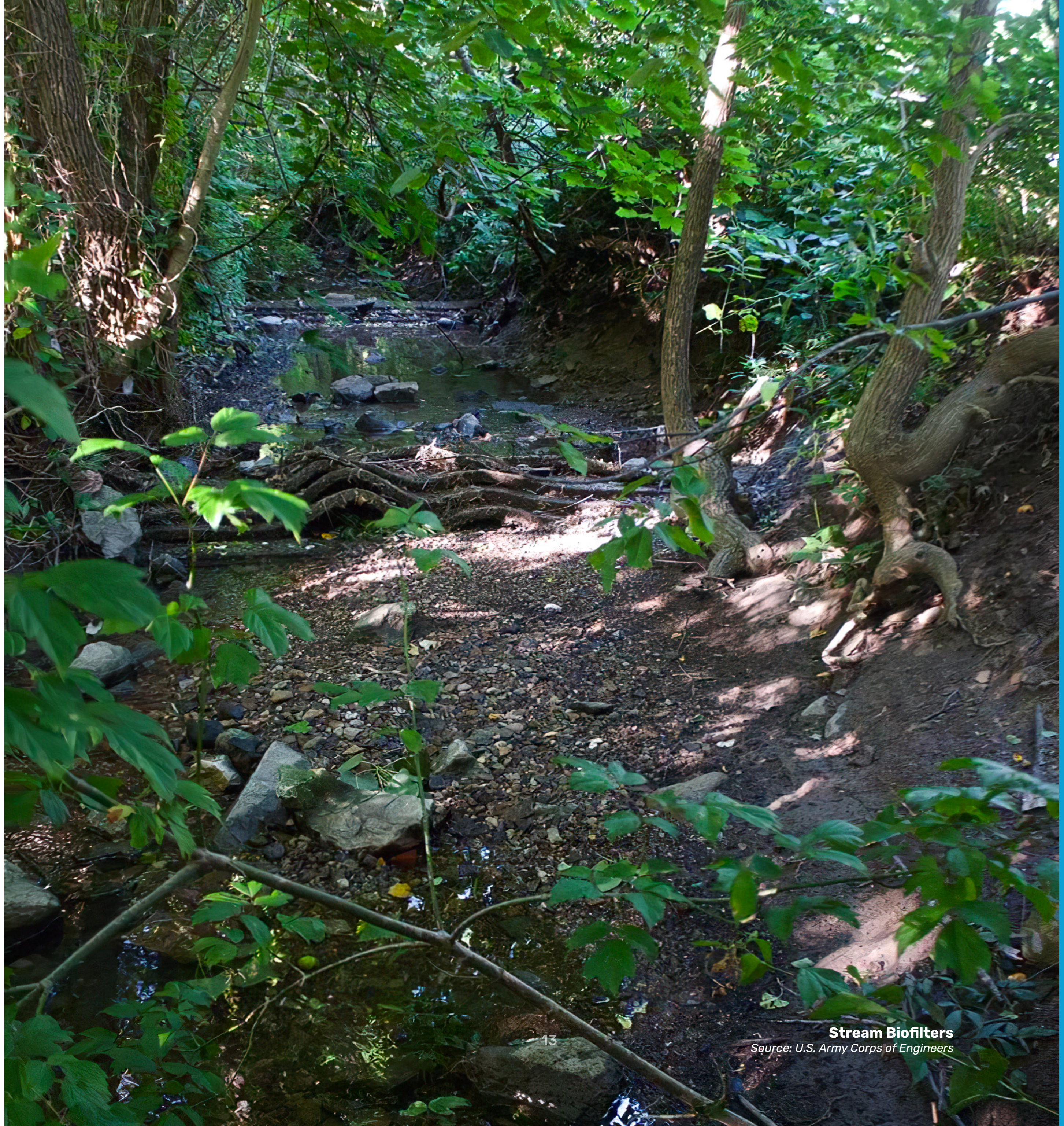
Risk is a function of the probability that an adverse event (e.g., flooding or coastal erosion) will occur and the consequence associated with that event. Thus, risk = *f* (probability and consequence), generally simplified to risk = probability x consequence.

Uncertainty arises as a result of imperfect or missing knowledge. In the context of FRM, two types of uncertainty in processes are commonly distinguished—natural variability (*aleatoric* uncertainty) and limitations in knowledge (*epistemic* uncertainty).

NNBF Framework

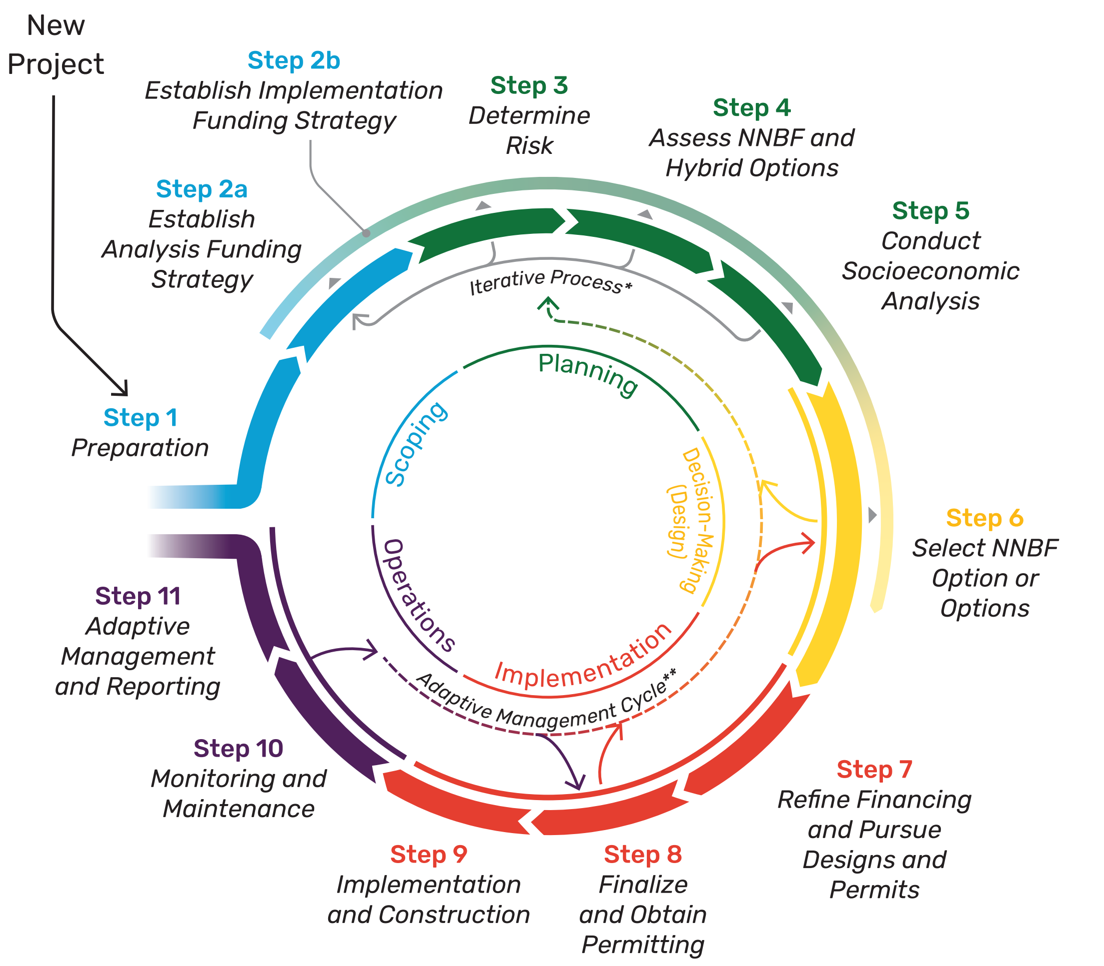
Having a framework is useful to successfully undertaking NNBF projects. The recommended framework is separated into five phases (each with subsidiary steps)—Scoping, Planning, Decision-Making, Implementation, and Operations. These phases highlight a general progression from the initial Scoping Phase to the Operations Phase of a project. However, the framework progression need not be strictly linear; in particular, (1) the iterative approach for refining NNBF options will likely require a return to previous steps in the process; and (2) in the early stages, financial considerations (costs and funding strategy) will need to be considered in parallel with scoping and planning activities.

Project proponents should anticipate high-level outcomes for each of the framework phases. Familiarity with these outcomes and knowing their connectivity to applicable framework phases will promote the sequential completion of necessary activities and minimize the risk of omitting aspects that are critical to success.



Stream Biofilters
Source: U.S. Army Corps of Engineers

Framework Phases and Their Corresponding Steps in Undertaking NNBF Projects



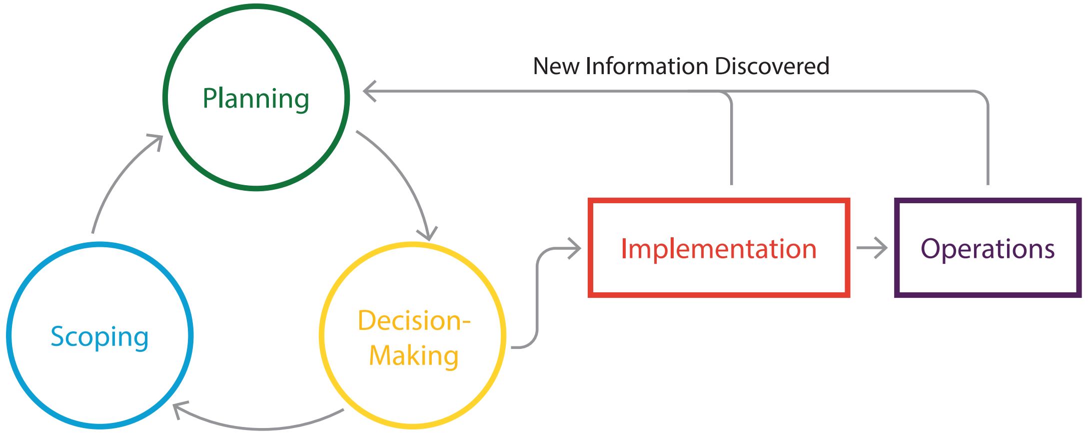
*Iterative process to identify practical and preferred NNBF options

**Adaptive management cycle that supports practical and preferred NNBF options

As illustrated in the graphic, the recommended framework has five phases and 11 steps. The framework is presented here as a roadmap for future NNBF applications. In the past, most experience with FRM project development has focused on structural measures; nonstructural measures; and, to a limited degree, NNBF, with the possible exception of beach and dune projects. This framework assumes that an analysis of the systems of interest has revealed that NNBF should be considered in the overall approach to storm and flood risk reduction and focuses on how NNBF fit within the project development process. However, the framework does not include an evaluation or an explicit comparison of conventional measures to NNBF infrastructure. This framework also does not contrast one approach against another (i.e., use of only structural measures versus exclusive use of NNBF). Ultimately these framework steps are offered as a guide to practitioners for pursuing a combination of measures that achieves the integration of NNBF into their broader, multidimensional approach for FRM.

This framework is divided into five phases that sequentially organize several concepts. The phases are Scoping, Planning, Decision-Making, Implementation, and Operations.

Phases of the Project Development Framework and How They Relate to One Another



As depicted, these phases highlight a general progression from the initial Scoping Phase to the Operations Phase of a project. However, there are times when information discovered or revealed during a later phase of project development can require additional considerations, which then results in a previously completed phase being revisited. The cycle depicted in the top-right portion of graphic of the phases (on page 15) highlights the additional time that is likely needed to consider different options and additional input that is accruing prior to the selection of the preferred NNBF option or options. From this phase, there is a logical progression to implementation and operation of the project. Of course, there are factors inherent to this flow diagram that would result in a need to revisit any one of the previous phases. For example, design processes are iterative by definition; however, they also require revision when new data are available, or when new information is obtained on the functionality and success of previously implemented measures (sometimes in other systems).

Outcomes

When considering the development of NNBF projects, it is important to identify an approach that will render the highest likelihood of success and avoid predictable problems and unexpected costs. This approach should include identifying desirable outcomes at each phase. Many successes over the past 10 years with incorporating NNBF projects into an overall strategy for FRM have been based on well-crafted, organized, and incremental approach plans. Within each of the framework phases presented herein, there are anticipated outcomes that will advance the project to the next level of completion.

Different Phases of the Framework and the High-Level Outcomes that Should Be Anticipated in Association with Each of the Phases

Scoping	***Outcome 1:*** Stakeholder engagement: communication processes established with all stakeholders and the public (early and often) ***Outcome 2:*** Problem identified and stakeholders committed to action
Planning	***Outcome 3:*** Funding streams explored and identified ***Outcome 4:*** Benefits for at-risk systems identified and impacts and benefits for natural systems accepted
Decision-Making	***Outcome 5:*** Preferred NNBF option or options selected
Implementation	***Outcome 6:*** Approvals and authorities in place ***Outcome 7:*** Overall solution portfolio delivered with NNBF elements optimized
Operations	***Outcome 8:*** Monitoring and adaptive management processes established

CHAPTER 3

Engaging Communities and Stakeholders in Implementing NNBF

NNBF engagement is any interaction between the organization or agency responsible for delivering the NNBF project and relevant stakeholders, including communities where NNBF projects may be built. This interaction can include a wide range of different types of engagement, from one-way communication of information to consultation and collaborative discussion. The tools and methods for engagement should reflect the type of engagement—either “light touch,” “moderate,” or “extensive” interaction. Engagement is an important and necessary part of all planning and decision-making for any infrastructure project. Engagement is included at each step of the NNBF framework because we assume an adaptive management approach to the project and, therefore, an iterative, flexible process using built-in feedback loops to inform all aspects of the project plan, including the engagement component.

Meydenbauer Stakeholder Meeting, Bellevue, Washington, United States
Source: City of Bellevue

Key Messages

1. Stakeholders expect early, broad, and professional engagement.

2. NNBF provide unique opportunities for engagement, including participation in defining the problem in scoping, developing, and evaluating alternatives in the project design, maintenance, monitoring, and evaluation.

3. Engagement is important because of the increased likelihood of multiple benefits and, therefore, multiple beneficiaries, with NNBF projects.

4. Successful community and stakeholder engagement require that the engagement be integrated in all phases of NNBF projects.

5. NNBF projects should include an engagement plan and the resources to carry it out.

A well-planned process for engagement enables all those who have an interest in, have influence over, or will be potentially impacted by a project to be involved from an early stage to be kept informed, understand and add unique perspectives, and influence positive outcomes. Engagement processes should focus on the overarching objectives of the communities[2] and agencies involved, which should generally require a neutral approach to any specific final solution. Good engagement minimizes the risk of project failure and project schedule delays and enhances opportunities for long-term, sustainable outcomes that benefit multiple parties.

It is important to acknowledge that genuine engagement is rarely easy. Many projects come with some form of resistance, particularly in early stages. Stakeholders are often better than project staff at framing and successfully involving the press, politics, and the broader community. The manner and timing in which projects are communicated matter greatly to the success of the project. Projects will be better positioned to overcome any challenges if engagement is open, is transparent, and includes a genuine desire for stakeholder involvement.

Volunteers Help with Plantings in Dunes, Padre Island, Texas, United States
Source: Reuben Trevino, U.S. Army Corps of Engineers

Summary of the Products (or Deliverables) for Each Step of the Engagement Process

	Engagement step	Products
1	Articulate the engagement principles and objectives.	Documented principles Documented objectives
2	Assess the context and stakeholders.	*Issue list* The contextual analysis should result in a list of potential physical, environmental, legal, historical, cultural, and social issues that may be encountered in project development and implementation. *Database of stakeholders* The identification and analysis process should ultimately lead to a database of stakeholders, identifying who they are, their level of influence and impact in relation to the NNBF project, and the intensity of engagement they are likely to require, potentially with an additional consideration of the level of interest they are likely to have in the project.
3	Assess the resources.	*Resource matrix* The matrix should include the identification of people, tools and knowledge, practical resources, time, and budget available for the engagement process.
4	Determine the engagement methods.	Selected tools and methods
5	Plan the engagement.	*Engagement plan* The plan should incorporate all products above; it may take the form of a spreadsheet, a text document, or a combination of the two, and should have a public-facing summary.
6	Deliver the engagement.	*Information materials* These can include letters, posters, presentations, flyers, and other materials to provide information. *Record of stakeholder input* The records should include both in raw form and summary form a plan for how and when stakeholder input will be taken on board and how stakeholders will be told about what change has occurred (or not) as a result.
7	Evaluate the engagement.	*Evaluation plan* The plan should include the original engagement objectives, a set of evaluation indicators, measurement tools, and an understanding of how, when, where, and from whom specific data will be collected. This can feed into the development of an evaluation plan or framework; the plan may take many forms—from a simple spreadsheet to an additional project plan.

It is the hope that NNBF project teams will adopt a new paradigm that includes a deeper commitment to engagement than may have been the norm previously. The following reminders should serve as a quick reference to support the NNBF project engagement process:

- Deliver earlier, broader, and professional engagement at all NNBF project phases.
- Take advantage of the unique opportunities for engagement afforded by NNBF.
- Define the principles for engagement and set objectives early.
- Analyze the context and the stakeholders.
- Choose the tools and methods for engagement based on the type of engagement required—light touch, moderate, or extensive.
- Plan the engagement and assign the appropriate resources.

Evaluate the effectiveness and impact of the engagement. Be flexible and adaptive in the engagement plan.

CHAPTER 4

Planning and Implementing NNBF Using a Systems Approach

Guidance on the mitigation and management of flood risk often recommends that a systems approach be used to define, characterize, and manage water resources (usace.army.mil 2002; APFM 2009; National Research Council 2013; WWF 2016; World Bank 2017; Burgess-Gamble et al. 2018[3]). A systems approach is essential for the successful implementation of flood risk reduction measures, including NNBF, because it incorporates an early appreciation of the context and further enhances the breadth of perspective on the natural system by including the interplay of ecology, geomorphology, and hydrodynamics, as well as the interface with the social system (i.e., the engagement of local stakeholders). In addition, it results in tailor-made multifunctional and sustainable solutions.

Key Messages

1. Systems thinking means considering physical, biological, and social processes, and their interactions, in evaluating flood risk problems and solutions, and identifying ways to reduce conflict and maximize synergies to produce sustainable solutions.

2. Bringing people and different interests together is a way to explore holistic, system-wide issues, which can lead to innovative partnerships and potential leveraging of resources, accelerating identification and implementation of suitable, sustainable, and well-functioning solutions.

3. NNBF solutions for flood risk reduction develop over time and space. A multidisciplinary team that creates an understanding of biophysical, socioeconomic, and governance system dynamics is essential for sustainable, long-term management and to verify performance criteria are met.

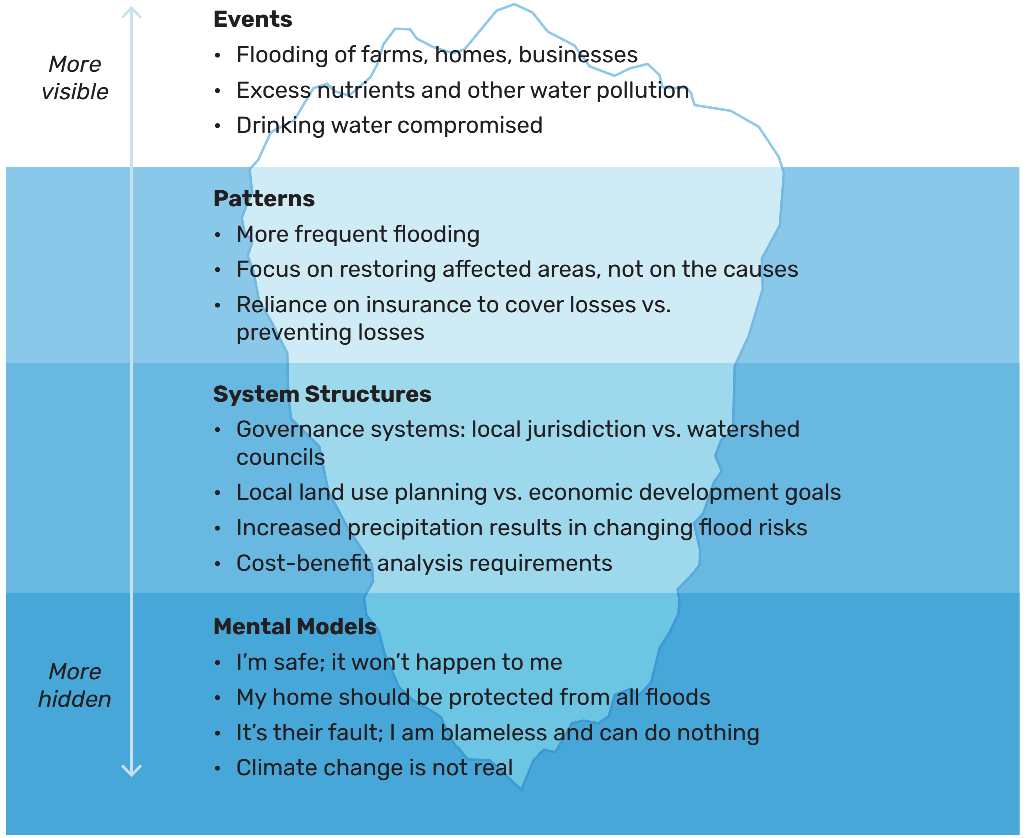
4. NNBF solutions can provide a variety of ecosystem benefits. Systems thinking enables the assessment of multiple potential outcomes, supports multifunctional design, and facilitates direct engagement with stakeholders and consideration of social benefits.

5. Systems thinking can be used to implement NNBF solutions on a large-system scale (think big), to integrate the effects of many small projects (start small), and either as standalone projects or as part of larger FRM efforts.

Source: Arnel Hasanovic

One of the fundamental features of a systems approach is that it emphasizes a broad view that looks beyond immediate events or local problems by identifying patterns and relationships within a system. This deeper and broader understanding provides the basis for more effective, multifunctional solutions with added value for both society and nature. To date, different aspects of a systems approach have been used in NNBF and conventional FRM projects around the world. However, there are few examples, whether NNBF or conventional, that have considered all aspects of the systems approach, including the dynamic physical, ecological, and relevant cultural aspects and processes within a system, and feedback among them. Because the use of NNBF in FRM is relatively new, there are few mature examples of its application using a systems approach. This is particularly the case for the role of systems thinking in the long-term development and adaptive management of NNBF under changing (climate) conditions, which is relatively uncharted territory. Further expanding the evidence base will help the mainstreaming of systems thinking and NNBF, resulting in more optimized, sustainable solutions focused on long-term benefits.

Revealing Potentially Hidden Consequences in Decisions Is a Widely Recognized Advantage of a Systems Approach, as Characterized by the Iceberg Model



Case Study: Acting on Different Scales (Dutch Coast, the Netherlands)

As a low-lying country, the Netherlands has a long history in its struggle against rising water. In the last centuries, the fight against rising water was mainly fought on a local level with local solutions. Over the last decades, the thinking has shifted to a more integrated, system-wide approach, including multiple governmental bodies, research institutes, and local stakeholders. In 1990, the foundation for this vision was established by the decision to maintain a stable coastline at the level of 1990 (the Basiskustlijn ["reference coastline"]) by means of sand nourishments. This political (and legal) decision enabled collaborative development of a dynamic coastal management approach based on sandy solutions, where natural processes play a key role. This vision also acknowledges that nourishments in the nearshore have an impact on the landward part of the coastal system (e.g., protected dune ecosystems), thereby connecting coastal defense to the management of several national and European Union nature reserves. After the formation of this vision, the entire Dutch coastline has been aligned according to these standards, with NNBF projects such as the Sand Motor and Hondsbossche Dunes.

The application of a long-term vision for the entire Dutch coast can be seen as the overarching example of systems thinking. On a smaller spatial scale, a system-based approach is used to develop custom-made solutions that include other ecosystem services. NNBF solutions are preferred where possible and structural solutions are chosen when necessary (e.g., near coastal cities or in different natural systems). For example, the Dutch coast can be separated into the following three distinct subsystems: the Zeeuwse Delta/Scheldt-Meuse Estuary in the southwest, the closed Holland coast to the west, and the Wadden Sea barrier island system in the north (see figure). Each system requires different approaches and has different cost-benefit analyses and solutions.

Overview of Dynamic Coastal Management Projects along the Dutch Coast

Note: Interventions are indicated in red and green.

Nature-based solutions have existed around the world for decades, though their performance and benefits may not have been closely tracked. Setting the context is an important step in systems thinking and is especially important as a way to find common ground between different stakeholders. However, the best approach to find common ground is always location-specific and requires local experience. Acting on multiple spatial and temporal scales can further complicate the contextualization of a flood risk problem. Consideration of relevant processes and feedback mechanisms operating on different scales introduces additional knowledge gaps and uncertainties. These should be considered in the planning and design of NNBF but may also require further investigation and monitoring once an NNBF project has been built. Filling these knowledge gaps and sharing the lessons learned will be beneficial for future NNBF projects.

The assessment of the suitability of NNBF through a systems approach is characterized by the inclusion of multidisciplinary knowledge of physical and ecological processes. The potential to include the wide-ranging benefits of NNBF can lead to more expansive consideration of how the project influences the system than might occur in traditional FRM. Such a comprehensive view requires consideration of these co-benefits in the evaluation of alternatives (and the willingness to pay for them), and additional effort will be required to develop best practices that enable the co-benefits of NNBF to be considered by decision-makers.

As more information is developed on the long-term evolution and performance of NNBF projects, future management to ensure continued effectiveness will benefit from the systems approach. Future development and land-use modifications, as well as changes in flood risk, will alter the systems' context for any project, and as gaps in knowledge are filled, new ones will arise. Using a systems approach from the start will enable stakeholders, planners, and managers to work together on common goals and be better prepared for what the long term brings.

CHAPTER 5

NNBF Performance

Performance is the ability of a system to meet one or more desired and declared objectives. Performance is measured using a set of predetermined metrics designed to ascertain whether the NNBF is producing the desired benefits. Metrics are specific parameters or properties of the NNBF, typically quantifiable, that are associated with some desired aspect of performance.

Key Messages

1. NNBF FRM performance and aspects of social and economic performance are examined using a source-pathway-receptor-consequence conceptual model commonly used for FRM.

2. Performance metrics include direct and indirect measurements, modeled parameters, or outputs and should be assessed based on predetermined performance criteria.

3. Sources of uncertainty in NNBF performance are largely similar to those of structural measures, although natural variability of NNBF may be greater than that of structural measures.

4. Because monitoring budgets are usually limited, monitoring metrics should be chosen carefully to capture the most critical aspects of the project (typically those related to the objectives), and metrics that can inform multiple types of performance should be used when possible.

5. Performance of NNBF over a project life cycle requires periodic assessment at a frequency commensurate with the natural dynamism of the NNBF and the location.

6. For NNBF and structural measures in a world with increasing disturbance events, there is a real need to get better values on long-term rates of failure (fragility) and the associated maintenance costs.

7. FRM and the ecological, social, and economic performance of NNBF are interrelated, and proper ecological function of NNBF is critical to ensuring proper FRM, social, and economic functions.

Multiple interrelated categories of performance relate to NNBF and include the following:

FRM performance, in the context of NNBF, is the reduction in physical forces that produce flooding or damages or that otherwise contribute to FRM for the full range of possible events over a project's life. Erosion reduction is included as a component of FRM performance because future FRM performance can be compromised by persistent erosion. The two aspects of FRM performance are the *system performance*, which is the effect of the system of measures including NNBF on the hazard, and the *structural performance*, which is the effect of the hazard on the NNBF and other measures.

Ecological performance is the production of the desired ecological functions by the NNBF. Ecological performance includes the production of desired ecosystem goods and services such as water quality.

Social performance refers to the desired social co-benefits produced by the NNBF, including human health, well-being, and equity, as well as recreational, cultural, and educational co-benefits.

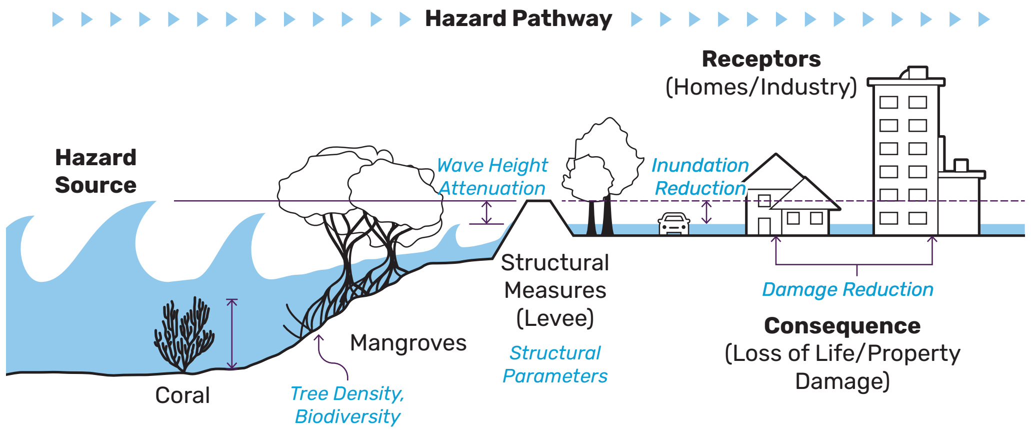
Economic performance pertains to the reduction in economic damages, as well as the economic value related to other FRM, ecological, and social co-benefits produced by the feature.

Performance should be considered over an entire project life cycle and should consider the full array of possible environmental conditions that drive performance for present and future conditions alone and in combination with each other (e.g., future sea-level rise coupled with a full range of storm events). Performance should be estimated for both robust and deteriorated or otherwise suboptimal NNBF conditions (e.g., if two flood events occur consecutively). Like structural measures, NNBF performance may deteriorate over time, requiring routine maintenance to sustain performance over the course of an entire project lifetime. However, unlike structural measures, many NNBF are able to adapt to future conditions and performance may even improve over time (e.g., wetlands migration in response to sea-level change).

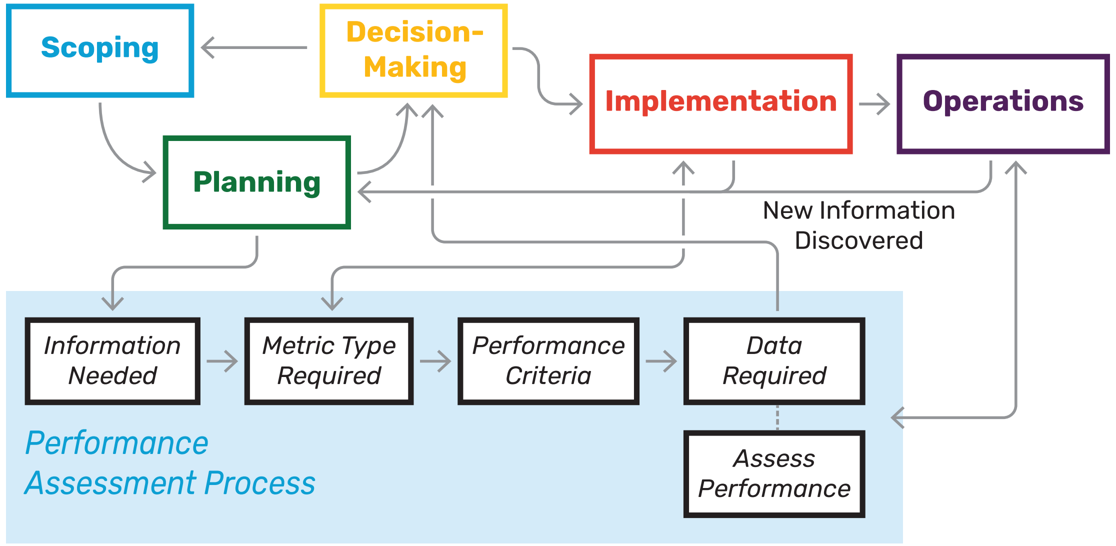
Performance concepts and analyses are applicable to existing NNBF, not just NNBF solutions that require active construction or modifications. Conservation and maintenance of existing NNBF are both valuable to FRM goals. If existing NNBF are providing FRM functions—especially if new NNBF, structural measures, or nonstructural measures rely on those functions to perform—the performance of those existing FRM functions should be quantified. For example, if a levee is fronted by a wetland, the levee toe is protected by the wetland, and the benefit of that wetland should be quantified in the analysis of the levee's performance and reliability. If these benefits are not quantified, the only provisions for their continued conservation and maintenance are related to avoiding adverse environmental impacts, which may not be adequate to ensure their long-term sustainability.

Optimizing NNBF performance and determining best NNBF practices for specific locations or stressor scenarios require clear conceptualization of project actions and outcomes. Performance measurements are, therefore, a constantly evolving process, and form a key component of an effective adaptive management strategy.

Source-Pathway-Receptor-Consequence Model for NNBF with Connections to Performance Categories and Metrics



Performance Assessment Requirements during the Course of an NNBF Project



As we move into the future, the following steps would be ideal to advance the field of performance measurement for NNBF projects:

- Methods and tools are needed that can better capture the dynamic nature of NNBF performance.
- Additional work is needed on how to consider risk across project life cycles, especially in cases where future conditions may be changing.
- Methods are required to enable consideration and quantification of the multiple facets of NNBF performance with respect to benefit and co-benefit production.

CHAPTER 6

Benefits and Costs of NNBF

Flooding and erosion affect vulnerable communities around the globe. Each year from 2016 to 2018, an average of 3,400 lives were lost and more than $30 billion U.S. dollars (USD) in damages resulted from floods (EM-DAT 2019[4]). Without the presence of NNBF, annual losses are expected to increase dramatically; for example, the global annual avoided damages due to the presence of mangroves and coral reefs have been estimated at USD$65 billion and USD$4 billion, respectively (Beck et al. 2018; Menéndez et al. 2020[5]). The primary goals of protecting and restoring NNBF are to reduce the risk of flooding and erosion, adapt to climate change, and build coastal resilience. In addition to reducing disaster risk and building resilience, NNBF can provide co-benefits that support the development of the blue economy and address specific societal challenges such as water security, food security, and human health (World Bank 2017; IPCC 2019; GCA 2019; IUCN 2020[6]). These co-benefits help to support the positioning of NNBF in relation to alternative structural measures. Recovery from the Coronavirus Disease 2019 (COVID-19) pandemic provides a strong additional rationale for investing in NNBF because investing in nature has proven to be an effective way to create jobs, while enhancing our natural environment, with estimates in the United States of up to 17 jobs per USD$1 million invested in the United States (Edwards, Sutton-Grier, and Coyle 2013[7]).

Unlike those of gray infrastructure (e.g., seawalls, breakwaters, groins, and jetties), the risk reduction benefits of NNBF historically have not been estimated in metrics that relate to human well-being—such as the amount of property damage prevented, or the number of people protected—so NNBF are often not considered on the same terms in decision-making processes. Comparing NNBF with structural alternatives requires an understanding of their relative costs and benefits, including both disaster risk reduction and co-benefits.

Flooding and erosion risk reduction by NNBF can be achieved via different processes depending on the type of NNBF, including trapping sediments, dampening waves, and storing water. Advances in modeling have increased the capacity to value the risk reduction benefits of NNBF. For example, recent analyses estimate that coral reefs in the United States provide more than USD$1.8 billion per year in flood risk reduction benefits (Storlazzi et al. 2019; Reguero et al. 2021[8]). In addition, salt marsh and mangrove wetlands reduce annual flood risks to properties by 15% to 25% in regions across the United States (Narayan et al. 2017; Narayan, Bitterwolf, and Beck 2019[9]). Recently, global benefit-cost ratios for protecting mangroves were estimated at more than five to one (GCA 2019[10]).

Root of Life Mangrove Conservation in Lampung Shore, Lampung, Indonesia
Source: Aldino Hartan Putra

Key Messages

1. NNBF provide risk reduction benefits as well as additional co-benefits that are all highly valued by society.

2. Benefits should be considered in each phase of the project cycle.

3. Benefits often take time to accrue until the NNBF becomes fully functional.

4. Multiple valuation approaches and metrics can be used to qualitatively and quantitatively assess benefits and social vulnerability outcomes.

5. Different metrics and related decision-support tools (e.g., cost-benefit analysis, multicriteria analysis) may be suitable for different stakeholders and audiences.

6. Measuring and quantifying benefits and costs are important when comparing NNBF and structural measure alternatives for consideration in management strategies and designs, as well as for the identification of project funding and financing.

7. Monitoring and evaluating benefits, as well as ecological and physical changes, are important for ensuring NNBF meet the multiple needs of coastal communities and for communicating the benefits of NNBF to stakeholders.

8. In data-poor environments, benefit assessment can adopt participatory and qualitative approaches, as well as utilize secondary and Earth observation data for quantitative assessment and monitoring.

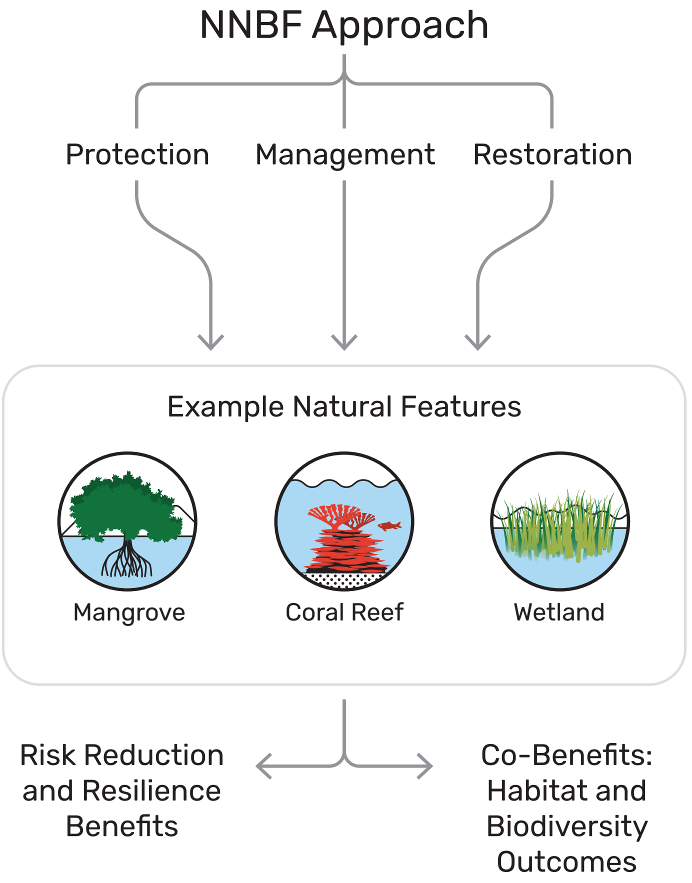
Guidance is needed to help practitioners better incorporate co-benefits of NNBF into the assessment of design alternatives for risk reduction and into other decision-making contexts such as habitat restoration and coastal management. These co-benefits include habitat for fisheries, opportunities for tourism and recreation, carbon storage and sequestration, and human health benefits (Barbier et al. 2011[11]). Assessing co-benefits is also important for anticipating trade-offs and potential impacts to target resources, and for establishing a vernacular through which multiple agencies and stakeholders can define shared objectives and support the development of performance standards that capture economic, social, and ecological outcomes of implementing NNBF (NSTC 2015[12]).

In these guidelines, benefits are divided into the following two categories:

Risk reduction and resilience benefits. These are the risk reduction properties of NNBF, specifically flood protection and erosion control. Flood protection is achieved through (storm) water absorption through infiltration, flood storage, or wave and surge attenuation. NNBF can help to build and stabilize shorelines and riverbanks, thus reducing erosion. NNBF are often a more resilient solution because they are able to adapt to changing conditions such as sea-level rise or land subsidence.

Co-benefits. These are defined as any other relevant benefit derived from NNBF. For example, the co-benefits of NNBF include habitat for fisheries, nature-based tourism and recreational opportunities, carbon storage and sequestration, and human health benefits. Co-benefits are highly specific to each type of NNBF.

Model for NNBF with Connections to Performance Categories and Metrics



Common approaches to NNBF and their interconnectivity to the performance categories and metrics are illustrated in the figure in the previous page, with protection or preservation of the natural system being the primary focus. All interventions and structural measures, both hybrid and NNBF, involve analyzing costs and trade-offs throughout the project life cycle. For NNBF to be considered as alternatives to, or in combination with, structural measures such as seawalls, bulkheads, and levees, it is necessary to also analyze their costs and potential trade-offs. The following are the main costs in the total life cycle of a typical NNBF project:

- Planning costs
- Design and permitting costs
- Costs of the land required for the project, including opportunity costs
- Costs of creation, protection, or restoration
- Costs of maintenance and monitoring

Recent years have brought growing interest, research, and case studies related to NNBF for flood risk reduction and co-benefits, bridging the gap between environmental economics, hydrology and hydrodynamic modeling, and sustainability science. Quantifying the social and economic benefits of NNBF continues to be an active area for research and an opportunity to test new strategies for implementation and monitoring.

Indicator-Based Approach to Assessing Societal Benefits

There are four core steps to an indicator-based approach to assessing societal risk reduction and co-benefits provided by NNBF, as follows:

Step 1. Choose a set of societal indicators. Examples of indicators are key infrastructure (e.g., roads, schools, and hospitals) that stakeholders would want to benefit from risk reduction, as well as ecosystems and demographic groups that may be particularly vulnerable to coastal or fluvial hazards. The following are some important questions to ask:

- Does the indicator reflect the changes in NNBF ecological condition in units that are relevant to the benefit and beneficiaries of interest?
- Does the indicator capture relevant physical and institutional access constraints on the flow of the benefit from the NNBF?

Step 2. Develop a causal chain linking the influence of an action or scenario with its impact on the NNBF, the function of the NNBF, and the change in societal benefit.

Step 3. Apply a coastal or fluvial hazard index that includes or could be modified to include the role of NNBF, along with other key variables that influence risk from flooding and erosion, including shoreline geomorphology, wave power and direction, sea-level rise, storm surge, and elevation. Use the hazard index to identify areas most at risk from coastal or fluvial flooding and erosion. Then estimate the influence of NNBF on exposure from coastal or fluvial hazards by calculating exposure to those hazards with and without the protective role of NNBF included in the hazard index.

Step 4. Combine results from the coastal or fluvial hazard analysis with maps of social indicators (e.g., critical infrastructure and vulnerable populations) to estimate the number of people and amount of critical infrastructure at risk from coastal or fluvial hazards with, compared to without, the risk reduction benefits from NNBF.

Opportunities and priorities for future work include the following:

- Need to account for the fragility of NNBF to the fluvial or coastal hazard in a quantitative way (i.e., development of fragility curves).
- Learning from a growing body of practice of NNBF projects, a better alignment between financing models for NNBF and benefit assessment methodologies is a priority. NNBF can be financed or co-financed through bonds, insurance, public-private partnerships engaging the tourism sector, carbon offsets, and global funding streams for climate mitigation and adaptation.
- Bringing these approaches to scale will go hand-in-hand with the development of improved benefit assessment methodologies to unlock funding and financing.
- There is a growing global momentum for bringing the application of ecologic-economic models and natural capital accounting to scale (Dasgupta 2021; Johnson et al. 2021[13]). New methodologies need be to be developed to accurately reflect the risk reduction and co-benefits of NNBF in coastal, fluvial, and island natural capital accounts.

CHAPTER 7

Adaptive Management

Adaptive management is an iterative decision-making method that can be used to reduce levels of uncertainty and risk in predicting and achieving desired results by using NNBF or structural solutions. This iteration can aid project optimization by enabling designers to avoid, in the initial stages, "overbuilding" to account for uncertainty because the adaptive steps (measure and monitor, refine and adapt) facilitate future adjustments or enhancements, as necessary.

Coastal and fluvial systems are flexible and dynamic systems. The use of NNBF couples the physical and ecological systems with the social system, thereby capturing the complexity of interactions between the systems. Future uncertainties, as well as existing data and knowledge gaps, can limit the ability to predict the functions and response to management actions of both systems. Specifically, interactions among and between the various aspects of the hydrodynamic, morphologic, ecological, economic, and social landscape currently and in the future of a dynamic and ever-changing environment (e.g., sea-level rise) become more variable. This increased uncertainty in outcomes reduces levels of certainty in making science and FRM predictions for both NNBF projects and more traditional (structural) flood risk reduction projects.

Key Messages

1. Adaptive management is an essential process for addressing and reducing uncertainties in structural and NNBF projects in a phased implementation. NNBF involve complex, dynamic environmental and social processes with varying uncertainties. Adaptive management addresses these uncertainties to optimize risk management while taking advantage of the flexibility of NNBF.

2. **Improved Outcomes.** By reducing uncertainties over time, adaptive management can modify NNBF to improve their performance and facilitate attainment of the desired benefits.

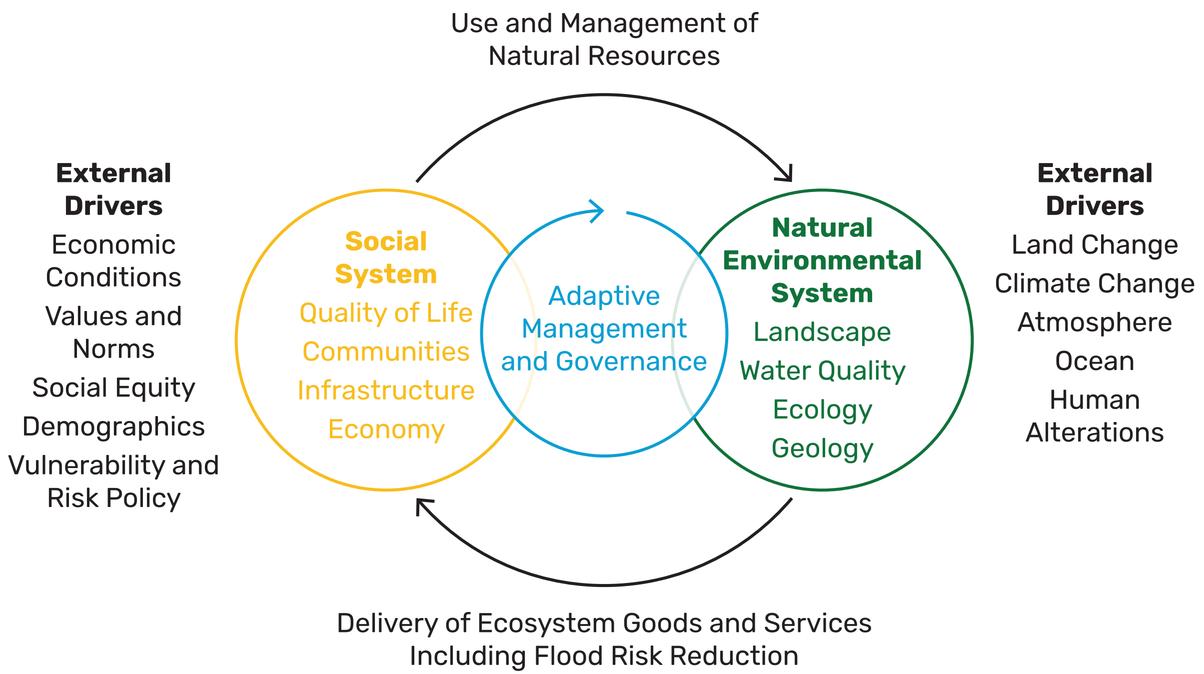
3. **Flexibility.** While acknowledging factors that cannot be controlled, adaptive management focuses on those project aspects that can be controlled or adapted to increase flexibility in project design over time to achieve desired project performance.

4. **Reflect and Adapt.** Adaptive management provides a structured and informed decision-making process that is critical to manage unexpected and unintended outcomes and that enables managers and stakeholders to take timely corrective or adaptive actions. Adaptive management should be used throughout the planning, design, construction, and post-construction project phases.

5. **Continuous Improvement.** Adaptive management has the ability to make adjustments to the project throughout its life cycle to meet or improve expected outcomes and benefits at either the project or system level and to inform future projects for the benefit of the social and environmental systems.

6. **Communication and Commitment.** Leadership and stakeholder groups play a critical role throughout the entire adaptive management process through commitment to long-term monitoring and assessment and a transparent and responsive process.

NNBF Adaptive Management Process Model



Benefits of Investing in Adaptive Management

Reducing Life-Cycle Project Costs

- Reduces up-front costs by allowing management of unknowns over time
- Saves cost by not overdesigning up front, while providing the ability to adapt the design over time, as needed, sustaining project life span and benefits
- Optimizes operations and maintenance costs over time

Reducing Risk and Improving Outcomes

- Improves outcomes and robustness by using adaptive actions over time
- Allows phasing of projects, instead of needing to minimize uncertainties up front
- Provides flexibility to change direction or adapt overall strategy
- Allows acceptance of risk to innovate with confidence where uncertainty and risk are addressed over time
- Facilitates environmental permitting, acknowledging uncertainties regarding impacts
- Enhances ability to meet multiple objectives and benefits over time
- Improves design life via asset resilience

Adapting to Improve Knowledge

- Improves future work through lessons learned from ongoing projects
- Enhances knowledge about performance of features through monitoring and evaluation
- Quickly builds knowledge of system functionality and performance by accepting risks early during planning and design phases
- Leads to more innovative design by evaluating new technologies in the field

A number of items can pose challenges when implementing adaptive management, which has led to some successes and some failures. Some of the overarching challenges are obtaining consistency in adaptive management definitions and frameworks; leadership and stakeholder acceptance; shifting baselines (which make it hard to assess project performance); risk management (including regulatory constraints and desire for front-loaded analysis); and funding challenges, especially formulating a process for long-term funding, once the project has been completed. These will continue to be the focus of future research studies.

Case Study: Glen Canyon Dam (Arizona, United States)

Source: usbr.gov 2021[14]

The significant levels of uncertainty surrounding the resources of the Colorado River ecosystem and the effects of dam operations on those resources led to the creation and implementation of the Glen Canyon Dam Adaptive Management Program. From its inception, the Glen Canyon Dam Adaptive Management Program has developed and implemented research and monitoring to analyze impacts and build a knowledge base of dam operations on the Colorado River and its downstream resources. This emphasis on active adaptive management via scientific experimentation has enabled the program to measure and monitor resource responses in the Colorado River ecosystem. With time and maturity, these experiments have grown from a single focus on dam releases to also looking at flow and nonflow action. A variety of stakeholders have interests in the ecosystem, including federal and state agencies, Native American tribes, the Colorado River Basin states, electrical utilities, and recreational and environmental groups. Stakeholder representatives participate in the official federal advisory committee—the Glen Canyon Adaptive Management Work Group—and develop operations recommendations for the Secretary of the U.S. Department of the Interior on how to best protect the resources and meet legal requirements. A subgroup comprising technical representatives—the Glen Canyon Technical Working Group—develops research questions, criteria, and standards for monitoring and research. Independent review panels comprising individuals not participating in long-term monitoring assess the quality of science conducted by the Glen Canyon Dam Adaptive Management Program and make recommendations for improvement.

CHAPTER 8

Introduction to NNBF in Coastal Systems

Coastal NNBF encompass a variety of approaches, including the creation or re-creation of natural habitats (e.g., salt marshes, mangrove forests, reefs, beaches, and dunes), the enhancement of existing habitats (e.g., foreshore recharge of beaches), the use of more-organic materials for structures (e.g., wood rather than stone), and the ecological enhancement of existing hard infrastructure (e.g., the creation of rock pools within seawalls or the use of textured concrete to improve colonization by marine organisms). Coastal NNBF elements can also be combined with hard structures in a multilayered approach to FRM (e.g., foreshore recharge or marsh restoration combined with levees).

Coastal NNBF deliver FRM benefits in various ways, including the following:

- Attenuate the energy and height of incoming waves
- Attenuate storm surge water levels along the shoreline
- Provide storage of floodwater in the upper tidal reaches of estuaries
- Reduce erosion of sediments and soils
- Attract and stabilize sediments
- Attract and sustain flora and fauna, which can stabilize structures such as dikes

Camps Bay, Cape Town, South Africa
Source: Delano Ramdas

Key Messages

1. There is a need to support and manage the coastal landscape that provides the foundation for flood risk management (FRM). This landscape physically provides a risk mitigation function in its own right, supports the maintenance of structural measures, or limits the impact of waves or storm surge on those measures. Management of the associated sediment and ecology should reflect the relevant ecological or sediment system, commonly divided for the purposes of management and analysis into a nested or hierarchical set of units.

2. The immediate focus of FRM tends to be either side of the coastline, normally defined in relation to mean high water level, with a concern to limit the risk to the people and property in the hinterland from flooding and coastal erosion. This often involves maintenance of an FRM system that could either be a single-line system (e.g., a wall or a levee) or a multizoned, cross-shore system with both structural and NNBF elements.

3. The coastal environment is subject to continual change, which may be cyclical or continuous, including, in particular, the following:
    - Wave and water level forcing are known to be nonstationary (e.g., relative sea-level rise and fall, changes in storminess).
    - Profile and condition of the defense line may deteriorate or improve.
    - Number of people and amount of development of property behind the defense line are frequently growing.

The following coastal NNBF are discussed in subsequent chapters, with a focus on the specific feature, conceptual system understanding, performance metrics, design and construction considerations, and long-term monitoring aspects:

- Beaches and dunes
- Coastal wetlands
- Islands
- Reefs
- Submerged aquatic vegetation (SAV)

In seeking to apply any of these measures for flood and coastal risk reduction, it should be recognized that there is a spectrum in the maturity of knowledge and understanding about their application. An example of a mature and well-accepted measure is beaches and dunes, which have provided protection to coasts (whether managed or not) for many years in ways that are relatively well understood. An example of a less-mature measure in terms of the understanding of its coastal risk reduction is SAV.

Use of Anchored Rootwads as NNBF Beach Stabilization and Habitat Enhancement Features at Seahurst Park, Washington, United States
Source: Anchor QEA

CHAPTER 9

Beaches and Dunes

Coastal beaches and dunes are valuable to FRM because they can dissipate wave energy, can trap sediments, and have the potential to grow with rising sea levels—they are vital NNBF.

For beach and dune systems, the design should align with the original beach and dune as much as possible. Care should be taken to mimic or re-create the natural conditions of the shoreline as far as possible to let nature do most of the work and reduce maintenance requirements. For example, place sediments where winds, waves, and tides can assist in transport for beach and dune building. Whenever feasible, the design of beaches should allow a degree of profile dynamism by focusing on beach slope, volume, and width as primary design parameters, rather than attempting to create a static system.

Naturally Vegetated Dunes at Cape May Beach, New Jersey, United States
Source: Anchor QEA

Key Messages

1. Beaches and dunes are inherently dynamic systems that reduce land loss and inundation risk of the hinterland while providing high amenity and environmental benefits.

2. The development of sustainable and cost-effective beach and dune measures requires a cross-disciplinary approach. Essential disciplines include engineering, coastal geomorphology, ecology, and governance.

3. Understanding the past, present, and possible future physical system dynamics—more specifically, sediment budgets, associated hydrodynamics, sediment dynamics, and interactions with ecological systems—is critical for determining the scale and feasibility of a given project.

4. It is essential to consider past and future scenarios, notably the effects of socioeconomic developments and climate change impacts, such as sea-level rise and possible changes to frequency and intensity of storms, when designing beaches and dunes.

5. The design of beach and dune NNBF should include management requirements, strategies, and associated monitoring needs.

6. Plan to let nature do most of the work when managing or implementing a beach and dune system as NNBF for coastal resilience.

Beaches are one of the most dynamic coastal geomorphic landforms. They constitute a natural transition zone between land and sea, are an amenity and an economic resource, and provide habitat for diverse species. Beaches are situated on the interface between dry land and the sea and are actively affected by hydrodynamic processes and wind (CIRIA 2010[15]). Their spatial limits are not fixed and will change at a range of different timescales. One possible set of spatial extents, according to Davis (1985[16]), is the uppermost limit of wave action and the low tide mark, comprising the backshore and foreshore of the coastal profile. The foreshore usually has a steep slope and is the most active part of the beach. The development and width of beaches are largely controlled by the slope of the inner shelf and coastal area, abundance and composition of sediments, tidal range, and wave energy (Wright and Short 1984[17]). The zone immediately landward of the beach (the hinterland) should be considered along with the beach when designing NNBF. When present or planned for, dunes are an integral part of a sandy coastal system. Dunes are accumulations of windblown sand starting on the backshore, usually in the form of small hills or ridges, stabilized by vegetation or control structures (CIRIA 2010[18]). They occur where sand from the beach dries out at low tide and is transported inland by wind and deposited in the hinterland, where specialized vegetation may subsequently colonize the sandy deposits. Dunes form a necessary temporary store of sediment that can be reclaimed by the sea during extreme events, helping to buffer against the erosion of the beach naturally. The size and shape of dunes are a function of climate, geology and geomorphology, wind and wave regime, and tidal range (Davidson-Arnott 2010[19]). Ecologically sustainable beach and dune systems require healthy habitat conditions (including a feeding beach and foreshore) and supporting processes to be in place. Once these conditions exist, colonization by appropriate flora and fauna is likely. Additional dune-specific considerations include promotion of natural vegetation and features, whenever possible.

Example of the Annual Assessment of Sedimentation and Erosion Trends along the Dutch Beaches and Dunes Coast

Rijkswaterstaat (the agency responsible for the design, construction, management, and maintenance of the main infrastructure facilities in the Netherlands) carries out regular assessments of the Dutch beaches and dunes coast to support the dynamic maintenance of the Dutch coast. Every year, the sedimentation and erosion trends for each coastal transect are determined. Large-scale and long-term sedimentation and erosion trends are assessed every few years for the coastal system and its subsystems.

Most parts of the Dutch sandy coastline are surveyed annually with single-beam echosounders and lidar equipment. The surveys result in an annual dataset with harmonized transect profile data from approximately 10 meters below to 10 meters above mean sea level (MSL). The Dutch coastal monitoring database JARKUS (JAaRlijkse KUStmetingen, Dutch for "annual coastal measurements") contains yearly surveys since 1965.

Each year, the current volume trend between approximately 5 m below and 3 meters above MSL is calculated and assessed to a reference coastline. The result of this assessment forms the basis for the Dutch national beach and shoreface nourishment scheme. An online map and book (Rijkswaterstaat Coastline Map Database; Rijkswaterstaat Kustlijnkaarten 1992–2020[20]) provide the results of this assessment.

Sedimentation and Erosion Trends near The Hague, the Netherlands

Abbreviations: BKL: Basis KustLijn, which is the reference line for coastal management in reference to the RSP; RSP: RijksStrandPalen lijn, which is a Dutch reference for monitoring

Beaches and dunes are coastal landscapes that can gradually adapt to, for example, sea-level rise when supplied with enough sediments and given space to adjust. In locations where this accommodation of space is limited and NNBF are maintained within a narrow spatial envelope, the approach is effectively prolonging the time before other strategies are implemented including coastal retreat, hybrid or hard defenses, and relocation of vulnerable receptors is necessary.

Methods such as the Dynamic Adaptive Policy Pathways approach, communities of practices such as Climate Risk Informed Decision Analysis, and adaptive management of beach and dune projects support decision-making and adaptation over time as the uncertain future unfolds. In locations where cost-benefit analysis indicates that maintaining the beach and dune feature in situ is no longer a viable option, it will be necessary to explore options to relocate vulnerable people, properties, and infrastructure inland. Integration with existing spatial and land-use planning tools will be essential in this endeavor.

Area West of 61st Street (Babes Beach) before and after the 2015 Galveston, Texas (United States) Beneficial Use Project

Source: Coraggio Maglio, U.S. Army Corps of Engineers

The top photograph was taken before the project, and the bottom photograph was taken after the project was completed.

Example NNBF Application in a Sandy Beach and Dune System, Texas, United States
Source: Texas Department of Parks and Wildlife

CHAPTER 10

Coastal Wetlands and Tidal Flats

Coastal wetlands and intertidal areas are valuable because they can dampen wave, surge, and current energy, trap sediments, and, in the correct settings, be self-sustaining under rising sea levels and other pressures. These features also provide co-benefits—benefits other than those related to FRM, such as fish production, filtration of pollutants from upland runoff, water quality mediation, recreation, and carbon sequestration.

Sunken Meadow State Park, New York, United States
Source: New York State Parks

Key Messages

1. Coastal wetlands and tidal flats can reduce flood and erosion risks in coastal environments. They do this by raising bed levels and offering greater frictional resistance to the movement of water, which can reduce both waves and surge.

2. Coastal wetland and tidal flat NNBF projects can include the conservation of existing wetlands, restoration of degrading or degraded wetlands, or construction of new wetlands. In urban environments where there is limited space, wetland NNBF may involve creating more limited extents of features (e.g., using terracing) to reduce erosion and partially attenuate waves. Wetland NNBF approaches may also be combined with other structural (e.g., nearshore breakwaters, levees) or NNBF measures (e.g., reefs, upland vegetation communities).

3. Wetland NNBF performance is largely controlled by location, coastline geometry, and storm characteristics.

4. The ability of salt and brackish marshes and mangroves to reduce wave heights is particularly well documented through modeling, laboratory, and field studies. Significant wave reduction can occur within relatively narrow feature widths. Wave reduction depends on several factors such as topography, vegetation characteristics, and characteristics of the storm events (e.g., water level, wave height, wave period).

5. The reduction of surge water levels requires greater wetland size and extent. These reductions occur at both local (across the width of the features) and wider (e.g., along the length of an estuary) scales.

6. Coastal wetlands can also be used as flood storage areas to reduce water levels in estuarine environments, but their efficacy depends on the location and design.

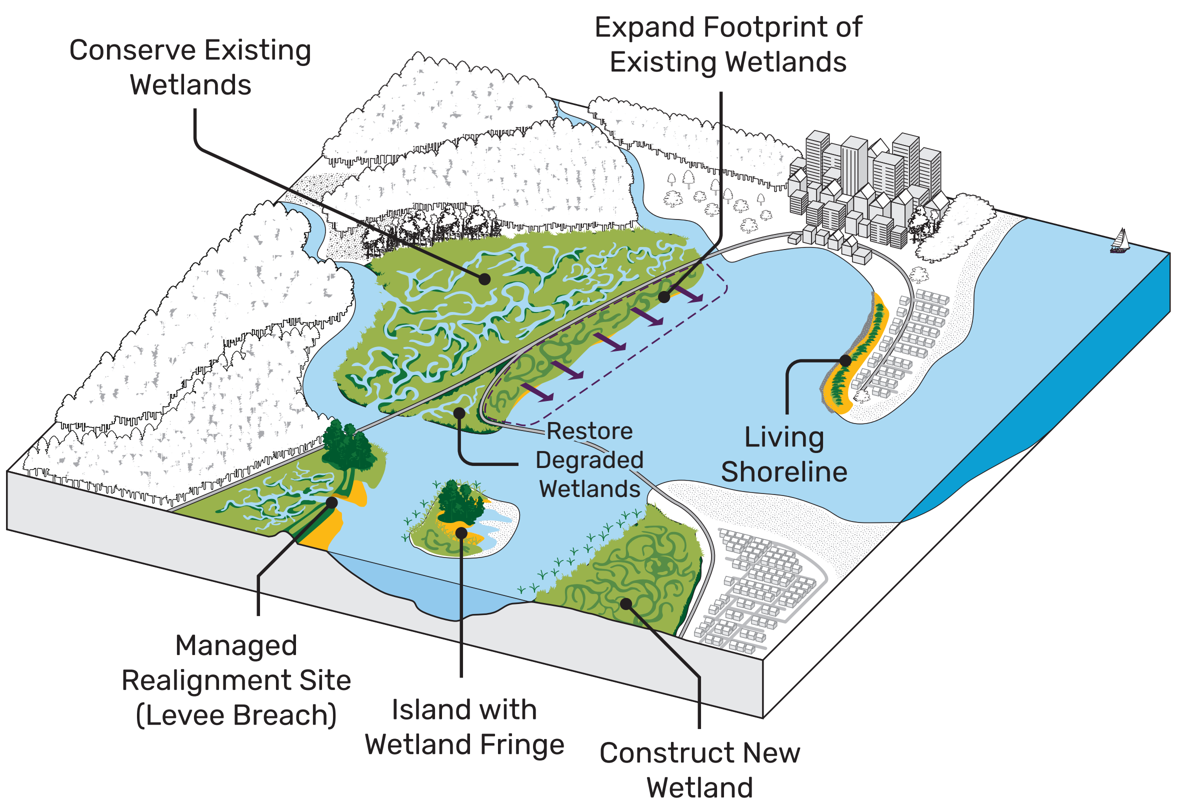
7. Coastal wetland and tidal flat NNBF projects can draw upon the extensive experience in the restoration of marshes and mangroves, which has led to the creation of thousands of hectares of features worldwide over the last few decades. Wetland NNBF are a subset of wetland restoration, which aims to achieve primary goals in flood and erosion risk management.

8. In the correct setting, coastal wetland and tidal flat NNBF have the potential to be self-maintaining over time. For example, with sufficient sediment supply, mangroves and marsh features may accrete vertically with sea-level rise. Wetland NNBF also require other suitable environmental parameters to be met (e.g., salinity, tidal inundation).

9. Wetland NNBF projects should consider where they are expected to persist now and into the future, in addition to where they were located in the past. As coastal conditions change, historical wetland locations may be or become unsuitable for wetlands.

10. The performance of wetland and tidal flat NNBF projects may vary over time as vegetation establishes and develops. Designs should consider likely storm damage, recovery, and maintenance requirements.

Wetland NNBF Projects of All Types Can Be Implemented at the Scale of an Estuary



Although FRM functions of coastal wetlands are often cited as a benefit of wetland restoration, relatively few studies systematically quantify costs, benefits, and co-benefits of existing and restored coastal wetlands. A regional assessment of the value of wetlands across the eastern and Gulf coasts of the United States provides USD$3,200 (2004) per hectare in avoided damages annually (Costanza et al. 2008[21]). A more recent study of marsh and mangrove wetlands found a 1% loss in coastal wetland coverage resulted in a 0.6% increase in property damages, including increased damages from wind (Sun and Carson 2020[22]). Over a 30-year period, the expected value of storm protection from coastal wetlands is on average (the mean value) USD$36 million per square kilometer, with a median value of USD$2 million per square kilometer. The difference in the mean and median values indicates wetlands in some locations may provide a large marginal value, emphasizing the role of location on coastal wetland function with respect to FRM.

Other studies used insurance industry models to quantify the value of coastal wetlands for FRM. Narayan et al. (2017[23]) showed that the presence of coastal marshes in Ocean City, New Jersey, United States, on average reduced flood damages by 16% annually. Regionally, the effects of wetlands for a single storm, Hurricane Sandy, were mixed, with wetlands reducing damages on average by 11% in zip codes that were flooded, although wetlands increased damages in some areas and provided little benefit in urban areas with very little remaining wetland area. Generally, states with the greatest wetland cover (i.e., Virginia, Maryland, Delaware, and New Jersey) within the model domain observed the greatest reduction (approximately 20% to 30%) in damages from Hurricane Sandy. Using similar modeling approaches, mangroves were found to reduce flood damages by 25.5% annually in Collier County, Florida, United States (Narayan et al. 2019[24]). During Hurricane Irma in 2017, mangroves reduced damages an average of USD$7,500 per hectare. Where existing wetlands are insufficient in area or quality to provide the desired FRM function, wetland restoration or creation projects are required.

Although the number of studies of wetland NNBF benefits and implementation examples is growing, some questions still remain. These issues are not insurmountable and should not preclude consideration of wetlands as part of a comprehensive FRM approach. However, additional studies on the following would further advance the practice:

- More field and modeling studies should address the long-term stability and, thus, the cost-effectiveness of restoration projects compared to other nonstructural and structural measures.
- Future studies should use a consistent cost-benefit framework that accounts for the full array of benefits, co-benefits, and life-cycle costs so studies can be compared and replicated.
- The knowledge base of wetland NNBF performance should be further developed so potential efficacy of wetland NNBF projects under different conditions can be better understood.
- Methods and tools are needed to quantify the system-scale benefits and co-benefits of wetland NNBF and the linkages between wetland NNBF and other measures.

Poplar Island Restoration, Maryland, United States
Source: Maryland Environmental Service

CHAPTER 11

Islands

Islands in estuaries, major river deltas, and open-coast environments reduce the severity of hazards, including erosion and flooding from wind-driven waves and extreme water levels, on the nearby habitats and shorelines. Islands also provide critical ecosystem function for threatened and endangered species and migratory birds while providing access to recreational opportunities and navigation co-benefits. In general, there are three types of islands—barrier islands, deltaic islands (including spits), and in-bay or in-lake islands. These islands may be new construction or, as in most cases, the restoration of island remnants. The degradation and loss of islands through combined processes such as sea-level rise, subsidence, and inadequate sediment input (e.g., upstream impoundments, navigation channels, evolving natural processes) are reducing the coastal resilience benefits of these features.

Restoration of the Historical Cat Island Chain, Wisconsin, United States
Source: U.S. Army Corps of Engineers

Key Messages

1. Islands are proven to deliver coastal resilience benefits, especially as part of a multiple-lines-of-defense strategy. Islands can be effective in areas where other, land-based NNBF are not feasible (e.g., urban areas).

2. Islands can simultaneously provide multiple services, including storm surge reduction, wave dissipation, erosion control, dredged material management, safe navigation and safe harbor, ecosystem diversity, recreation, and commercial opportunities.

3. Island features may have a regional influence and, therefore, must be placed in the regional context. For example, islands that provide coastal resilience benefits will significantly influence circulation, sediment transport, water quality, waves, and habitat within their domain of influence.

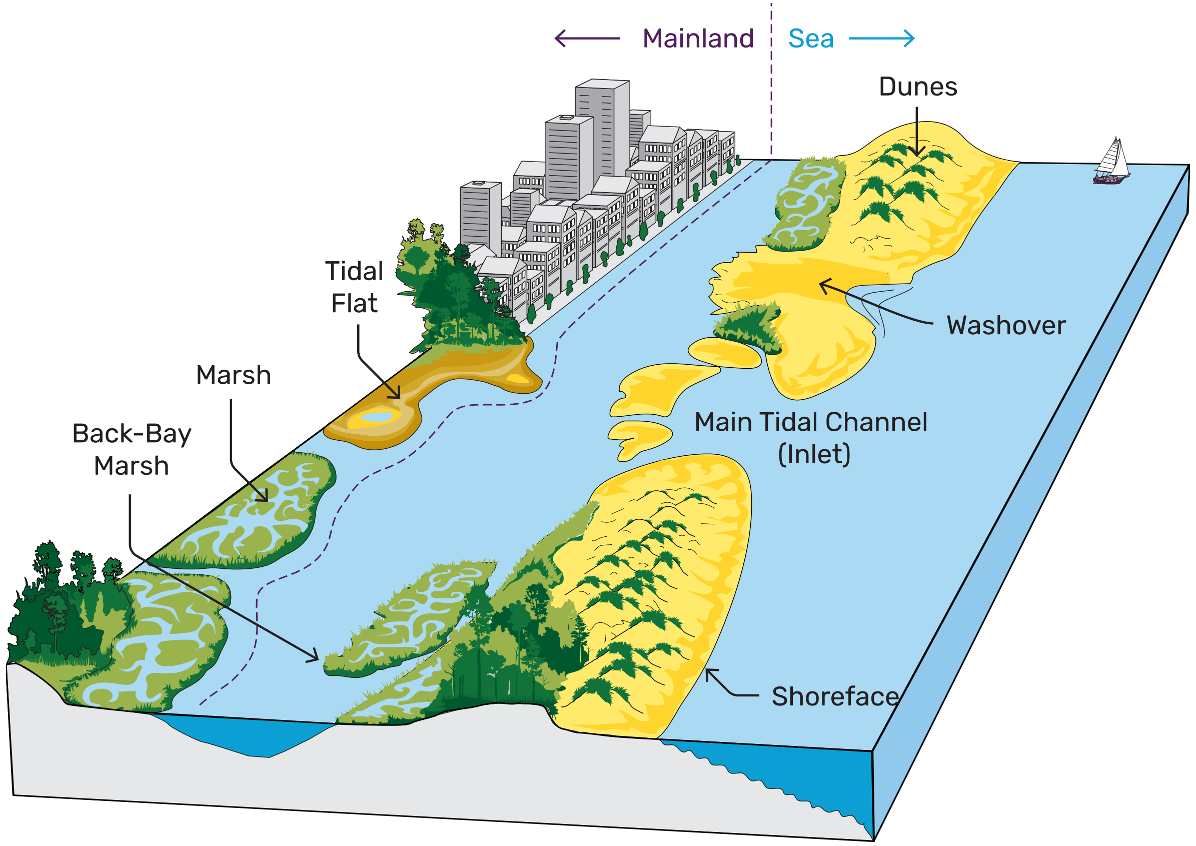
4. Islands may be multihabitat features; therefore, guidance from previous feature chapters may apply here. For example, large islands often include beach and dune, wetland, and upland plant community components.

5. Habitat trade-offs are inevitable—island construction almost always involves changing habitat types from subtidal to intertidal and supratidal. Short-term impacts must be considered within the context of long-term ecosystem co-benefits, especially within the context of sea-level rise.

6. The complexity of physical processes at island NNBF settings, coupled with limited case studies for some conditions, results in significant uncertainty and risk during the construction process. Experienced contractors, capable of adaptively managing construction, are required to reduce risk and meet project goals within cost, regulations, and schedule.

7. Islands are typically dynamic features, and, therefore, their success in achieving predefined objectives and observed metrics may fluctuate or change over time.

Barrier Island Setting and Key Features



The Marker Wadden in the Netherlands, a Good Example of the Construction of a Partly Muddy Island
Source: Natuurmonumenten (Dutch Nature Conservancy)

Islands serve multiple functions, including storm surge reduction, wave dissipation, erosion control, dredged material management, safe navigation and safe haven, ecosystem diversity, wildlife habitat, recreation, and commercial opportunities. Islands often comprise multiple habitat types (e.g., reef, beach, dune, upland plant community, wetland, and SAV bed) and have a hydrodynamic footprint that influences the formation and protection of adjacent coastal habitats. Islands are a critical element in the multiple-lines-of-defense strategy, in which multiple features, in a sequence, from offshore to onshore, provide greater coastal resilience benefits than a single feature. For example, overwash and windblown sand can nourish dunes and marshes on the back side of islands, and the protective environment in back bays can facilitate the formation of beds of SAV, salt marsh, and other habitat that requires protection from large waves. In turn, SAV beds, salt marsh, and dune vegetation interact with, and can exert a strong influence on, the hydrodynamics and morphology of barrier islands and back-bay systems through biostabilization of sediment and wave attenuation. Back-bay marsh subsequently reduces loss of beach and dune sediment during overtopping or high wind events. However, most studies focus on the benefits of single habitat types like wetlands, coral reefs, or mangroves.

Islands may be an efficient and cost-effective FRM measure, where other shore-based solutions are not feasible or are ineffective (e.g., high-energy areas or urbanized shorelines), especially in areas near navigation channels, where clean dredged sediments are available for construction and maintenance. Many islands are at risk due to sea-level rise, subsidence, and inadequate sediment supply such as in the Chesapeake Bay, eastern Canada, and along the Gulf Coast of the United States. If evolving conditions are captured in design and maintenance—considering processes such as sediment budget (source and net transport), expected sea-level rise, and island nourishment requirements—resilient island features can be created.

The following are some of the recommendations for future work to advance the utility of islands as NNBF:

- Research on the potential combined, complementary effect of multiple habitat types from offshore to onshore in terms of both short-term and long-term protective benefits is required to justify larger NNBF projects such as islands.
- Quantitative studies on island areas of influence are required to address habitat switching issues and potential impacts of island restoration.
- Innovative practices and field experimentation should be encouraged.

CHAPTER 12

Reefs

Coral and shellfish reefs can reduce flooding and erosion in coastal areas, but not all reefs provide significant coastal protection benefits. For many reef-lined coasts around the world, reefs act as the first line of defense against flooding, storm damage, and erosion. However, the various ways in which reefs provide coastal protection are not always fully recognized and accounted for, in part due to the historical focus on understanding and predicting flooding and erosion impacts for certain open-coast sandy shorelines lacking reefs. Yet, understanding the coastal protection services of reefs and assessing how they can reduce risk are critical because reefs will need to be effectively incorporated into climate adaptation programs, hazard mitigation strategies, and coastal development and management decisions. Reefs also provide several co-benefits, including fisheries production, habitat and biodiversity, recreation and tourism revenue, and improved water quality.

Underwater Reef off
the Coast of Florida, United States
Source: U.S. Geological Survey

Key Messages

1. Reefs provide many ecosystem services, such as fisheries, recreation, and tourism. One of the most important services is protection from coastal flooding and erosion.
2. By protecting coastlines from wave energy, natural coral and shellfish reefs can provide similar levels of coastal protection to artificial submerged coastal engineering structures.
3. Healthy reef ecosystems provide greater benefits to coastlines than simply reducing wave energy because reef organisms also produce calcium carbonate material that can eventually be a source of sand nourishment.
4. In contrast to engineered coastal structures, natural and engineered reefs can be self-sustaining ecosystems, meaning that healthy reefs can, in some cases, continue to grow and maintain a structure that can protect shorelines without assistance from humans and keep pace with sea-level rise.
5. The geometry and placement of a reef governs its capacity for flood and erosion reduction by determining how it modifies nearshore wave and current fields, and shoreline responses.
6. The design and construction of a reef NNBF should aim to mimic the natural geomorphology of a pre-existing or existing reef platform to favor biological growth, and materials used should be similar to those present in the surrounding environment.
7. Quantifying and maintaining the role of reefs in reducing coastal flooding and erosion should be factored into long-term coastal development and management strategies.
8. Maintaining the structural and biological benefits of reefs can be challenging in the context of global environmental change; thus, adaptive management is needed to support reef resilience and responsive decision-making.

The Value of Hawai'ian Reefs for Flood Risk Reduction

THE MILLION DOLLAR REEFS OF O'AHU | Each kilometer of these highlighted reefs provides over one million dollars in flood protection benefits each year.

Source: Adapted from Reguero et al. 2021[25] by Jessica Kendall-Bar and Chris Lowrie, University of California, Santa Cruz.

Note: The highlighted reefs around O'ahu all provide greater than USD$1 million in expected flood reduction benefits per kilometer per year. The values in the figure are the sum of the annual expected benefits for reef sections that are several kilometers long.

Shellfish Reef Pilot Project Using Pacific Oysters as Shoreline Protection (Eastern Scheldt, the Netherlands)
Source: T. Ysebaert, Wageningen Marine Research

Natural and artificial reefs provide coastal protection and risk reduction services by dissipating wind waves originating from the open ocean as the waves propagate over shallow and rough reef structures. Healthy coral reefs, for example, often dissipate most incident wave energy before the waves reach the shore. This wave-energy buffering reduces risk to coastal communities by wave-driven coastal flooding and associated losses. Recent research shows that the cost of annual damages from flooding would likely double without coral reefs (Storlazzi et al. 2018, 2019; Beck et al. 2018; Reguero et al. 2019[26]).

The effectiveness of reefs to attenuate wave energy and protect coastlines depends on their size, orientation, elevation, and location relative to shore, as well as tidal range, among other characteristics. One of the most important characteristics that governs coastal protection is the elevation of the reef crest (i.e., the shallowest part of a reef) relative to sea level. The capacity of a reef to dissipate wave energy decreases as the elevation of the reef crest becomes deeper. For instance, for subtidal shellfish reefs found in deep water, their coastal protection services are often less, because most of the wave energy is transmitted to the shoreline. Tidal variations and other sources of sea-level variability can also greatly diminish the effectiveness of reefs to dissipate wave energy when water levels are high. For natural coral and shellfish reefs, reef degradation can also reduce the elevation and roughness of a reef structure over time and thus also reduces their ability to protect shorelines.

Hybrid Reef Structure Using Rock-Filled, Metal-Rebar Baskets Mounted onto the Degraded Fringing Coral Reef Crest at Grenville Bay, Grenada

This photograph shows the surface of a single metal-rebar basket with a variety of naturally recruited coral colonies, crustose coralline algae, and associated organisms 3 years after installation.

Source: B. Hancock, The Nature Conservancy

Conventional approaches to mitigate coastal erosion rely on constructing engineering structures, yet natural coral and shellfish reefs can often provide comparable protection. Furthermore, the effect of reefs on sediment transport can also have similar effects to other natural and engineered structures that promote the stability of shorelines. For example, healthy coral reefs can maintain shorelines in a stable equilibrium, similar to natural headlands and engineered breakwaters in many pocket beaches around the world (Hsu et al. 2010[27]), whereas the degradation of reefs can alter wave and current patterns, leading to areas of chronic coastal erosion and enhanced flooding. In contrast to engineered coastal structures, natural and artificial reefs can be self-sustaining ecosystems, meaning that healthy reefs can, in many cases, continue to grow and maintain a structure that can protect shorelines without human intervention (Reguero et al. 2018[28]). For example, research indicates that the vertical growth rates of unharvested oyster reefs are faster than predicted rates of sea-level rise (Rodriguez et al. 2014[29]), meaning that they could maintain their coastal protection benefits in the face of climate change and adapt to sea-level rise in contrast to conventional engineering structures (Grabowski et al. 2012[30]). However, reef degradation may reduce their ability to keep up with sea-level rise (Perry et al. 2018[31]); for example, for coral reefs to maintain their coastal protection benefits, they must continue to accrete calcium carbonate structures by maintaining the health of calcifying reef organisms that build reefs.

In addition to directly reducing wave energy, both coral reefs and shellfish reefs often play less recognized critical roles in protecting and facilitating the establishment of other coastal habitats. For example, wave attenuation by coral reefs often allows tropical seagrass beds to form in protected lagoons, mangrove forests to form along coastlines, and beach and dune systems to be established. Because seagrass meadows and mangroves also attenuate wave energy and trap sediments (Duarte et al. 2013[32]), reefs may also act synergistically with other forms of NNBF to further mitigate risks of coastal flooding and erosion (Guannel et al. 2016[33]). Similarly, by buffering waves and improving water quality, shellfish reefs can provide suitable conditions for salt marshes and temperate seagrass beds. These associated benefits of reefs greatly increase overall protection services of other ecosystems in their lee (Alongi 2008; Christianen et al. 2013[34]). Thus, multiple layers of natural protection may be the most effective strategy when habitats are healthy, interconnected, and working together to maximize benefits to coastal communities (Guannel et al. 2016[35]).

As discussed in this chapter, reefs can be a very effective form of NNBF for coastal flood risk reduction while also delivering added benefits of ecosystem services provided by natural reefs. Following are some of the key areas of research needs specific to reef NNBF:

- To scale up the implementation of NNBF, further work is still needed to help optimize the performance of a reef NNBF to achieve both ecological and coastal protection benefits.
- A greater number of long-term NNBF projects with long-term monitoring programs (decades and longer) will be essential to better understand changes to the sources and composition of coastal sediments and the influence on the long-term trajectories of local coastlines.
- Technological advances are also needed to support increased survival and fitness of shellfish reared in hatcheries (e.g., use of probiotics) and selective breeding programs for disease resistance.
- Economic studies that account for the full suite of ecosystem benefits that natural reefs provide are needed to incentivize the protection and restoration of coral and shellfish reefs.

Oyster Restoration, Alabama, United States
Source: Erika Nortemann, The Nature Conservancy

CHAPTER 13

Plant Systems: Submerged Aquatic Vegetation and Kelp

Plant systems represent an important NNBF component that can provide aboveground and belowground benefits. Upland plants can modify soil stability by trapping and binding particles (Feagin et al. 2015[36]), aboveground and belowground plant structure can alter wave energy during storms, and upland plants can alter wind energy and provide land surface stability, as well as protection for built coastal infrastructure.

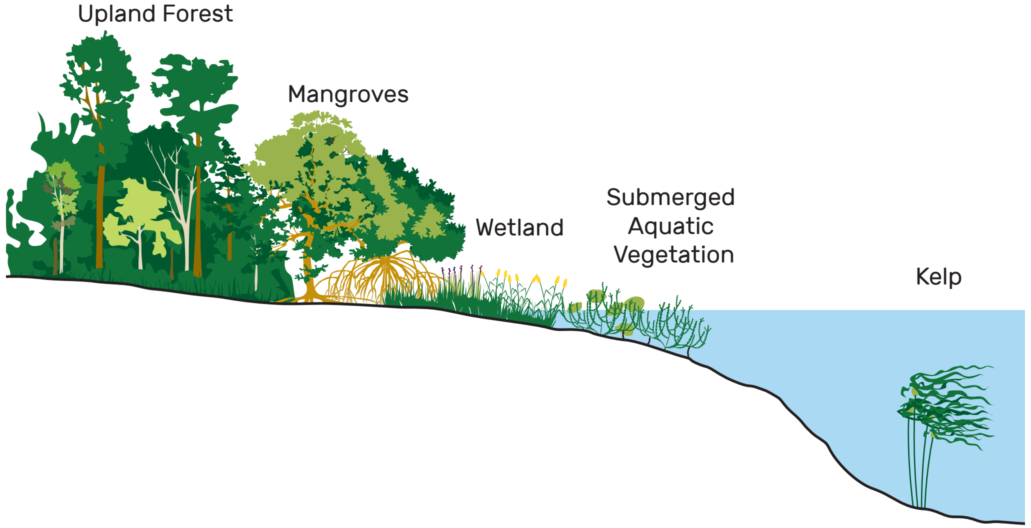
Eel Grass of the Coast of Massachusetts, United States
Source: National Oceanic and Atmospheric Administration

Key Messages

1. Plant systems can provide coastal protection through sediment stabilization and wave attenuation. SAV near shorelines can absorb waves and slow water movement, which can provide valuable shoreline protection. Kelp beds can also attenuate wave energy.
2. The magnitude of wave attenuation is dependent on the height and rigidity of the canopy relative to the total water-column height. For SAV, the protective value is maximized when canopy height and water-column height are equal.
3. SAV can also provide ecological benefits, such as nursery habitat for commercially important fish and shellfish, and water quality improvements, such as excess nutrient removal.
4. Due to its size and ephemeral qualities, it is important to use SAV or kelp at appropriate scales to be effective. SAV or kelp can complement other NNBF techniques (such as beaches, islands, dunes, or wetlands) and should be considered for use in larger NNBF projects that incorporate multiple features. Small-scale projects in low-energy environments are well suited for SAV and would maximize its effectiveness in coastal protection.
5. Restoring or introducing a plant system NNBF in conditions that are not suitable for the habitat of interest will likely result in failure. It is critical to match the plant system to the site.
6. SAV habitats are spatially dynamic and as a result, robust monitoring is required to understand their condition and health trajectory.

Over the past 50 years, the protective role of coastal dune vegetation during storm events has been largely acknowledged but has not been measured extensively in the field (Bruun 1962; Edelman 1972; McHarg 1969; Silva et al. 2016[37]). Through their natural ability to protect shorelines against erosion and flood risks and to grow up with long-term sea-level rise, vegetated systems—such as beach and dune grasses, tidal salt marshes, mangroves, and seagrass beds—play an important role in sustainable coastal flood reduction strategies and can increase the resilience of the coast (Temmerman et al. 2013; Silva et al. 2016[38]). Empirical data suggest some vegetated habitats have the capacity to reduce wave energy substantially, with estimates of up to 40% in seagrasses, 72% in mangroves, and 82% in salt marshes (Wayne 1975; Horstman et al. 2014; Möller et al. 2014[39]). Because plant systems themselves are subject to natural habitat succession, it is critical to understand that functional, plant-based NNBF may not persist as a particular habitat type in perpetuity. Habitat succession, switching, and change are all to be expected.

Coastal Plant Systems That Can Serve as NNBF



Note: Mangroves and wetland vegetation are discussed in Chapter 10. Dune vegetation is discussed in Chapter 9. Chapter 13 discusses SAV and kelp.

Incorporating SAV or kelp in an NNBF project is a useful option for project planners due to their ability to reduce wave energy. Planting SAV or establishing kelp near shorelines can attenuate waves and reduce in-canopy currents, which can provide valuable shoreline protection.

In contrast to many of the NNBF discussed elsewhere in these guidelines, the benefits of SAV or kelp for coastal protection are optimized in relatively low-energy environments and when used in conjunction with other techniques. For practitioners who need to supplement and enhance a larger coastal protection scheme such as an island, wetland, beach, or dune, or are in a low-energy wave environment, SAV or kelp can fill an important NNBF niche, providing valuable coastal protection.

SAV and kelp can play a vital role in coastal protection by attenuating wave energy and reducing the current velocity in the canopy, near the bed. The reduced hydrodynamic conditions can influence sediment transport in the canopy by increasing bed stabilization, reducing sediment resuspension, and creating an environment more conducive for suspended sediment deposition. Where canopy height and water-column height are equal (i.e., leaves extend all the way to the water surface), the wave-attenuation value of SAV is maximized.

Kelp requires available hard substrate (usually, rocky surfaces) for holdfast attachment, high-nutrient conditions, and light for growth.

Source: Colette Cairns, National Oceanic and Atmospheric Administration

Note: Photograph taken in Kachemak Bay State Park, Alaska, United States.

Where canopy height is much less than total water-column height, the movement of waters overlying the canopy are relatively unaffected by the presence of SAV below. In these cases, SAV still provides a valuable service by trapping and stabilizing sediments.

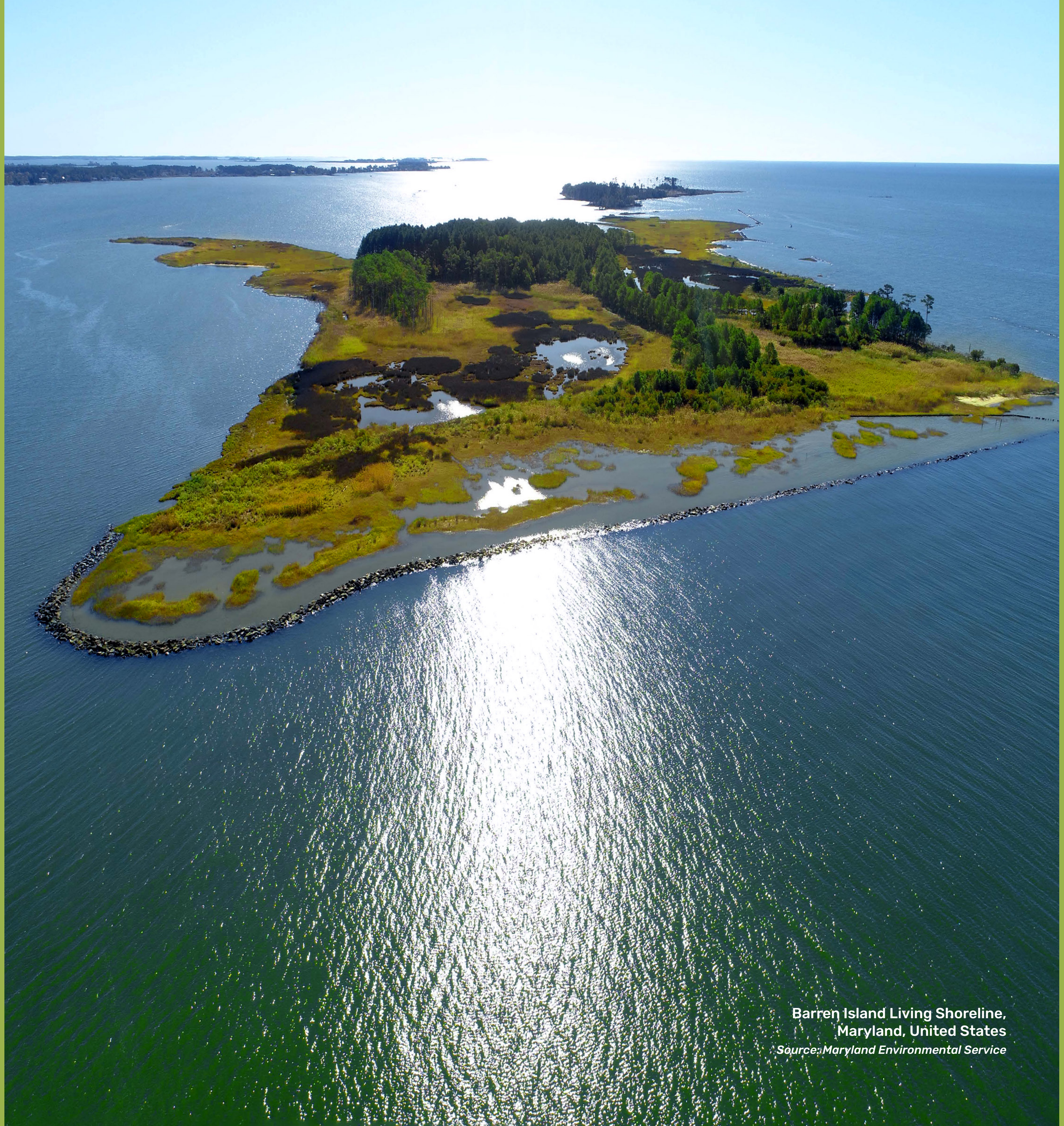
In the future, changing ocean temperatures and sea-level rise are expected to present challenges to coastal resiliency. If carefully planned for, SAV can be a part of NNBF projects that provide coastal protection in the face of changing conditions. Data on sea-level rise forecasts at a proposed site can allow managers to design a project to have space for SAV colonization and species succession as conditions change in the future.

Collecting baseline data is crucial in informing future decisions. Obtaining metrics for baseline information such as beach erosion rate and beach-profile changes would be very useful in quantifying the contribution of SAV to coastline protection. In projects where SAV has been planted near beaches to prevent erosion, using remote-sensing techniques (Cheng, Wang, and Guo 2016[40])—such as the lidar method and unmanned aerial vehicles—to collect images before and after storm events can help determine the efficacy of SAV in providing storm protection.

CHAPTER 14

Enhancing Structural Measures for Environmental, Social, and Engineering Benefits

The application of nature-based elements into conventional structural measures (e.g., levees, seawalls, breakwaters) is sometimes considered. For such projects, potential options fall along a spectrum—from enhancements to the structural measure to create environmental benefits (e.g., modifying the surface texture of a concrete breakwater to facilitate the development of hard-bottom communities) to the full-scale integration of NNBF with conventional structural measures (e.g., construction of a wetland complex in front of a levee).



Barren Island Living Shoreline, Maryland, United States
Source: Maryland Environmental Service

Key Messages

1. Enhancing structures through the use of NNBF can take multiple forms, serving as a continuum of measures over broad scales and structure types in both coastal and fluvial environments.

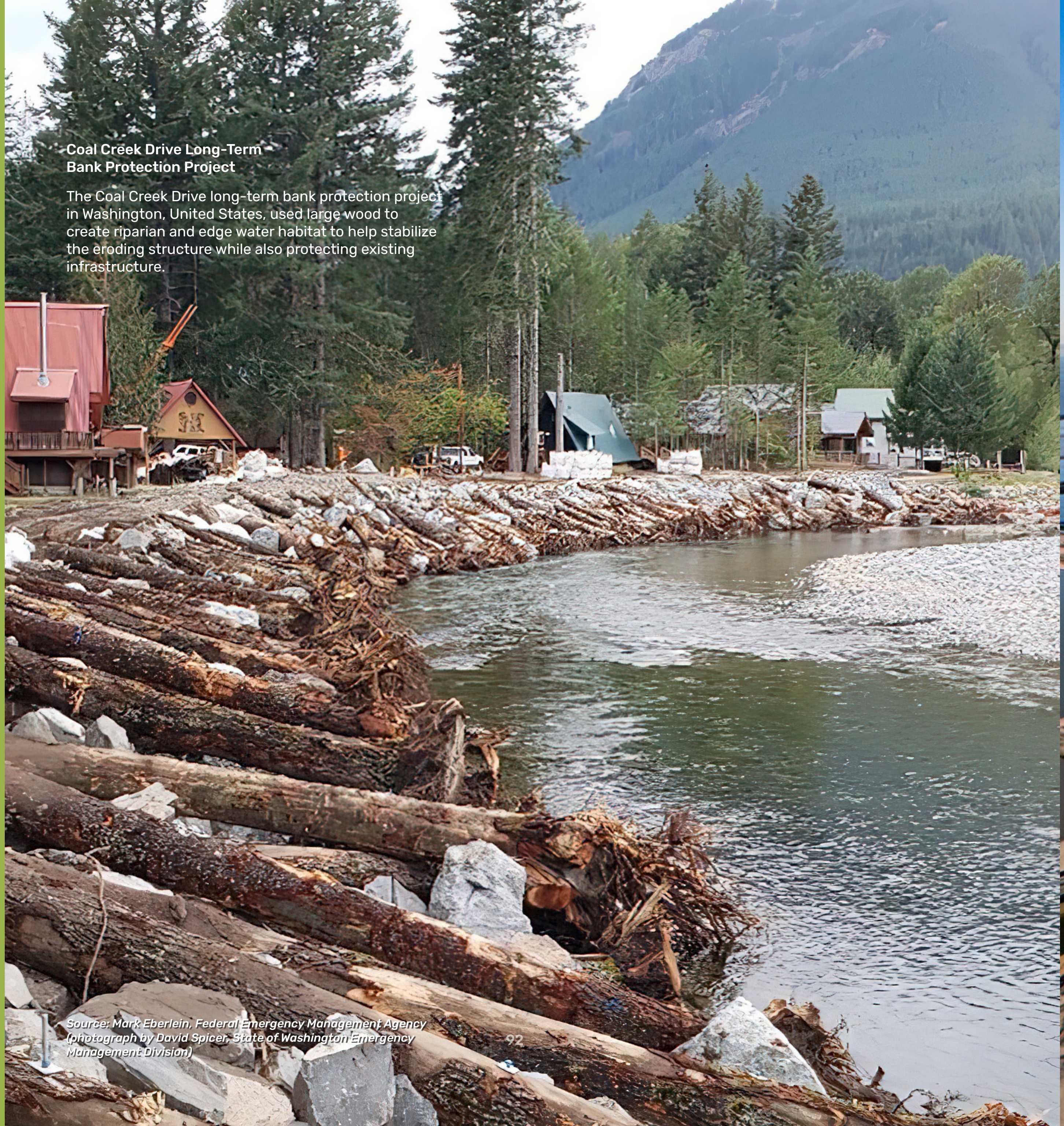
2. Ecological enhancements have the potential to offer multiple benefits, such as structural in the form of increased engineering design life and flood risk reduction, environmental in the form of ecological habitat, and societal in the form of recreational opportunities and improved well-being.

3. Opportunities to enhance structures can occur at any stage during the design life of the structure, including new construction and repair, maintenance, or modification of the structure.

4. The implementability of enhancements can be increased by identifying and quantifying the value NNBF provide so that the costs and benefits associated with them can be compared effectively against conventional structural measures.

NNBF can be used in some instances to expand the environmental and social value of existing conventional FRM structures. Conventional structural measures play an important role in FRM and may include rock or concrete structures such as bulkheads, seawalls, sheet piling, and floodwalls, in addition to levees and dikes that may combine earthen and rock and concrete structures. These conventional structural measures provide FRM benefits by attenuating flood surge and waves. The environmental value of these conventional structures may be enhanced through the inclusion of nature-based elements that expand their ecological value by enhancing habitat or social benefits. Such opportunities can occur throughout the life cycle of the structural measure, at the initial construction, or during repair or maintenance of the structure. Engaging stakeholders in the process of identifying opportunities to enhance value and benefits from structural measures, including recreational benefits or improvements to habitat and water quality, can broaden the base of support for infrastructure projects. Incorporation of nature-based elements can also aid project owners and local governments in their efforts to comply with environmental laws and regulations.

Applying NNBF to existing infrastructure is characterized by a continuum across many forms and scales. Simple examples in coastal areas include the following: applying small-scale features on existing structures to create habitat at the base of the food chain, adding large wood to a rubble mound structural repair after storm damage along a riverbank, reinforcing an existing aging coastal dike to reduce flood risk and increase habitat, and adding fish passage features to existing dam structures.



Coal Creek Drive Long-Term Bank Protection Project

The Coal Creek Drive long-term bank protection project in Washington, United States, used large wood to create riparian and edge water habitat to help stabilize the eroding structure while also protecting existing infrastructure.

Source: Mark Eberlein, Federal Emergency Management Agency (photograph by David Spicer, State of Washington Emergency Management Division)

Sand Reinforcement of the Houtribdijk Dam

Sand reinforcement of the Houtribdijk dam along the coast of the Netherlands helped to reinforce the dike, which no longer met revised flood risk reduction standards, and also was strategically placed to create habitat for a wide variety of aquatic species.

Source: Rijkswaterstaat

Fish Passage Feature at the Mosellum Erlebniswelt

The addition of a fish passage feature—such as the Mosellum Erlebniswelt in Koblenz, Germany—to an existing dam structure supports fish migration to spawning grounds upstream.

Source: Rijkswaterstaat

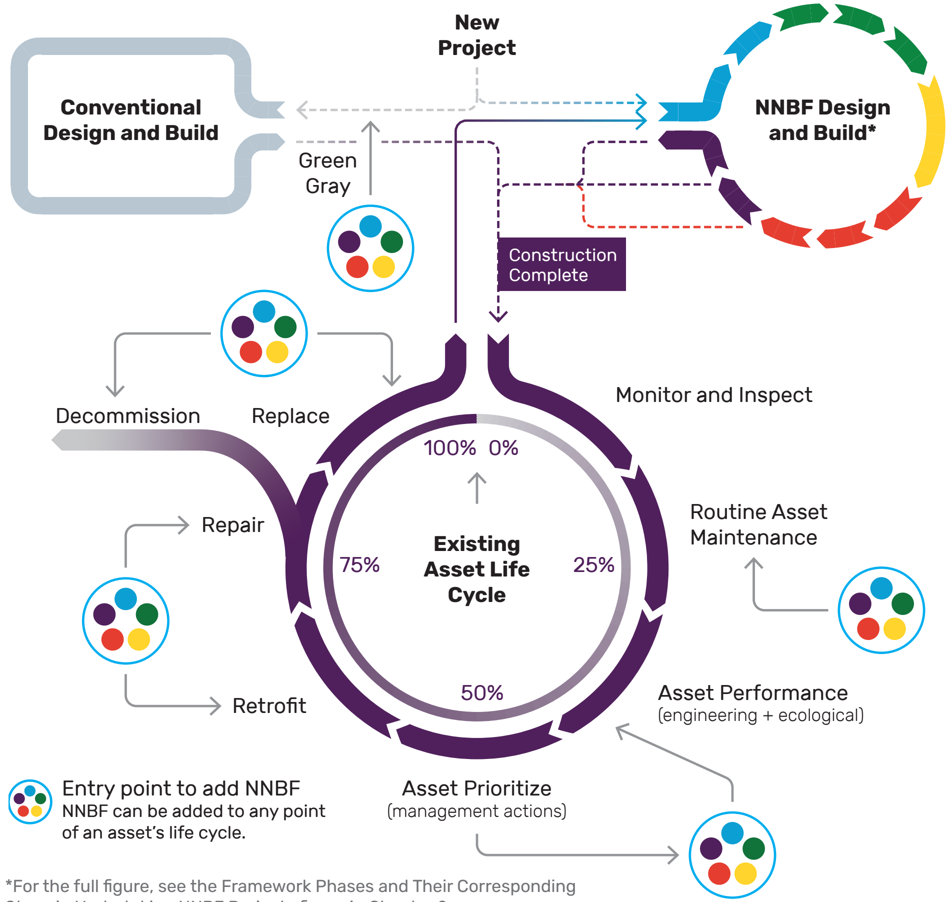
The primary emphasis here is on enhancing existing conventional infrastructure, because most of the current opportunities to enhance structures in the United States, the Netherlands, the United Kingdom, and elsewhere are during maintenance, repairs, and modifications of existing structures (e.g., there are 48,280 kilometers [30,000 miles] of levees in the United States alone that are aging). Nevertheless, the concepts and guidance provided here can also be applied to the design and construction of new or replacement structures and are recommended for use where standalone NNBF measures in other chapters are not technically, economically, or socially feasible (Naylor et al. 2017[41]).

Formed Blocks Applied to Existing Coastal Structures Create Habitat for Invertebrates and Other Species

Larissa Naylor shows how existing coastal structures can be enhanced by applying relatively small, formed blocks to create habitat for invertebrates and other species in the intertidal zone along the coast at Edinburgh, Scotland.

Source: Burton Suedel, U.S. Army Corps of Engineers

Activities Associated with Enhancing Existing Conventional Infrastructure Following the NNBF Framework



*For the full figure, see the Framework Phases and Their Corresponding Steps in Undertaking NNBF Projects figure in Chapter 2.

Notes: Discussions ideally need to take place with the NNBF team members to determine which enhancements can coexist with the engineering purpose of the feature and when and where in the design life of a structure these enhancements can be incorporated.

NNBF enhancement opportunities exist at various phases of a project, including at the design and build, maintenance, and repair phases, with both new and existing assets.

The enhancement of existing infrastructure for environmental, social, and engineering benefits in both coastal and fluvial environments across multiple scales has seen meaningful progress over the past decade. Yet, work remains that would advance this practice from merely occasional implementation to being the preferred alternative. There are several knowledge gaps and data needs that need to be overcome to promote increasing practice. Research needs include developing more widely distributed documentation of existing projects and conducting pilot studies to establish proof of concepts (Fredette et al. 2011[42]). Such pilot studies could include adding NNBF to breakwater structures, creating habitat on the protected sides of jetties or breakwaters using dredged sediments, creating shelves in channel side slopes at the optimum depth for seagrasses, and seeding infrequently dredged anchorages with shellfish.

Education, training, and technical transfer-related needs include documentation of case studies, development of webinars and workshops to disseminate best practices, and coordination of site visits to observe firsthand how innovations are being implemented in practice. Education efforts should be promoted because NNBF may be a relatively new concept for some stakeholders. Just simply introducing the idea may produce an immediate change in how a risk manager might perceive a proposed project. The focus is on the primary project objective (i.e., reducing coastal flood risk), but NNBF introduces the question, *Could we be creative and do more for ecosystem services in addition to serving the primary objective?*

Enhanced projects that relay lessons learned are informative and useful for applying these concepts elsewhere. In this respect, additional projects are needed to further demonstrate and document that NNBF enhancements can be successfully applied at multiple spatial and temporal scales.

Emerging technologies should be considered within the adaptive management framework to improve planning and ensure the most effective infrastructure enhancement practices are used. Technological advancements regularly occur in terms of NNBF enhancement options, materials available for construction, remote-sensing capabilities for planning and monitoring, and model advancement for evaluating design performance and project siting. Novel designs are regularly emerging for creating habitat niches for a variety of species, thereby promoting biodiversity and replacing conventional hardened shoreline structures with innovative hybrid structures (Bridges et al. 2018, 2021[43]). Advancement in construction materials expands design possibilities and offers added value, such as reduced carbon dioxide emissions during construction of hardened materials (e.g., enhancing concrete with natural materials to create Reef Balls).

Improvements to remote sensing, including lidar-derived and real-time kinematic GPS-adjusted topography to improve elevation data (Alizad et al. 2020; Buffington et al. 2016[44]) and unmanned aerial and surface systems that have miniaturized payloads (e.g., lidar) offer the ability to capture higher-resolution and more accurate data. These detection systems can also help monitor hard-to-access NNBF and animal populations (e.g., birds) to better quantify enhancement performance. The improved available data have enabled advancements in the development of integrated models that provide dynamic predictions of project performance under land management, sea-level, and storm-surge scenarios (Bilskie et al. 2014[45]). Finally, documentation of the use of these emerging technologies will be key to the proliferation of the most valuable advancements.

Rijkswaterstaat-Executed Beach Nourishment at Brouwersdam Beach, the Netherlands, Looking toward the North Sea from a Beach Vendor

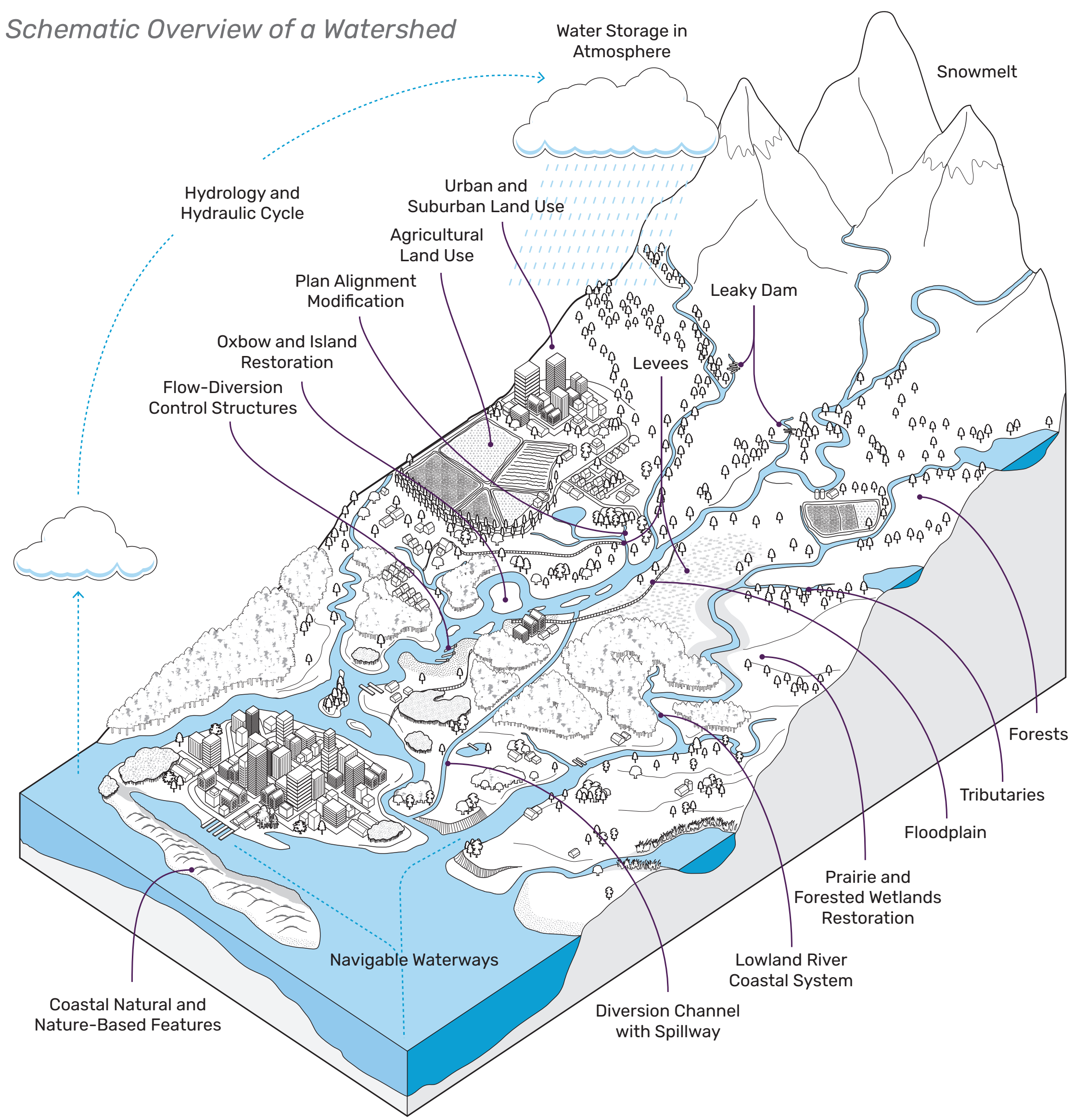
Source: Marian Lazăr

CHAPTER 15

Introduction to Fluvial Systems: Key Themes, Gaps, and Future Directions

The next five fluvial chapters are interconnected but can also be read independently. They provide generalities about fluvial systems and their connection with human use of the landscape.

Schematic Overview of a Watershed



Key Messages

1. Applications of NNBF in fluvial systems can reduce flood risk by integrating hydrologic, hydraulic, morphological, and ecological principles. Despite the variety in scales of catchments, there are common measures that apply to all scales.
2. Incorporating NNBF in FRM has, apart from reducing flood risk, many economic, social, and environmental co-benefits.
3. Use a holistic watershed approach to fluvial FRM—avoid transferring risks downstream, upstream, or to adjacent areas.
4. Where possible, use nested NNBF responses within the watershed.
5. Conserve, as much as possible, the natural features and processes throughout the watershed that store and attenuate floodwaters.
6. Employ proactive watershed management strategies to minimize sediment input into the fluvial system, while minimizing stormwater runoff.
7. Formulate a plan and involve stakeholders, nongovernmental organizations, landowners, and local authorities to get their full support.
8. Develop a long-term plan to monitor specific processes and parameters including adaptive management.

Watersheds are the appropriate scale for planning and designing FRM infrastructure in fluvial systems. They comprise numerous natural features and physical processes that together regulate the flow of water, sediment, and nutrients through the system. Watersheds include forests and prairie uplands, wetlands ranging from alpine wet meadows to bottomland swamps, glacial landscapes, and river channels and floodplains.

Fluvial geomorphic processes interact with vegetation and with large wooded and floodplain environments, and they work with aquifers that retain and release water over time into surface waterbodies in a process of groundwater-surface water exchange. Fluvial and associated floodplain ecosystems naturally store floodwaters, dissipate flow energy, store sediments, cleanse water, cycle nutrients, and provide habitats and food sources for aquatic, riparian, and terrestrial biological communities.

Watersheds often include developed urban areas, where a combination of human-made infrastructure and the natural environment control the flow of water.


Overflow Channel through the Floodplain That Provides High-Flow Refugia and Habitat Diversity, Washington, United States

Source: Washington Department of Fish and Wildlife

Floodplain Woodland Restoration in Galesburg, Illinois, United States

Source: Christopher Haring, U.S. Army Corps of Engineers

The primary objective in applying NNBF in fluvial settings is to reduce flood risk by restoring, enhancing, or mimicking natural hydraulic, morphological, and ecological functions and processes (Lane 2017[46]). Although the scale and physiography of watersheds vary, there are common reasons to apply NNBF, such as the following:

- To capture, retain, slow, or disperse floodwaters throughout the upper and middle watershed, using native vegetation where possible to capture and retain water and sediment and to slow erosion
- To improve the connectivity and interaction of the watercourse with the floodplain (creating space for water and room for the river)—especially where open spaces are also designated floodways
- To preserve or restore sediment balance to maintain not only stream channel geomorphology but also floodplains and deltas through appropriate sediment-building processes
- To restore or maintain lowland and river delta functions in ways that replicate or mimic natural features or processes

Fluvial NNBF may involve enhancements, redesigns, or realignments of existing engineered systems—not necessarily the wholesale replacement of structural measures. Therefore, NNBF measures should be viewed as integral components of the FRM portfolio that can often enhance conventional flood-control infrastructure.

Opportunities to use NNBF to counteract climate change effects need additional research. We foresee the following areas of development in the field of fluvial FRM:

- Improve the empirical basis for better understanding of the performance of NNBF measures.
- Invest in long-term (10 years and longer) monitoring programs (e.g., ecological, morphological, flood risk, social support) at the planning stage and analyze the data.
- Develop new approaches to participatory decision-making, involving all key stakeholders.
- Use modeling tools for ecology, morphology, and hydraulics and perform benchmark studies to learn from the different models and implement best practices.
- Strengthen the policy and legal frameworks to support the implementation of EWN measures.

CHAPTER 16

Fluvial Systems and Flood Risk Management

As humans maximized not only access to rivers but also their use of the adjoining land, they came into conflict with the natural water cycles and processes. Floods in natural rivers (defined here as rivers unaffected or almost unaffected by humans) are not considered to be major events or even catastrophes. A disaster starts when the river floods areas where there is human occupation or economic activity. In those cases, the river is most often (but not always[47]) engineered, with engineered floodplains and confined by embankments. If there are then periods of increased precipitation, the system will respond in the same way—floodplains are inundated and, if the capacity is insufficient, the levees, embankments, or walls overflow or break. It is because of this that the renowned U.S. geographer Gilbert White said, “Floods are ‘acts of God,’ but flood losses are largely acts of man” (White 1945[48]). In the United States alone, there are more than 23,600 kilometers of federally built or regulated levees and floodwalls, and up to 140,000 kilometers of historical and nonfederal levees (ASCE 2013[49]).

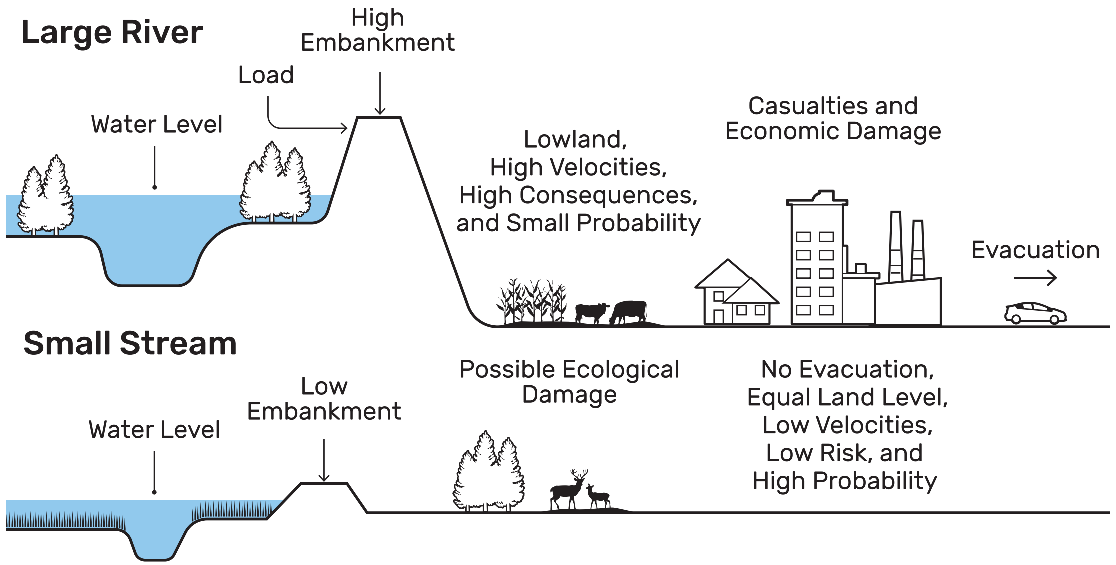
Key Messages

1. Past modifications of rivers and their basins have increased the risk of flooding. Climate change, anthropogenic features, and land use changes have increased the stress on natural fluvial systems and their functions, asserting more pressure on FRM infrastructure.
2. NNBF help mitigate these impacts, reducing both the level of flood risk and our dependence on engineered flood control structures while also restoring the natural environment, providing societal and ecological co-benefits.
3. As the benefits of NNBF are realized, more people are likely to see these benefits and want NNBF implemented in their watersheds. Monitoring and adaptive management of NNBF are needed to demonstrate the added benefits.

Note that storms that cause floods do not necessarily occur at the location of the flooding. Flooding is often the result of multiple days or even weeks of precipitation falling in upstream areas of a watershed. As water runs off into tributaries and then into the main river channel, flooding occurs downstream of the precipitation event. Flood risks are being exacerbated by a number of factors, including climate change (which causes increased discharges), land use changes (e.g., urbanization, deforestation, or transforming floodplains into agricultural land), and river engineering (e.g., construction of embankments and dams or the straightening of river stretches).

By resolving or mitigating flood risk, NNBF also provide important co-benefits and thus NNBF can be used for reasons other than reducing flood risk (e.g., river restoration for ecological purposes) and in those cases, will also provide additional benefits.

Elements Used to Evaluate Flood Risk for a Large River and a Small Stream



FRM Levee System Depicting Confined Flood Levels with No Access to Adjacent Floodplain—Example of the Extreme Changes a Levee System Can Make to a Floodplain by Confining Floodwater to Reduce Risks to a Community

Source: Christopher Haring, U.S. Army Corps of Engineers

Note: This photograph of levees on the Upper Iowa River, Decorah, Iowa, United States, depicts confined and elevated flood levels with no access to the adjacent floodplain.

CHAPTER 17

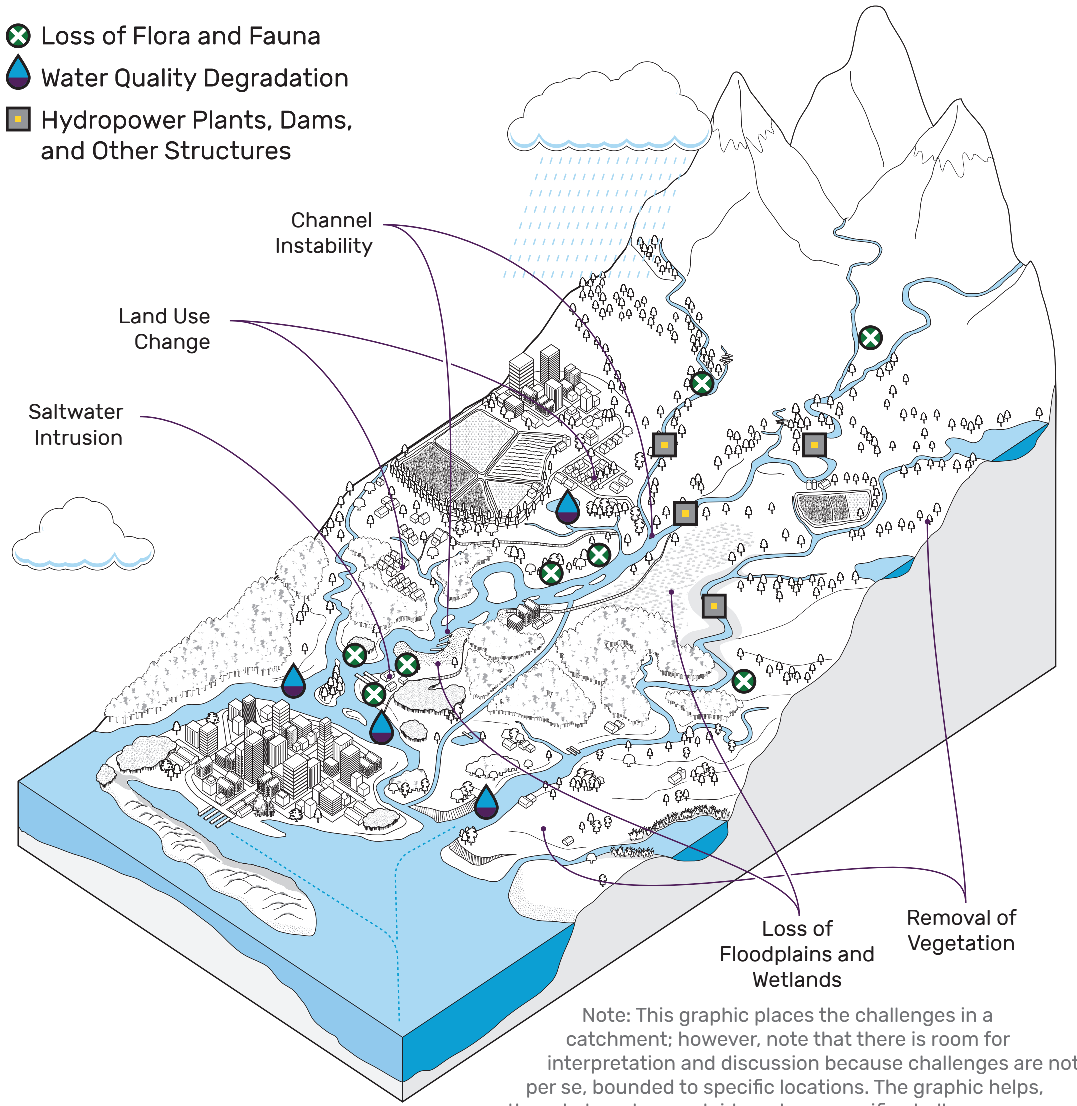
Benefits and Challenges in the Application of NNBF in Fluvial Systems

River management often involves adopting measures to modify the planform of the river reach. For many rivers, this kind of management already started decades or even hundreds of years ago by removing meander bends, changing the land use of floodplains, and constructing embankments. The river itself adapts to those changes by changing its slope, width, and bed surface texture (Blom et al. 2017[50]). The construction of embankments often means that adaptations in river width are limited, but slope and bed surface texture changes are still possible, leading to incision (riverbed erosion) and coarsening. Along with this, other issues arise such as lowering of the groundwater table, reduction in biodiversity, and disconnection of main channels and floodplains. NNBF can help reduce flood risk by protecting, restoring, and emulating the natural functions of watersheds, floodplains, rivers, and coasts (Environment Agency 2010, 2012, 2017[51]). In general, fluvial NNBF categories may seek to manage one or more of the following elements: rivers and floodplains, vegetation, rural and urban runoff, and erosion.

Key Messages

1. Measures in the past have altered river systems considerably and have left us with multiple challenges that come from the response of the river system to these changes. The challenges are associated with symptoms, causes, consequences, and benefits and co-benefits of NNBF.
2. Many challenges are related to a river system that is out of balance, which is reflected by morphological changes such as incision and soil erosion from land into the river and degrading biodiversity. Most challenges can be addressed by applying NNBF.
3. There are multiple constraints to consider when applying NNBF (e.g., applying a systems approach), but application also leads to additional co-benefits.
4. NNBF can be categorized—each category has its own way of reducing flood risk by retaining, storing, or increasing conveyance capacity, in addition to managing natural erosion and sediment dynamics.
5. There are NNBF best practices to consider based on individual project characteristics. The list can be reviewed and case study examples can be studied to determine which suite of NNBF is appropriate for a project.

Indicative Location of Challenges in a Catchment



Note: This graphic places the challenges in a catchment; however, note that there is room for interpretation and discussion because challenges are not, per se, bounded to specific locations. The graphic helps, though, to get a rough idea where specific challenges occur.

Waal River Floodplain with Agricultural Use, the Netherlands

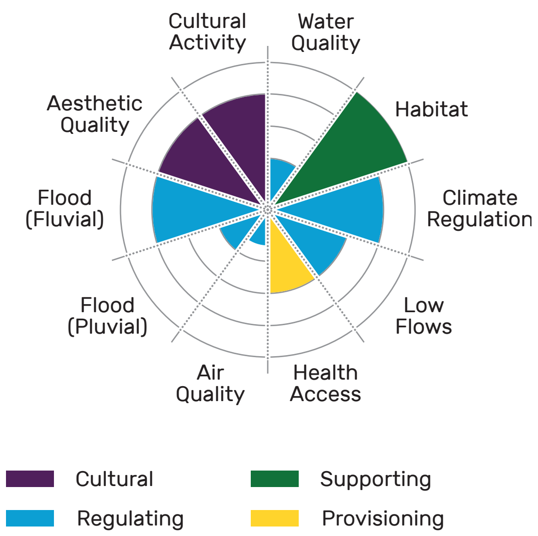
Probably the Most Important Form of Land Use Change is Using Floodplains for Agriculture, which is Often Accompanied by the Construction of Small Levees to Keep the Frequency of Inundation within Limits

Source: Joop van Houdt, Beeldbank, Rijkswaterstaat

Illustration of One of the Challenges of NNBF, Wetland and Floodplain near Santa Fe, Argentina

Source: Ralph Schielen, Beeldbank, Rijkswaterstaat

Example of a Benefits Wheel



Note: This benefit wheel depicts visually the multiple benefits that can be achieved through river restoration. The wedges could be larger or smaller depending on how well the NNBF was designed and constructed. A poorly designed project could result in fewer benefits.

Besides providing FRM benefits, NNBF can deliver a range of co-benefits. Although in the past, the co-benefits associated with NNBF-based projects typically were not documented, it is essential to assess not only FRM but also the full suite of social, environmental, and economic co-benefits. There are important factors to consider when assessing the range of benefits from NNBF projects. Among them are the scale of the NNBF application, the type of project, the features to be included, and the local or regional influences on physical landscape processes associated with FRM.

NNBF for FRM benefits occur across a wide range of spatial scales. A simple example of providing co-benefits associated with ecological enhancements to project design is adding natural materials to the upstream surface of a loose-rock, riffle-grade control structure to provide spawning habitat for fish. The primary FRM benefits were stabilizing the stream bed and reducing sedimentation downstream (effectively lowering the water-surface profile) and re-establishing access to the floodplain to allow flood flows to naturally dissipate energy and cycle nutrients and sediment across the floodplain. The additional benefit of expanded spawning habitat could be obtained by enhancing an existing structure or implementing this enhancement in a new project design.

Reintroducing floodplain connections by removing levees is an example of a larger-scale NNBF project. The project's primary FRM benefits are increased conveyance, reduction of peak flows, and retention and attenuation of floodwaters. Among its co-benefits are the re-establishment of groundwater recharge areas, nutrient recycling and sediment storage, and ecological enhancements for riparian functions including habitat for terrestrial and aquatic species. Contextual watershed, valley, slope, geologic, and other considerations require further investigation when comparing final benefits.

One way to visualize benefits in a reproducible and objective way is to use benefits wheels (see figure on page 115) that can be used to describe the services an NNBF could deliver. The benefits wheels are made up of 10 different benefit and co-benefit indicators that can be influenced by an NNBF. Each different benefit indicator is scored on a 1-to-5 scale according to the impact an intervention or measure can have on it. The higher the score, the greater the benefit. This semiquantitative ranking indicates the relative contribution a measure or intervention can make to the provision of certain benefits. Scores are assigned on the assumption that the measure or intervention is well planned, well designed, and well maintained. The scoring is undertaken collaboratively by the organization developing the NNBF project, its partner organizations, and local community groups. Scoring is qualitative, based on available knowledge of the river, its watershed, and the potential benefits of different types of NNBF. The benefits wheels developed for this document use the 10 benefit indicators used by the Environment Agency (in the United Kingdom) in its own NNBF guide (Environment Agency 2017[52]).

There is increasing support for the use of NNBF in reducing flood risk. Additional future research topics include the following:

- Longer-term and higher-frequency system-wide monitoring to improve performance-based system understanding
- Processes that proactively explore and consider the benefit of local context and maximize the benefits arising from the application of NNBF
- Studies to identify and evaluate costs and benefits, especially co-benefits, from a review of various types of NNBF projects
- Need for governmental and institutional protocols to include NNBF in their strategic policy and tactical processes

CHAPTER 18

Description of Fluvial NNBF

NNBF can help reduce flood risk by protecting, restoring, and emulating the natural functions of watersheds, floodplains, rivers, and coasts (Environment Agency 2010, 2012, 2017). NNBF can also provide wave attenuation by slowing the movement of water and waves over the feature. The selection of the appropriate NNBF requires a watershed-wide understanding of the hydrological system, morphological and ecological processes, and history of changes that have occurred and any societal constraints. NNBF can have the following effects on flooding:

- Retain runoff from rainfall, thus reducing the downstream flow
- Increase the proportion of rainfall that infiltrates into the ground, thus reducing the amount of runoff from rainfall and, therefore, the downstream flow
- Delay the flow of water by reducing the velocity
- Retain sediments that could otherwise deposit in river channels, reducing their conveyance
- Decrease lowland floodwater levels by increasing conveyance capacity

NNBF takes many different forms and can be applied in urban and rural areas and in small streams, rivers, estuaries, and coasts.

Key Messages

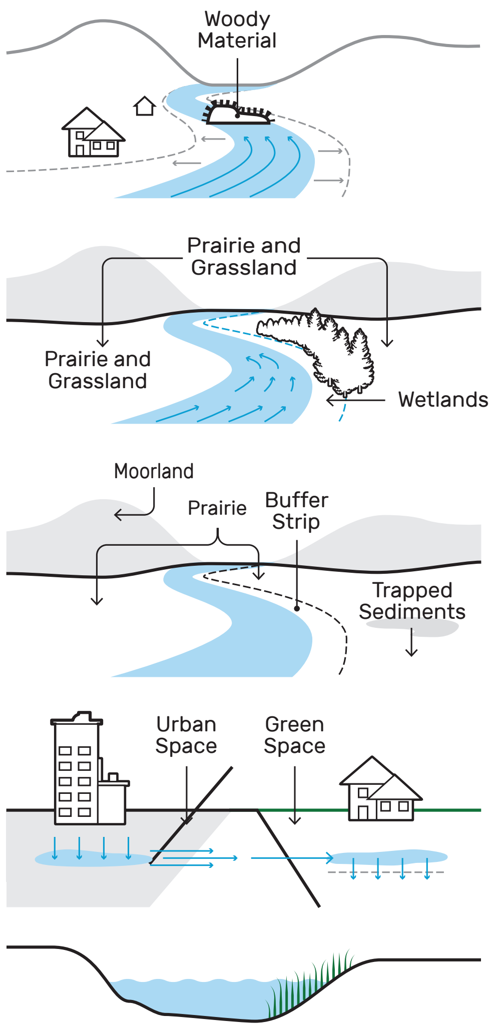
1. There are many different types of fluvial NNBF that can be used throughout a watershed to help reduce the risk of flooding.
2. Fluvial NNBF measures can be implemented in both rural and urban environments.
3. NNBF measures can be used alone. However, in many cases, they are most effectively used in combination with engineered FRM infrastructure, helping to enhance their resilience in the face of climate change.
4. Before selecting NNBF, it is important to fully understand the sources, pathways, and receptors of flooding because this will help in selecting the right measures to address the flood risk problems at their source.
5. In most circumstances, there will be no “silver bullet” solution to a flooding problem; instead, a range of NNBF will usually need to be implemented upstream of the area at risk of flooding.
6. NNBF measures can be designed in such a way that they not only reduce flood risk but also provide a range of co-benefits and help redress specific environmental challenges faced within a watershed.

Natural Floating Breakwater at Buffalo River, New York, United States

Source: Anchor QEA

The extent to which NNBF can reduce upstream, local, and downstream flooding depends on many factors including the magnitude of the storm (annual exceedance probability and duration); the morphological and ecological condition of the watershed; the number, size, and location of the NNBF; and the arrangement of the NNBF within the watershed. Environment Agency (2017), Oxford Martin School (2017), and POST (2014)[54] describe in detail the scientific evidence behind the effectiveness of NNBF at reducing flood risk. Understanding the effect of NNBF requires a systems approach, which needs an understanding of how the watershed functions and how it will interact with the hydrological cycle. Among the NNBF previously described for coastal flood risk reduction in this overview, wetlands are the most common NNBF that are also applied in fluvial systems.

NNBF Categories for Application in Fluvial Systems



River and Floodplain Management
- Slows flood flows
- Encourages flood storage
- Creates bypasses to move water away from communities
- Provides ecological and aquatic habitat benefits

Vegetation Management
- Slows water
- Encourages infiltration in soil
- Enables evapotranspiration
- Increases roughness and slows flow

Rural Runoff Management
- Captures water flow
- Slows and stores water
- Encourages infiltration
- Traps sediments

Urban Runoff Management
- Retains and stores water in green space
- Slows delivery of water to sewer system

Erosion Management
- Protects riverbanks
- Reduces erosion of banks
- Replaces hard engineering with vegetated banks

CHAPTER 19

Fluvial NNBF Case Studies

Although using NNBF to help alleviate flooding is relatively new, there are already a wide range of examples of their application globally. Case studies can act as an inspiration for river managers worldwide to select the appropriate NNBF to reduce flood risk. Depending on the region, success can be attributed to strong stakeholder and public engagement, proper siting and technical considerations during project scoping, flexible approaches and adaptive management considerations, and nurturing a sense of ownership and pride among local population, for long-term success. Case studies enable river managers to learn and share their experiences so that others can learn from past successes and failures; and reflect back and understand what worked well and what could have been done differently, which enables the science and practice of NNBF to develop further.

Daugava River, Viciebsk, Belarus
Source: Irina Iriser

Missouri River Floodplain Connectivity via Large-Scale Levee Setbacks, Iowa, United States

Project funders:
U.S. Army Corps of Engineers

Construction date:
2012 to 2013

Total cash cost of the project:
USD$60 million (approximately USD$4 million per kilometer of setback)

Measures included:
Levee setback

Lessons learned:
- Community and political desire for levee setbacks greatly supports prioritization and construction of levee setbacks
- Multiagency coordination and cooperation are critical for successful and timely implementation of levee setbacks
- The ability to be flexible and to find creative solutions to complex problems will be required of all parties for successful setback implementation

Source: David Crane, U.S. Army Corps of Engineers, Omaha District

Challenges addressed:

Challenge	Present
Channel instability	Yes
Land use change	Yes
Water quality degradation	Yes
Loss of flora and fauna	Yes
Saltwater (tidal) intrusion	No
Removal of vegetation	No
Loss of floodplains and wetlands	Yes
Hydropower plants, dams, and other hydraulic structures	Yes

IJssel River near Deventer, the Netherlands

Project funders:
Ministry of Infrastructure and Water Management, Ministry of Economic Affairs

Construction date:
2010 to 2015

Total cash cost of the project:
€105 million euros (USD$124 million)

Measures included:
Constructing side channels

Lessons learned:
- Close coordination between the government and the local stakeholder made the project a success
- Project required a delicate balance of different functions (such as water safety, farming, nature, and recreation)

Source: gedin.nl 2013[55]

Challenges addressed:

Challenge	Present
Channel instability	Yes
Land use change	Yes
Water quality degradation	No
Loss of flora and fauna	Yes
Saltwater (tidal) intrusion	No
Removal of vegetation	No
Loss of floodplains and wetlands	No
Hydropower plants, dams, and other hydraulic structures	No

Slowing the Flow, Pickering, Yorkshire, United Kingdom

Project funders:
Defra, Forestry Commission England, Environment Agency, North Yorkshire Moors National Park Authority, Natural England, North Yorkshire County Council, Ryedale District Council, Pickering Town Council, Sinnington Parish Council, and Yorkshire Flood and Coastal Committee

Construction date:
2009 to 2015

Total cash cost of the project:
More than GBP£3.1 million (USD$4.3 million) (GBP£2.7 million [USD$3.7 million] for construction)

Measures included:
Woodland planting, leaky woody structures, farm and moorland management measures, and conventional flood storage reservoir

Lessons learned:
- Land management measures can make a significant contribution to downstream flood alleviation
- Measuring the impact of land management measures on flood flows at the watershed level is extremely difficult
- Modeling is an important step in the process of locating and designing land management measures to reduce downstream flood risk

Source: Forest Research

Challenges addressed:

Challenge	Present
Channel instability	Yes
Land use change	Yes
Water quality degradation	Yes
Loss of flora and fauna	Yes
Saltwater (tidal) intrusion	No
Removal of vegetation	Yes
Loss of floodplains and wetlands	Yes
Hydropower plants, dams, and other hydraulic structures	No

Arvari River Watershed, Rajasthan, India

Project funders:
Local community leaders and community groups

Construction date:
Ongoing since 1985

Total cash cost of the project:
Not available

Measures included:
Johads (water retention measures shown in the photograph to the right)

Lessons learned:
- Participation of the local population is a prerequisite for success
- Work to rejuvenate a local area becomes sustainable and replicable only when local knowledge is applied in addition to science
- Every member of the rural community is forever engaged in the process, bearing the onus of ownership of the river and its waters responsibly

Source: The Flow Partnership

Challenges addressed:

Challenge	Present
Channel instability	Yes
Land use change	Yes
Water quality degradation	Yes
Loss of flora and fauna	Yes
Saltwater (tidal) intrusion	No
Removal of vegetation	Yes
Loss of floodplains and wetlands	No
Hydropower plants, dams, and other hydraulic structures	No

CHAPTER 20

The Way Forward

Nature-based solutions have a significant role to play in infrastructure systems in the twenty-first century, and NNBF will be an important part of future FRM strategies and systems. The goal of these guidelines is to inform future practice for NNBF by drawing together knowledge and experience from around the world. Effective and timely implementation of NNBF to address current and future FRM challenges will depend on progress in three overarching areas of activity—developing and delivering, communicating and collaborating, and elevating and educating.

Braddock Bay Ecosystem Restoration Project, Greece, New York, United States
Source: U.S. Army Corps of Engineers

Developing and Delivering

These guidelines were written to support developing and delivering FRM projects that incorporate NNBF. Organizations and teams responsible for infrastructure projects will be familiar with the call to deliver projects "faster, cheaper, and better." NNBF can, do, and will contribute to all three parts of this refrain. Although efforts to deliver infrastructure projects on time and within budget will continue to be important, organizations must also be careful to deliver the "right" project that provides sustainable and resilient solutions over the long term.

A systems approach to FRM provides a comprehensive view of and vision for processes, functions, relationships, and engineering interventions that are critical to achieving successful project outcomes. Ultimately, interventions, whether structural or NNBF, will work as part of a system that includes physical, environmental, social, and political elements. Understanding and working with the myriad connections among these elements is central to the long-term success, sustainability, and value achieved within the system. When project sponsors, developers, planners, and engineers are explicit and intentional about incorporating NNBF and supporting processes, the FRM system will be strengthened and the long-term value from infrastructure investments will be expanded.

Measuring and managing engineering interventions—whether structural, nonstructural, or NNBF measures—within FRM systems is an evolving discipline. The combination of aging, decades-old FRM projects and climate change is prompting new thinking and practices regarding performance, especially in relation to improving overall resilience. Project performance can be viewed narrowly in terms of the integrity and functioning of the physical structures that compose a system. Performance can also be viewed broadly to include a project's long-term benefits and value, such as economic damages avoided, co-benefits produced, and greater system resilience provided. In both a narrow and a broad sense, further progress in the multidisciplinary activity of assessing project performance is needed and should be encouraged.

The modern age of FRM engineering, which has emerged over the past 100 years, provides a wealth of data and experience that can inform future work. As today's surge in infrastructure investment continues, we should be deliberate about learning from FRM and NNBF projects so we can advance policy and technical practices. Particularly important is the opportunity to expand our consideration of all the costs and benefits of projects, including their structural, nonstructural, and NNBF components. Failing to fully consider all of a system's relevant costs and benefits has led in the past—and will lead in the future—to dissatisfying outcomes and missed opportunities to create diversified value from infrastructure investments.

There is a need to continue improving numerical models and practices for FRM, and for NNBF in particular. Much of today's modeling capability to support FRM is designed to support the analysis of structural measures. Developing truly integrative approaches to FRM that include NNBF measures will require advancing models and modeling practice with respect to natural features, processes, and systems.

As the modern environmental movement enters its seventh decade, there is a need to continue advancing environmental regulation and management to conserve and protect natural systems. There is also a need to build on the growing recognition of natural value and capital so that communities can fully leverage natural systems and functions to address the dynamic challenges posed by FRM and climate change. Efficient and timely regulatory decision-making will support the delivery of NNBF projects and the wide range of benefits for ecosystems and the people who depend on natural systems.

Communicating and Collaborating

In a world filled with competing interests, perspectives, and voices, communication and collaboration are increasingly important skills for individuals and organizations, including project teams. Many infrastructure projects in the past were implemented with little, if any, substantive engagement with the communities "receiving" the project. That more engagement is occurring now is a measure of progress; however, more can be done to improve communication and collaboration during the development of infrastructure projects. Engagement, communication, and collaboration that bridge the gaps between technical disciplines, organizations, and the public are increasingly recognized as fundamental to successful project development and implementation. The need for carefully planned and purposeful investments in communication and engagement when developing and implementing FRM projects remains critical.

Effective communication must be internal as well as external. Within an organization or agency, effective communication is necessary to align the internal stakeholders that hold different responsibilities and perspectives relative to NNBF. Such alignment might even be considered a precondition for effective external communication about NNBF with other organizations.

Because they can produce diverse benefits, NNBF provide an important opportunity to engage people and perspectives about value creation through infrastructure investment. Substantive dialogue about the diversity of economic, environmental, and social co-benefits of multipurpose FRM projects that include NNBF will pull from expertise across the physical, biological, and social sciences. Some benefits of FRM and NNBF projects

Blackwater National Wildlife Refuge, Cambridge, Maryland, United States
Source. U.S. Army Corps of Engineers

are readily monetized, but the inability to monetize a benefit does not necessarily make the benefit less “real” or important. Many environmental and social co-benefits that may be difficult or even inappropriate to monetize are critical to establishing a project’s overall value proposition. Habitat for threatened or endangered species, and biodiversity in general, are examples of such important co-benefits. The use of infrastructure to support social equity in communities is an increasingly important benefit to incorporate into twenty-first century investment planning.

Many challenging topics complicate communication about FRM and climate change. They include uncertainty about the dynamics of the physical and natural systems that comprise FRM projects and the effects and uncertainties of climate change. Progress here will directly support the implementation of adaptive management as a critical component of FRM and NNBF projects. People tend to think and communicate in terms of “either/or” with respect to FRM alternatives—either structural measures or NNBF. But most future FRM systems will include both structural and NNBF measures. Practitioners must be careful to think and communicate about FRM in inclusive, rather than exclusive, ways.

Collaboration across the public and private sectors is fundamental to delivering FRM solutions that include NNBF. Such collaboration includes the creative exchange of ideas between the public agencies that sponsor FRM projects and the private companies that support their delivery. It also includes opportunities for jointly financing NNBF projects and for developing markets (e.g., for carbon sequestration) relevant to the diverse benefits that NNBF can provide.

Elevating and Educating

NNBF often provide FRM by elevating part of the landscape to influence the movement of water. These guidelines were developed to promote FRM practice by providing information that is relevant to planning, designing, engineering, and operating FRM projects. Education and training are critical to influencing the long-term trajectory of FRM practice.

Education is sharing information. NNBF education has three primary goals. The first is to expand public awareness of NNBF options and share information about sustainable, resilient solutions for FRM problems. The second is to share emerging technical information and approaches with today’s engineers, environmental scientists, lawyers, and other professionals supporting infrastructure development. The third is to develop new educational programs and courses to support communities and future professionals in their efforts to develop infrastructure solutions. When society as a whole understands that natural systems can and do contribute to tangible human needs such as FRM, public and private institutions will be better able to support the natural systems and environmental conditions that are foundational to sustaining NNBF.

The organizations and agencies that develop and operate FRM projects and systems must be intentional about knowing the status and future condition of their projects and systems. Actively managing and adapting projects in a timely manner requires an ongoing financial commitment to monitoring and analysis to determine current conditions and future project needs.

Progress is a watchword of modernity. Progress is achieved through a collective commitment to harnessing innovation to meet future challenges. Policies at all levels should encourage—rather than intentionally or unintentionally hinder—appropriately managed innovation. Each institution contributing to FRM should consider its own policies, procedures, and practices in view of the process of innovation and whether there is evidence of sufficient innovation in its activities. Such self-assessment is part of an organization's commitment to continual learning and the stewardship of its technical competence.

We live in a period of increasingly rapid change and technological advancement. Although these conditions pose many challenges to society, organizations, and individuals, they also present opportunities to create value from the flood of data, information, and experience that flows around us. When we each take the time to document what happened in our own NNBF projects and share that experience across the international community of practice, the benefits generated will be good for humanity and for nature.

Long Island Beach Coastal Storm Damage Reduction, New Jersey, United States
Source: U.S. Army Corps of Engineers

Endnotes and References

1. McHarg, I. L. 1969. *Design with Nature*. Garden City, New York: Published for the American Museum of Natural History [by] the Natural History Press.

2. "Community" may be defined in a number of ways. Community boundaries may be based on legal, political, physical, or symbolic criteria. Most often for NNBF projects, the term "community" refers to a geographical and administrative designation in that there are physical boundaries around a place that operates with a governance structure (e.g., town, city, or county).

3. usace.army.mil. 2002. Environmental Operating Principles. *U.S. Army Corps of Engineers Headquarters*. http://www.usace.army.mil/Missions/Environmental/Environmental-Operating-Principles/.

   APFM (Associated Programme on Flood Management). 2009. *Integrated Flood Management: Concept Paper*. WMO-No. 1047. Geneva: World Meteorological Organization.

   National Research Council. 2013. *Sustainability for the Nation: Resource Connections and Governance Linkages*. Washington, DC: National Academies Press.

   WWF (World Wildlife Fund). 2016. *Natural and Nature-Based Flood Management: A Green Guide*. Washington, DC: World Wildlife Fund. https://www.worldwildlife.org/publications/natural-and-nature-based-flood-management-a-green-guide.

   World Bank. 2017. *Implementing Nature-Based Flood Protection: Principles and Implementation Guidance*. Washington, DC: World Bank.

   Burgess-Gamble, L., R. Ngai, M. Wilkinson, T. Nisbet, N. Pontee, R. Harvey, K. Kipling, et al. 2018. *Working with Natural Processes – Evidence Directory*. SC150005. Bristol: Environment Agency.

4. EM-DAT (The International Disaster Database). 2019. (Centre for Research on the Epidemiology of Disasters [CRED], Université catholique de Louvain, Brussels, Belgium).

5. Beck, M. W., I. J. Losada, P. Menéndez, B. G. Reguero, P. Díaz-Simal, and F. Fernández. 2018. "The Global Flood Protection Savings Provided by Coral Reefs." *Nature Communications* 9 (1): 2186.

   Menéndez, P., I. J. Losada, S. Torres-Ortega, S. Narayan, and M. W. Beck. 2020. "The Global Flood Protection Benefits of Mangroves." *Scientific Reports* 10 (1): 1–11. https://doi.org/10.1038/s41598-020-61136-6.

6. World Bank. 2017. *Implementing Nature-Based Flood Protection: Principles and Implementation Guidance*. Washington, DC: World Bank.

   IPCC (Intergovernmental Panel on Climate Change). 2019. "Summary for Policymakers." In *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*. Edited by H. O. Pörtner, D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, et al. Principality of Monaco: IPCC. https://www.ipcc.ch/site/assets/uploads/sites/3/2019/11/03_SROCC_SPM_FINAL.pdf.

   GCA (Global Commission on Adaptation). 2019. *Adapt Now: A Global Call for Leadership on Climate Resilience*. Washington, DC: World Resources Institute. https://openknowledge.worldbank.org/handle/10986/32362.

   IUCN (International Union for Conservation of Nature). 2020. *IUCN Global Standard for Nature-Based Solutions: A User-Friendly Framework for the Verification, Design and Scaling Up of NbS*. First Edition. Gland, CH: International Union for Conservation of Nature.

7. Edwards, P. E. T., A. E. Sutton-Grier, and G. E. Coyle. 2013. "Investing in Nature: Restoring Coastal Habitat Blue Infrastructure and Green Job Creation." *Marine Policy* 38: 65–71. https://www.sciencedirect.com/science/article/abs/pii/S0308597X12001182. https://doi.org/10.1016/j.marpol.2012.05.020.

8. Storlazzi, C. D., B. G. Reguero, A. D. Cole, E. Lowe, J. B. Shope, A. E. Gibbs, B. A. Nickel, R. T. McCall, A. R. van Dongeren, and M. W. Beck. 2019. *Rigorously Valuing the Role of U.S. Coral Reefs in Coastal Hazard Risk Reduction*. U.S. Geological Survey Open-File Report 2019–1027. Reston, VA: U.S. Department of the Interior and U.S. Geological Survey. https://doi.org/10.3133/ofr20191027.

   Reguero, B. G., C. D. Storlazzi, A. E. Gibbs, J. B. Shope, A. D. Cole, K. A. Cumming, and M. W. Beck. "The Value of US Coral Reefs for Flood Risk Reduction." *Nature Sustainability* 4: 688–698. https://doi.org/10.1038/s41893-021-00706-6.

9. Narayan, S., M. W. Beck, P. Wilson, C. J. Thomas, A. Guerrero, C. C. Shepard, B. G. Reguero, G. Franco. J. C. Ingram, and D. Trespalacios. 2017. "The Value of Coastal Wetlands for Flood Damage Reduction in the Northeastern USA." *Scientific Reports* 7 (1): 9463. https://doi.org/10.1038/s41598-017-09269-z.

   Narayan, S., S. Bitterwolf, and M. W. Beck. 2019. *The Costs of Mangrove and Reef Restoration Relative to Coastal Protection Structures in the Caribbean. Policy Brief*. Arlington, VA: Nature Conservancy.

10. GCA (Global Commission on Adaptation). 2019. *Adapt Now: A Global Call for Leadership on Climate Resilience*. Washington, DC: World Resources Institute. https://openknowledge.worldbank.org/handle/10986/32362.

11. Barbier, E. B., S. D. Hacker, C. Kennedy, E. W. Koch, A. C. Stier, and B. R. Silliman. 2011. "The Value of Estuarine and Coastal Ecosystem Services." *Ecological Monographs* 81 (2): 169–183.

12. NSTC (National Science and Technology Council). 2015. *Ecosystem Service Assessment: Research Needs for Coastal Green Infrastructure*. Washington, DC: White House Office of Science and Technology Policy.

13. Dasgupta, P. 2021. *The Economics of Biodiversity: The Dasgupta Review*. London: HM Treasury.

    Johnson, J. A., G. Ruta, U. Baldos, R. Cervigni, S. Chonabayashi, E. Corong, O. Gavryliuk, J. Gerber, T. Hertel, C. Nootenboom, and S. Polasky. 2021. *The Economic Case for Nature: A Global Earth-Economy Model to Assess Development Policy Pathways*. World Bank, Washington, DC. https://openknowledge.worldbank.org/handle/10986/35882.

14. usbr.gov. 2021. Glen Canyon Unit. *Bureau of Reclamation*. https://www.usbr.gov/uc/rm/crsp/gc/.

15. CIRIA (Construction Industry Research and Information Association). 2010. *Beach Management Manual*. Second Edition. London: Construction Industry Research and Information Association.

16. Davis, R. A. 1985. *Coastal Sedimentary Environments*. New York: Springer. https://doi.org/10.1007/978-1-4612-5078-4.

17. Wright, L., and A. Short. 1984. "Morphodynamic Variability of Beaches and Surf Zones, A Synthesis." *Marine Geology* 56 (1-4): 92–118. https://doi.org/10.1016/0025-3227(84)90008-2.

18. CIRIA (Construction Industry Research and Information Association). 2010. *Beach Management Manual*. Second Edition. London: Construction Industry Research and Information Association.

19. Davidson-Arnott, R. 2010. *Introduction to Coastal Processes and Geomorphology*. Cambridge: Cambridge University Press.

20. Rijkswaterstaat Kustlijnkaarten. 1992–2020. Rijkswaterstaat Coastline Map Database. https://puc.overheid.nl/doc/PUC_48455_31/1/#ee75d980-305a-4ff9-b002-b163f27da19f.

21. Costanza, R., O. Perez-Maqueo, M. L. Martinez, P. Sutton, S. J. Anderson, and K. Mulder. 2008. "The Value of Coastal Wetlands for Hurricane Protection." *Ambio* 37 (4): 241–248.

22. Sun, F., and R. T. Carson. 2020. "Coastal Wetlands Reduce Property Damage during Tropical Cyclones." *Proceedings of the National Academy of Sciences* 117 (11): 5719–5725.

23. Narayan, S., M. W. Beck, P. Wilson, C. J. Thomas, A. Guerrero, C. C. Shepard, B. G. Reguero, G. Franco, J. C. Ingram, and D. Trespalacios. 2017. "The Value of Coastal Wetlands for Flood Damage Reduction in the Northeastern USA." *Scientific Reports* 7: 9463. doi:10.1038/s41598-017-09269-z.

24. Narayan, S., C. J. Thomas, J. Matthewman, C. C. Shepard, L. Geselbracht, K. Nzerem, and M. W. Beck. 2019. *Valuing the Flood Risk Reduction Benefits of Florida's Mangroves*. University of California, Santa Cruz and The Nature Conservancy. http://www.conservationgateway.org/SiteAssets/Pages/floridamangroves/Mangrove_Report_digital_FINAL.pdf.

25. Reguero, B. G., C. D. Storlazzi, A. E. Gibbs, J. B. Shope, A. D. Cole, K. A. Cumming, and M. W. Beck. "The Value of US Coral Reefs for Flood Risk Reduction." *Nature Sustainability* 4: 688–698. https://doi.org/10.1038/s41893-021-00706-6.

26. Storlazzi, C. D., S. B. Gingerich, A. van Dongeren, O. M. Cheriton, P. W. Swarzenski, E. Quataert, C. I. Voss, et al. 2018. "Most Atolls Will Be Uninhabitable by the Mid-21st Century Because of Sea-Level Rise Exacerbating Wave-Driven Flooding." *Science Advances* 4 (4): eaap9741.

Storlazzi, C. D., B. G. Reguero, A. D. Cole, E. Lowe, J. B. Shope, A. E. Gibbs, B. A. Nickel, R. T. McCall, A. R. van Dongeren, and M. W. Beck. 2019. *Rigorously Valuing the Role of U.S. Coral Reefs in Coastal Hazard Risk Reduction*. Open-File Report 2019–1027. Reston, VA: U.S. Department of the Interior and U.S. Geological Survey.

Reguero, B. G., F. Secaira, A. Toimil, M. Escudero, P. Díaz-Simal, M. W. Beck, C. D. Storlazzi, R. Silva, and I. J. Losada. 2019. "The Risk Reduction Benefits of the Mesoamerican Reef in Mexico." *Frontiers in Earth Science* 7: 125.

27. Hsu, J. R-C., M-J. Yu, F-C. Lee, and L. Benedet. 2010. "Static Bay Beach Concept for Scientists and Engineers: A Review." *Coastal Engineering* 57 (2): 76–91.

28. Reguero, B. G., M. W. Beck, V. N. Agostini, P. Kramer, and B. Hancock. 2018. "Coral Reefs for Coastal Protection: A New Methodological Approach and Engineering Case Study in Grenada." *Journal of Environmental Management* 210: 146–161. https://doi.org/10.1016/j.jenvman.2018.01.024.

29. Rodriguez, A. B., F. J. Fodrie, J. T. Ridge, N. L. Lindquist, E. J. Theuerkauf, S. E. Coleman, J. H. Grabowski, et al. 2014. "Oyster Reefs Can Outpace Sea-Level Rise." *Nature Climate Change* 4: 493–497.

30. Grabowski, J. H., R. D. Brumbaugh, R. F. Conrad, A. G. Keeler, J. J. Opaluch, C. H. Peterson, M. F. Piehler, S. P. Powers, and A. R. Smyth. 2012. "Economic Valuation of Ecosystem Services Provided by Oyster Reefs." *BioScience* 62 (10): 900–909.

31. Perry, C. T., L. Alvarez-Filip, N. A. Graham, P. J. Mumby, S. K. Wilson, P. S. Kench, D. P. Manzello, et al. 2018. "Loss of Coral Reef Growth Capacity to Track Future Increases in Sea Level." *Nature* 558 (7710): 396.

32. Duarte, C. M., I. J. Losada, I. E., Hendriks, I. Mazarrasa, and N. Marbà. 2013. "The Role of Coastal Plant Communities for Climate Change Mitigation and Adaptation." *Nature Climate Change* 3: 961–968.

33. Guannel, G., K. Arkema, P. Ruggiero, and G. Verutes. 2016. "The Power of Three: Coral Reefs, Seagrasses and Mangroves Protect Coastal Regions and Increase Their Resilience." *PLOS ONE* 11 (7): e0158094.

34. Alongi, D. A. 2008. "Mangrove Forests: Resilience, Protection from Tsunamis, and Responses to Global Climate Change." *Estuarine, Coastal and Shelf Science* 76 (1):1–13.

Christianen, M. J. A., J. van Belzen, P. M. J. Herman, M. M. van Katwijk, L. P. M. Lamers, P. J. M. van Leent, and T. J. Bouma. 2013. "Low-Canopy Seagrass Beds Still Provide Important Coastal Protection Services." *PLOS ONE* 8 (5): e62413. doi:10.1371/journal. pone.0062413.

35. Guannel, G., K. Arkema, P. Ruggiero, and G. Verutes. 2016. "The Power of Three: Coral Reefs, Seagrasses and Mangroves Protect Coastal Regions and Increase Their Resilience." *PLOS ONE* 11 (7): e0158094.

36. Feagin, R. A., J. Figlus, J. C. Zinnert, J. Sigren, M. L. Martínez, R. Silva, W. K. Smith, D. Cox, D. R. Young, and G. Carter. 2015. "Going with the Flow or Against the Grain? The Promise of Vegetation for Protecting Beaches, Dunes, and Barrier Islands from Erosion." *Frontiers in Ecology and the Environment* 13 (4): 203–210. https://doi.org/10.1890/140218.

37. Bruun, P. 1962. "Sea-Level Rise as a Cause of Shore Erosion." *Journal of the Waterways and Harbors Division* 88 (1): 117–130.

Edelman, T. 1972. "Dune Erosion during Storm Conditions." *Coastal Engineering Proceedings* 1 (13): 66. doi:10.9753/icce.v13.66.

McHarg, I. L. 1969. *Design with Nature*. Garden City, NY: Natural History Press.

Silva, R., M. L. Martínez, I. Odériz, E. Mendoza, and R. A. Feagin. 2016. "Response of Vegetated Dune–Beach Systems to Storm Conditions." *Coastal Engineering* 109: 53–62.

38. Temmerman, S., P. Meire, T. J. Bouma, P. M. Herman, T. Ysebaert, and H. J. de Vriend. 2013. "Ecosystem-Based Coastal Defence in the Face of Global Change." *Nature* 504 (7478): 79–83.

Silva, R., M. L. Martínez, I. Odériz, E. Mendoza, and R. A. Feagin. 2016. "Response of Vegetated Dune–Beach Systems to Storm Conditions." *Coastal Engineering* 109: 53–62.

39. Wayne, C. J. 1975. "Sea and Marsh Grasses: Their Effect on Wave Energy and Nearshore Transport." PhD diss. and MS thesis, Florida State University College of Arts and Sciences.

Horstman, E. M., C. M. Dohmen-Janssen, P. M. F. Narra, N. J. F. van den Berg, M. Siemerink, and S. J. M. H. Hulscher. 2014. "Wave Attenuation in Mangroves: A Quantitative Approach to Field Observations." *Coastal Engineering* 94: 47–62.

Möller, I., M. Kudella, F. Rupprecht, T. Spencer, M. Paul, B. K. van Wesenbeeck, G. Wolters, et al. 2014. "Wave Attenuation over Coastal Salt Marshes under Storm Surge Conditions." *Nature Geoscience* 7 (10): 727–731.

40. Cheng, J., P. Wang, and Q. Guo. 2016. "Measuring Beach Profiles along a Low-Wave Energy Microtidal Coast, West-Central Florida, USA." *Geosciences* 6 (4): 44.

41. Naylor, L. A., H. Kippen, M. A. Coombes, B. Horton, M. MacArthur, and N. Jackson. 2017. *Greening the Grey: A Framework for Integrated Green Grey Infrastructure (IGGI)*. Glasgow: University of Glasgow. http://eprints.gla.ac.uk/150672/.

42. Fredette, T. J., C. M. Foran, S. M. Brasfield, and B. C. Suedel. 2011. “Environmental Engineering of Navigation Infrastructure: A Survey of Existing Practices, Challenges, and Potential Opportunities.” *Integrated Environmental Assessment and Management* 8 (1): 175–182.

43. Bridges, T. S., E. M. Bourne, J. K. King, H. K. Kuzmitski, E. B. Moynihan, and B. C. Suedel. 2018. *Engineering with Nature: An Atlas*. ERDC/EL SR-18-8. Vicksburg, MS: U.S. Army Engineer Research and Development Center. http://dx.doi.org/10.21079/11681/27929.

    Bridges, T. S., E. M. Bourne, B. C. Suedel, E. B. Moynihan, and J. K. King. 2021. *Engineering with Nature: An Atlas, Volume 2*. ERDC SR-21-2. Vicksburg, MS: U.S. Army Engineer Research and Development Center. http://dx.doi.org/10.21079/11681/40124.

44. Alizad, K., S. C. Medeiros, M. R. Foster-Martinez, and S. C. Hagen. 2020. “Model Sensitivity to Topographic Uncertainty in Meso- and Micro-Tidal Marshes.” *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing* 13: 807–814. doi:10.1109/JSTARS.2020.2973490.

    Buffington, K. J., B. D. Dugger, K. M. Thorne, and J. Y. Takekawa. 2016. “Statistical Correction of Lidar-Derived Digital Elevation Models with Multispectral Airborne Imagery in Tidal Marshes.” *Remote Sensing of Environment* 186: 616–625.

45. Bilskie, M. V., S. C. Hagen, S. C. Medeiros, and D. L. Passeri. 2014. “Dynamics of Sea Level Rise and Coastal Flooding on a Changing Landscape.” *Geophysical Research Letters* 41 (3): 927–934. http://dx.doi.org/10.1002/2013GL058759.

46. Lane, S. N. 2017. “Natural Flood Management.” *WIREs Water* 4 (3): e1211. https://doi.org/10.1002/wat2.1211.

47. In many countries (the United Kingdom being one of them), there are towns and small communities that are at risk of flooding, although there is no, or only limited, engineered flood infrastructure. Increased flood risk is then the direct result of increased discharge.

48. White, G. F. 1945. “Human Adjustment to Floods: A Geographical Approach to the Flood Problem in the United States.” PhD diss., University of Chicago.

49. ASCE (American Society of Civil Engineers). 2013. *2013 Report Card for America’s Infrastructure. Washington, DC*. https://doi.org/10.1061/9780784478837.

50. Blom, A., L. Arkesteijn, V. Chavarrias, and E. Viparelli. 2017. “The Equilibrium Alluvial River under Variable Flow and Its Channel Forming Discharge.” *Journal of Geophysical Research: Earth Surface* 122 (10): 1924–1948. doi:10.1002/2017JF004213.

51. Environment Agency. 2010. *Working with Natural Processes to Manage Flood and Coastal Erosion Risk*. Guidance Document. Bristol, UK: Environment Agency.

    Environment Agency. 2012. *Greater Working with Natural Processes in Flood and Coastal Erosion Risk Management: A Response to Pitt Review Recommendation 27*. Bristol, UK: Environment Agency.

    Environment Agency. 2017. *Working with Natural Processes: Evidence Directory*. Bristol, UK: Environment Agency.

52. Environment Agency. 2017. *Natural Flood Management Toolbox: Guidance for Working with Natural Processes in Flood Management Schemes*. Bristol, UK: Environment Agency.

53. Environment Agency. 2010. *Working with Natural Processes to Manage Flood and Coastal Erosion Risk*. Guidance Document. Bristol, UK: Environment Agency.

    Environment Agency. 2012. *Greater Working with Natural Processes in Flood and Coastal Erosion Risk Management: A Response to Pitt Review Recommendation 27*. Bristol, UK: Environment Agency.

    Environment Agency. 2017. *Working with Natural Processes: Evidence Directory*. Bristol, UK: Environment Agency.

54. Environment Agency. 2017. *Working with Natural Processes: Evidence Directory*. Bristol, UK: Environment Agency.

    Oxford Martin School. 2017. *A Restatement of the Natural Science Evidence Concerning Catchment-Based “Natural” Flood Management in the UK*. Oxford Martin Restatement 4. Oxford: Oxford Martin School, University of Oxford.

    POST (Parliamentary Offices of Science and Technology). 2014. *Catchment-Wide Flood Management*. POST-PN-484. London: POST.

55. gedin.nl. 2013. Rumte voor de Rivier – Deventer [in Dutch]. *Gedin Engineering*. http://gedin.nl/nl/projecten/ruimte-voor-de-rivier-deventer/.

Acknowledgments

Publication Management and Oversight

PARTNER ORGANIZATIONS

U.S. Army Corps of Engineers, National Oceanic and Atmospheric Administration, Environment Agency of the United Kingdom, Rijkswaterstaat, World Bank

Many other organizations also provided critical leadership and participation, including the National Institute of Standards and Technology, The Nature Conservancy, and the World Wildlife Fund.

CONTRIBUTING COUNTRIES

Australia, Canada, the Netherlands, New Zealand, United Kingdom, United States

EDITORIAL BOARD

Todd S. Bridges (Chair), *U.S. Army Corps of Engineers, United States*
Jeffrey K. King, *U.S. Army Corps of Engineers, United States*
Jonathan D. Simm, *HR Wallingford, United Kingdom*
Michael W. Beck, *University of California, Santa Cruz, United States*
Georganna Collins, *Aqua Strategies, Inc., United States*
Quirijn Lodder, *Rijkswaterstaat, the Netherlands*
Ram Mohan, *Anchor QEA, LLC, and Texas A&M University, United States*

PROJECT DIRECTORS

Todd S. Bridges, *U.S. Army Corps of Engineers, United States*
Jeffrey K. King, *U.S. Army Corps of Engineers, United States*
Courtney Chambers, *U.S. Army Corps of Engineers, United States*

Lead Authors and Co-Authors

Chapter 1: The Need and Opportunity for NNBF: An Introduction to the Guidelines

LEAD AUTHORS

Todd S. Bridges, *U.S. Army Corps of Engineers, United States*
Jeffrey K. King, *U.S. Army Corps of Engineers, United States*
Jonathan D. Simm, *HR Wallingford, United Kingdom*

Chapter 2: Principles, Frameworks, and Outcomes

LEAD AUTHORS

Jeffrey K. King, *U.S. Army Corps of Engineers, United States*
Jonathan D. Simm, *HR Wallingford, United Kingdom*

CO-AUTHOR

Todd S. Bridges, *U.S. Army Corps of Engineers, United States*

Chapter 3: Engaging Communities and Stakeholders in Implementing NNBF

LEAD AUTHOR

Maria Dillard, *National Institute of Standards and Technology, United States*

CO-AUTHORS

Cath Brooks, *Environment Agency, United Kingdom*
Helen Fisher, *3KQ, United Kingdom*
Hans Pietersen, *Rijkswaterstaat, the Netherlands*
Alwin Nijhuis, *Rijkswaterstaat, the Netherlands*

Anita van Breda, *World Wildlife Fund, United States*
Susan Durden, *U.S. Army Corps of Engineers, United States*

Chapter 4: Planning and Implementing NNBF Using a Systems Approach

LEAD AUTHORS

Jurre de Vries, *Rijkswaterstaat, the Netherlands*
Denise Reed, *University of New Orleans, United States*

CO-AUTHORS

S. Kyle McKay, *U.S. Army Corps of Engineers, United States*
Tjeerd Bouma, *Royal Netherlands Institute for Sea Research; Utrecht University; HZ University of Applied Sciences, the Netherlands*
Shannon E. Cunniff, *Environmental Defense Fund, United States*
Bart Grasmeijer, *Deltares, the Netherlands*
Pamela Mason, *College of William & Mary, United States*
Alex Nicholson, *Arup, United Kingdom*
Paul Quinn, *Newcastle University, United Kingdom*
Jane McKee Smith, *U.S. Army Corps of Engineers, United States*

Chapter 5: NNBF Performance

LEAD AUTHORS

Candice D. Piercy, *U.S. Army Corps of Engineers, United States*
Jonathan D. Simm, *HR Wallingford, United Kingdom*

CO-AUTHORS

Todd S. Bridges, *U.S. Army Corps of Engineers, United States*
Missaka Hettiarachchi, *World Wildlife Fund, Australia and Sri Lanka*
Quirijn Lodder, *Rijkswaterstaat, the Netherlands*

Chapter 6: Benefits and Costs of NNBF

LEAD AUTHORS

Boris van Zanten, *World Bank, United States*
Katie Arkema, *Stanford University, United States*
Todd Swannack, *U.S. Army Corps of Engineers, United States*

CO-AUTHORS

Rob Griffin, *University of Massachusetts-Dartmouth, United States*
Siddharth Narayan, *East Carolina University, United States*
Kim Penn, *National Oceanic and Atmospheric Administration, United States*
Borja G. Reguero, *University of California, Santa Cruz, United States*
Giselle Samonte, *National Oceanic and Atmospheric Administration, United States*
Steven Scyphers, *Northeastern University, United States*
Elizabeth Codner-Smith, *The Nature Conservancy, United States*
Stéphanie IJff, *Deltares, the Netherlands*
Marin Kress, *U.S. Army Corps of Engineers, United States*
Michele Lemay, *Inter-American Development Bank, United States*

Chapter 7: Adaptive Management

LEAD AUTHORS

Harry de Looff, *Rijkswaterstaat, the Netherlands*
Tim Welp, *U.S. Army Corps of Engineers, United States*

CO-AUTHORS

Natalie Snider, *Environmental Defense Fund, United States*
Rinse Wilmink, *Rijkswaterstaat, the Netherlands*

Chapter 8: Introduction to NNBF in Coastal Systems

LEAD AUTHOR

Jonathan Simm, *HR Wallingford, United Kingdom*

Chapter 9: Beaches and Dunes

LEAD AUTHORS

Quirijn Lodder, *Rijkswaterstaat, the Netherlands*
Claire Jeuken, *Deltares USA Inc., United States*

CO-AUTHORS

Richard Reinen-Hamill, *Tonkin + Taylor, New Zealand*
Oli Burns, *Environment Agency, United Kingdom*
Robert Ramsdell, III, *Dredging Consultant, United States*
Jurre de Vries, *Rijkswaterstaat, the Netherlands*
Brian McFall, *U.S. Army Corps of Engineers, United States*
Stéphanie IJff, *Deltares, the Netherlands*
Corragio Maglio, *U.S. Army Corps of Engineers, United States*
Rinse Wilmink, *Rijkswaterstaat, the Netherlands*

Chapter 10: Coastal Wetlands and Tidal Flats

LEAD AUTHORS

Candice D. Piercy, *U.S. Army Corps of Engineers, United States*
Nigel Pontee, *Jacobs, United Kingdom*

CO-AUTHORS

Siddharth Narayan, *East Carolina University, United States*
Jenny Davis, *National Oceanic and Atmospheric Administration, United States*
Trevor Meckley, *National Oceanic and Atmospheric Administration, United States*

Chapter 11: Islands

LEAD AUTHORS

Joseph Gailani, *U.S. Army Corps of Engineers, United States*
Paula Whitfield, *National Oceanic and Atmospheric Administration, United States*
Enda Murphy, *National Research Council Canada, Canada*

CO-AUTHORS

Jurre de Vries, *Rijkswaterstaat, the Netherlands*
Gordon Thomson, *Baird, United States*
Wendell Mears, *Anchor QEA, LLC, United States*
Danielle Szimanski, *U.S. Army Corps of Engineers, United States*

Chapter 12: Reefs

LEAD AUTHORS

Ryan J. Lowe, *The University of Western Australia, Australia*
Elizabeth McLeod, *The Nature Conservancy, United States*

CO-AUTHORS

Borja G. Reguero, *University of California, Santa Cruz, United States*
Safra Altman, *U.S. Army Corps of Engineers, United States*
Janine Harris, *National Oceanic and Atmospheric Administration, United States*
Boze Hancock, *The Nature Conservancy, United States*
Remment ter Hofstede, *Van Oord, the Netherlands*
Emma Rendle, *Resilient Coasts, United Kingdom*
Elizabeth Shaver, *The Nature Conservancy, United States*
Jane McKee Smith, *U.S. Army Corps of Engineers, United States*

Chapter 13: Plant Systems: Submerged Aquatic Vegetation and Kelp

LEAD AUTHORS

Safra Altman, *U.S. Army Corps of Engineers, United States*
Colette Cairns, *National Oceanic and Atmospheric Administration, United States*

CO-AUTHORS

Paula Whitfield, *National Oceanic and Atmospheric Administration, United States*
Jenny Davis, *National Oceanic and Atmospheric Administration, United States*
Mark Finkbeiner, *National Oceanic and Atmospheric Administration, United States*
Brian McFall, *U.S. Army Corps of Engineers, United States*

Chapter 14: Enhancing Structural Measures for Environmental, Social, and Engineering Benefits

LEAD AUTHORS

Burton C. Suedel, *U.S. Army Corps of Engineers, United States*
Larissa A. Naylor, *University of Glasgow, United Kingdom*

CO-AUTHORS

Trevor Meckley, *National Oceanic and Atmospheric Administration, United States*
Colette Cairns, *National Oceanic and Atmospheric Administration, United States*
Jason Bernier, *CBCL Limited, Canada*
Ed Morgereth, *Biohabitats, United States*
Wendell Mears, *Anchor QEA, LLC, United States*
Candice D. Piercy, *U.S. Army Corps of Engineers, United States*
Remment ter Hofstede, *Van Oord, the Netherlands*

Chapter 15: Introduction to Fluvial Systems: Key Themes, Objectives, Gaps, and Future Directions

LEAD AUTHORS

Christopher Haring, *U.S. Army Corps of Engineers, United States*
Ralph Schielen, *Rijkswaterstaat, the Netherlands*
Jo Guy, *Environment Agency, United Kingdom*
Lydia Burgess-Gamble, *Environment Agency, United Kingdom*

Chapter 16: Fluvial Systems and Flood Risk Management

LEAD AUTHORS

Christopher Haring, *U.S. Army Corps of Engineers, United States*
Ralph Schielen, *Rijkswaterstaat, the Netherlands*
Jo Guy, *Environment Agency, United Kingdom*
Lydia Burgess-Gamble, *Environment Agency, United Kingdom*

CO-AUTHOR

Brian Bledsoe, *University of Georgia, United States*

Chapter 17: Benefits and Challenges in the Application of NNBF in Fluvial Systems

LEAD AUTHORS

Ralph Schielen, *Rijkswaterstaat, the Netherlands*
Christopher Haring, *U.S. Army Corps of Engineers, United States*
Lydia Burgess-Gamble, *Environment Agency, United Kingdom*
Jo Guy, *Environment Agency, United Kingdom*

CO-AUTHORS

Brian Bledsoe, *University of Georgia, United States*
Randy Mandel, *Ramboll, United States*

Chapter 18: Description of Fluvial NNBF

LEAD AUTHORS

Lydia Burgess-Gamble, *Environment Agency, United Kingdom*
Christopher Haring, *U.S. Army Corps of Engineers, United States*
Ralph Schielen, *Rijkswaterstaat, the Netherlands*
Jo Guy, *Environment Agency, United Kingdom*

CO-AUTHORS

David Ramsbottom, *HR Wallingford, United Kingdom*
Bridget Woods Ballard, *HR Wallingford, United Kingdom*
Marta Roca Collell, *HR Wallingford, United Kingdom*
Rachel Glover, *Environment Agency, United Kingdom*
Felix van Zoest, *Rijkswaterstaat, the Netherlands*

Chapter 19: Fluvial NNBF Case Studies

LEAD AUTHORS

Lydia Burgess-Gamble, *Environment Agency, United Kingdom*
Ralph Schielen, *Rijkswaterstaat, the Netherlands*
Christopher Haring, *U.S. Army Corps of Engineers, United States*
Jo Guy, *Environment Agency, United Kingdom*

CO-AUTHORS

Rachel Glover, *Environment Agency, United Kingdom*
Randy Mandel, *Ramboll, United States*
Bridget Woods Ballard, *HR Wallingford, United Kingdom*
Marta Roca Collell, *HR Wallingford, United Kingdom*

Chapter 20: The Way Forward

LEAD AUTHOR

Todd S. Bridges, *U.S. Army Corps of Engineers, United States*

CO-AUTHORS

Jeffrey K. King, *U.S. Army Corps of Engineers, United States*
Jonathan D. Simm, *HR Wallingford, United Kingdom*

Technical Review and Production

All individuals listed below are part of Anchor QEA.

PRODUCTION MANAGERS

Ram Mohan *(Project Director)*
Zelini Hubbard *(Technical Review and Document Manager)*

PRODUCTION TEAM

Toni Salvador *(Editorial Lead)*
Zheng Fang *(Graphics Lead)*

TECHNICAL EDITORS

Katie Atkins
Hannah Garrison
Liz Hanbury
Ken Mayo
Megan Russo

TECHNICAL SUPPORT

Steven Bagnull
Billie-Jo Gauley
Dan Opdyke
Travis Merritts

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
09-15-2021

2. REPORT TYPE
SR

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Overview: International Guidelines on Natural and Nature-Based Features for Flood Risk Management

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Todd S. Bridges, Jeffrey K. King, Jonathan D. Simm, Michael W. Beck, Georganna Collins, Quirijn Lodder, and Ram K. Mohan, eds.

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Engineer Research and Development Center
3909 Halls Ferry Road
Vicksburg, Mississippi 39180-6199

8. PERFORMING ORGANIZATION REPORT NUMBER
ERDC SR-21-5

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Headquarters, U.S. Army Corps of Engineers
441 G Street Northwest
Washington, District of Columbia 20314-1000

10. SPONSOR/MONITOR'S ACRONYM(S)
USACE

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

Initially funded from the Dredging Operations Environmental Research Program (DOER), now out of the Engineering With Nature Program (EWN).

Project title "Developing Engineering Guidance for Natural and Nature-Based Features"

Project No. 16-12

14. ABSTRACT
This overview of the International Guidelines on Natural and Natured-Based Features for Flood Risk Management (NNBF Guidelines) provides a high-level review of each chapter of the guidance and outlines key principles, key messages, and data gaps requiring further study. It is meant to provide a quick read and, therefore, omits details that are found in the full document. The NNBF Guidelines is the product of a large-scale collaboration that included 5 years of working-level meetings and knowledge sharing involving key practice leaders from around the world. The project was initiated and led by the U.S. Army Corps of Engineers (USACE) as a part of its Engineering With Natures (EWN) Initiative. USACE in the United States, the Rijkswaterstaat Ministry of Infrastructure and Water Management in the Netherlands, and the Environment Agency in the United Kingdom were the three primary government institutions that organized and led the effort. Many other organizations also provided critical leadership and participation, including the National Oceanic and Atmospheric Administration, World Bank, National Institute of Standards and Technology, The Nature Conservancy, and the World Wildlife Fund.

15. SUBJECT TERMS
Environmental engineering, Flood risk management

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER *(include area code)*
Unclassified	Unclassified	Unclassified	None	159	