COMMISSION FOR ENVIRONMENTAL COOPERATION

Nature-based Solutions to Address Flood Risks in Coastal Communities

Monitoring Efficacy: Proposed Methodology and Indicators

Report Series:

Co-Benefits

Monitoring Efficacy

Retrofitting Existing Infrastructure

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List of Abbreviations and Acronyms

ADCP	Acoustic Doppler Current Profiler
BACI	Before-after Control-impact
CABIN	Canadian Aquatic Biomonitoring Network
CBWES	CB Wetlands and Environmental Specialists
CEC	Commission for Environmental Cooperation
CH_4	Methane
CO_2	Carbon Dioxide
CTD	Conductivity, Temperature, Depth Sensor
DEM	Digital Elevation Model
DHI	DHI Water and Environment Inc.
FAIR	Findable, Accessible, Interoperable, and Reusable
FrM	Flood Risk Management
GIS	Geographic Information Systems
HWL	High Water Line
IUCN	International Union for Conservation of Nature
NBS	Nature-based Solutions
NO_2	Nitrogen Dioxide
NGO	Nongovernmental Organization
O_2	Oxygen
pH	Potential Hydrogen
RCA	Reference Condition Approach
RTK GPS	Real-time Kinematic Global Positioning System
SMART	Specific, Measurable, Attributable, Realistic, Timely – Time-bound
SSS	Sidescan sonar
UNAM	National Autonomous University of Mexico *(Universidad Nacional Autónoma de México*)
YSI	Yellow Springs Instruments

Abstract

Flood-risk management is a major concern for coastal urban and peri-urban areas, particularly when considering sea-level rise caused by climate change. Nature-based solutions (NBS) have the potential to meet many flood-risk management objectives, while also providing social, environmental, and economic co-benefits. However, the uptake and implementation of NBS are limited by perceived uncertainty surrounding their efficacy. Monitoring NBS to demonstrate successes and lessons learned is one of the available tools for decision makers to manage and alleviate uncertainties associated with NBS.

This document supports the uptake of NBS in coastal communities across Canada, Mexico and the United States, by providing decision makers with practical information and guidance related to monitoring NBS. This document includes best practices for monitoring program design and considerations for the selection of performance metrics, performance indicators, and monitoring methodologies. It also provides guidance related to specific NBS types and ecosystems, and case studies illustrating how monitoring programs have been implemented in Canada, Mexico and the United States. Opportunities for future work are also identified.

Executive Summary

Monitoring is a crucial component of all flood-risk management (FrM) projects, including nature-based solution (NBS) projects. This report reviews methodologies and specific techniques used to develop monitoring programs for coastal NBS projects. Monitoring is essential to determine whether a project is meeting its performance goals and to inform adaptive management. The recommendations described herein are based on a comprehensive international literature review and on results from expert workshops organized as part of this project.

<u>Monitoring Stages</u>
In general, monitoring needs to be considered as a continuous process that begins prior to the implementation of NBS projects and tracks how well they perform against expected results and/or specified performance criteria. The key phases of monitoring programs typically include:

- <u>Scoping</u>: Identify scale and scope of the monitoring and adaptive management plan, prioritize actions, define rightsholders and stakeholders, and develop funding strategies. Early and meaningful engagement should begin during this phase.
- <u>Planning</u>: Identify parameters of concern, establish performance metrics, make inventory of existing monitoring networks, identify data gaps, and identify potential resources and staff to conduct the monitoring program.
- <u>Design</u>: Develop a monitoring program that includes baseline monitoring before the project is implemented, determine the frequency of monitoring suitable for each performance metric and identify appropriate methodologies, establish data collection and data management protocols.
- <u>Implementation</u>: Conduct monitoring program(s), adapting as needed if ground conditions require.
- <u>Reporting</u>: Review, analyze and report data, communicate findings with the project team (including contractor during construction and operation phases) and inform other stakeholders.
- <u>Evaluation</u>: Using monitoring results, evaluate the NBS performance, propose modifications to the NBS (adaptive management) when required, and reassess and adapt the monitoring program based on learned information.

A monitoring program should be designed during the scoping phase of the project, such that the overall feasibility of the program can be evaluated, the design can be informed by evidence from the early monitoring, and baseline conditions can be established for later comparisons. Monitoring activities should continue to occur throughout the project life, and include the collection of historical, baseline, compliance, and operational data. Additionally, monitoring is recommended following major events (e.g., post storm) to examine the resilience of the NBS project to disturbance events.

The collection of operational data is of particular importance for adaptive management of NBS to ensure both that FrM performance goals have been met and co-benefits have been realized. Adaptive management is central to the long-term success of NBS and allows for continuous improvement of the NBS project as a whole and of the monitoring program itself. Monitoring is foundational to providing data needed to assess NBS performance, identify thresholds, and determine if/when interventions are needed. In addition, long-term operational monitoring provides data and knowledge for future projects.

General Monitoring Approach

Monitoring programs generally follow BACI (before/after, control/impact) or RCA (reference condition approach) methodologies. These involve one or more sites that function as references, allowing key performance indicators for the NBS project to be directly compared with the same set of performance indicators from the reference site(s).

Fundamental objectives, performance metrics, and, performance indicators, all play an important role in the monitoring programs, and—for the purpose of this report—are defined as follows:

- **Fundamental objectives** are what the project is trying to achieve at its most basic level.
- **Performance metrics** are actionable targets which are specific to the site and the challenges that are present at the site.
- **Performance indicators** are measurable or otherwise observable elements of the NBS project that indicate the advancement of the system towards the project goals and objectives.

Performance indicators should be selected to achieve project-specific objectives and performance metrics. In general, they should:

- Be scientifically sound and SMART (specific, measurable, attributable, realistic, and timely or time-bound);
- Be practical and straightforward but fulfill technical requirements;
- Be conducted at an appropriate scale (spatial and temporal) that considers the variability of the indicator to be measured, regional characteristics, changing climate and urban morphology;
- Be conducted at an appropriate scale (spatial and temporal) that aligns with different decision-making contexts, policy principles, and reporting obligations;
- Clearly state and use reference conditions and baseline assessments;
- Facilitate rapid assessment of trajectories and adaptive management;
- Be based on a transdisciplinary approach; and
- Use common/standard indicators (where possible) to compare NBS efficacy between sites and ensure that results are transferable and scalable.

Performance Metrics, Indicators, & Monitoring Techniques

Both performance metrics and indicators are divided into the following categories: flood-risk management (FrM), environmental, social, and economic. **Core performance metrics are summarized below**. Additional—or optional—performance metrics may be necessary to include in monitoring programs on a project-specific basis.

- Flood-risk Management (FrM)
  - Reduced flood hazard area for a given event,
  - Reduced flood hazard exposure for a given event,
  - Reduced wave effects for target areas,
  - Maintain stability of structural components, and
  - Improved resilience of infrastructure or contingencies for failure.
- Environmental
  - Restoration of a more natural hydrological regime,
  - Improved ecosystem resilience,
  - Increased or maintained critical habitat features and connectivity within a site,
  - Increased biodiversity and habitat usage (flora and fauna), and
  - Carbon sequestration.
- Social
  - Improved security and peace of mind,
  - Connectivity to green space and natural systems,
  - Improved aesthetics,
  - Increased community engagement and environmental stewardship,
  - Favorable public perception,
  - Provides cultural, religious, or spiritual amenity,
  - Poverty reduction,
  - Participation and stewardship by Indigenous peoples or marginalized groups,
  - Equity and inclusion, and
  - Provides additional climate adaptation and mitigation benefits.
- Economic
  - Reduced capital costs,
  - Reduced maintenance and operational costs,
  - Reduced flooding impacts to communities,
  - Improved fisheries, agricultural or artisanal livelihoods, and
  - Local job opportunities (e.g., tourism).

Lists of additional—or optional—performance metrics that may be appropriate for certain projects, but are not considered core metrics, are provided for each category and discussed in detail within the report.

Case studies of specific NBS are provided to illustrate how various monitoring methodologies and metrics are included and adjusted according to project-specific contexts.

Selection of performance indicators will depend on project-specific set of metrics, as well as the NBS type, climate, monitoring program design, project goals, access to expertise and equipment, and budgetary constraints. Many performance indicators have multiple potential suitable monitoring methodologies. Potential trade-offs in cost, accuracy, or intensity and area are discussed.

<u>Special Considerations for Ecosystems and NBS Type</u>

The ecosystems in which NBS are located—or which they form an integral part of—play an important role in the selection of performance indicators and associated monitoring techniques. This document outlines considerations which should be incorporated when developing monitoring plans for a range of ecosystems and NBS types. Special considerations are broadly grouped into: Beaches and Dunes, Wetlands and Tidal Flats, Islands, Coastal Forests and Woody Areas, Submerged Features, and Hybrid features.

Data Analysis, Access, and Dissemination

In order to promote NBS and extend the benefits of these projects, reporting and information sharing are crucial components of any monitoring program. Data analysis methods should be documented and easily reproducible. Where possible, data processing files and methods should be published. Data should be made publicly available (where possible) and re-useable. Metadata (including details on measurement and analysis methodologies) must be included with all data to ensure future useability. Reporting needs to include key standardized elements, such a clear outline of project goals and timelines, site descriptions including relevant historical context, description of all methodologies, protocols and analyses, results, discussion of lessons learned and metadata. Refer to the *Monitoring Efficacy* report for additional recommendations and best practices on data analysis, access, and dissemination.

Because monitoring programs result in data that may be of interest to numerous individuals and groups (beyond the direct project team), data management needs to be carried out such that datasets are easily accessible, usable, and interpretable by others. Fortunately, there are established protocols for data archiving and sharing that can be adopted by NBS proponents, such as the FAIR approach (Findable, Accessible, Interoperable, and Reusable) (Wilkinson et al., 2016).

Opportunities and Future Directions

As more scientific evidence accumulates documenting the successes of NBS, these types of solutions are more likely to be adopted for FrM. However, scientists and engineers designing and assessing NBS need to engage in public outreach to make their findings accessible and understandable to the broader public. This could be achieved, for example, by engaging with communities via social media, preparing policy briefs or other plain-language summaries of research, and working with community scientists on monitoring programs.

Involvement of local residents in NBS monitoring is also an excellent way to promote public buy-in for NBS, spread awareness of the benefits of NBS projects, foster a sense of ownership and connection, and build local capacity for monitoring. Many of the key indicators listed above may be monitored using straightforward techniques that can have widespread and inexpensive application with minimal training. There are increasing opportunities for community members to get involved by contributing records to open-source natural history observation platforms such as iNaturalist, eBird, or CoastSnap. NBS project proponents could explicitly incorporate these tools into monitoring programs as a way to engender greater engagement.

Technological developments such as sensor networks and remotely piloted aircraft systems (drones) are also putting some monitoring techniques within reach of community groups. However, some key indicators for NBS monitoring are still difficult to implement without expensive equipment or involvement of trained professionals and subject matter experts. In such cases, linking experts and community members could help increase community involvement in effective monitoring.

Finally, while many appropriate monitoring protocols exist for a range of NBS situations, cost can limit implementation, especially for community groups. More research is required to develop inexpensive and accessible monitoring solutions for many indicators that currently require substantial technical expertise and expenses to access. In addition, there is a need for governments to shift from capital-intensive funding models (e.g., limited to design or construction, with minimal post-implementation monitoring) to longer-term project funding models that include life-cycle operations and adaptive management.

Preface

The Commission for Environmental Cooperation (CEC) is a trilateral organization that facilitates cooperation between Canada, Mexico and the United States to conserve, protect and enhance the North American environment. In 2021, the CEC initiated a project to help guide the broader implementation of nature-based solutions (NBS) for coastal flood-risk management (FrM) in North American communities. The initiative may be broadly partitioned into three phases, as follows:

1. **An intersectoral workshop series** to lay the foundation for a North American community of practice, convene practitioners to scope needs and opportunities, and identify barriers to implementation of NBS.
2. **A set of guidance documents** to address knowledge gaps and further develop opportunities identified during the workshop series, and guide best practices related to implementing NBS.
3. **Webinars** to improve the uptake and usage of the guidance documents.

As part of the first phase of the project, DHI Water and Environment Inc. (DHI) was engaged to develop and host the workshop series. The workshop series consisted of seven sessions held over a five-week period in May and June, 2022. The sessions were focused on the following topics:

- 1A and 1B: Nature-based Solutions Co-Benefits;
- 2A and 2B: Retrofitting Existing Infrastructure Using Nature-based Solutions;
- 3A and 3B: Monitoring Efficacy of Nature-based Solutions; and
- 4: Summary Workshop.

The workshop series saw the participation of 95 specialists, spanning a range of academia, private industry, government, and nongovernmental organizations (NGOs) from across North America. Group activities were included in the workshop series to build community, develop ideas, solicit feedback, and identify gaps and opportunities. Group activities included discussing ideas and concepts for six different case studies, four sets of collaborative online activities, and two interactive question series. The participation and idea development from participants with diverse backgrounds and experiences provided a strong foundation for building both a community of practice and guidance documents on NBS in North America.

The second phase of the project involved addressing knowledge gaps identified in the workshop series through the development and publication of a comprehensive set of guidance documents on NBS within an urban and peri-urban North American context. This document forms part of a series of guidance documents, that are intended to be referenced as a whole. The guidance documents include:

- Co-Benefits;
- Retrofitting Existing Infrastructure;
- Monitoring Efficacy; and
- Monitoring Efficacy: Proposed Methodology and Indicators (this document).

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1 Introduction to the Proposed Methodology

Coastal communities in low-lying areas are increasingly exposed to coastal flood hazards, particularly in consideration of increasing population densities and the effects of climate change (Bush and Lemmen, 2019; EPA, 2017; INECC, 2019). Storms and associated flooding, and erosion can cause significant economic, social, and ecological impacts (IPCC, 2022; Moudrak et al., 2018). Areas across Canada, Mexico, and the United States are subject to vastly different storm types—including extratropical storms, cold fronts, and tropical cyclones—which are capable of causing consequential coastal flooding. For instance, Hurricane Delta made landfall near Puerto Morelos, Mexico on October 7th, 2020, which left one-third of the population without power. Hurricane Delta is estimated to have caused around US$185 million in damages in Mexico (NOAA, 2020). More recently, in October 2023, Hurricane Otis made landfall in southern Mexico, causing immense damage and at least 27 deaths (Williams, 2023). In September 2022, Typhoon Merbok and two major hurricanes, Fiona and Ian, also caused some of the most consequential damages in the United States and Canada in recent history, impacts from which included loss of life. Typhoon Merbok struck the west coast of Alaska on September 17, 2022, with devastating floods, extensive infrastructure loss, and an interruption to the hunting season, which is essential to the livelihoods of Indigenous communities (Thoman, 2022). Hurricane Fiona made landfall on September 24, 2022, in Atlantic Canada, causing C$800 million dollars in insured damages and drastically altered coastlines and damaged infrastructure (IBC, 2023). Port aux Basques in Newfoundland and Labrador was devastated, with homes, livelihoods, and residents washed out to sea (CBC, 2022). Hurricane Ian made landfall in Florida, United States, only four days later, forcing the evacuation of 2.5 million Floridians and killing 89 people (Livingston, 2022).

Flood-risk management (FrM) is critical to protect urban and rural areas in Canada, Mexico, and the United States from flooding and erosion. In many regions of North America, FrM has historically relied heavily on gray infrastructure such as dikes, levees, and seawalls, which have failed catastrophically in some circumstances (e.g., levee failure during Hurricane Katrina, New Orleans, 2005) or have had unintended negative socio-economic or environmental impacts (Bridges et al., 2021). For example, protective infrastructure (e.g., seawalls) can have negative impacts for coastal biodiversity and can increase erosion in adjacent areas without protection. In contrast, nature-based solutions (NBS) are increasingly being recognized internationally as providing protective functions while also providing additional environmental, social, and economic co-benefits if appropriately designed and matched to local environmental conditions (Bridges et al., 2021; IUCN, 2020; Shiao et al., 2020). However, evidence of the delivery of these multiple co-benefits and the effectiveness of NBS in providing protective functions is limited compared to conventional engineering infrastructure (Kumar et al., 2021; Dumitru et al., 2021), leading to perceived uncertainties and barriers in their adoption (Kumar et al., 2021; Bridges et al., 2021). These barriers are discussed in more detail in the accompanying *Monitoring Efficacy* report. Effective adaptive management and monitoring are key to alleviating these uncertainties.

Adaptive management is a structured and iterative approach, which enables users to continuously adjust and revise management measures (such as maintenance activities) to reflect changing conditions (including changing conditions due to climate change) and variable project performance (Bridges et al., 2021). Adaptive management is an integral and cross-cutting theme for the implementation of NBS (Bridges et al., 2021; Silva Zuniga et al., 2020; World Bank, 2017). Regular, long-term monitoring forms the foundation for effective adaptive management and future implementation of NBS.

Monitoring is a continuous process that tracks both the implementation process (i.e., what takes place and when within the project cycle) and how well the NBS performs against expected results or performance criteria (Skodra et al., 2021). Performance is defined as the degree to which "NBS address an identified challenge and/or fulfill a specified objective in a specific place, time and socio-economic context" (Raymond et al., 2017 in Skodra et al., 2021, 49). It can assess changes in relation or comparison to baseline or reference conditions and/or changes towards certain targets or thresholds. Monitoring is a critical source of information about the effectiveness of any FrM project, including NBS. Monitoring provides the evidence base for existing and future NBS projects.

This document aims to support the uptake of NBS in coastal communities by providing decision makers with practical information and guidance related to monitoring the efficacy and impacts of NBS and by addressing several previously identified data gaps and barriers. This document, which was prepared by TransCoastal Adaptations Centre for Nature-based Solutions at Saint Mary's University and CB Wetlands and Environmental Specialists (CBWES), forms part of a series developed by DHI Water and Environment Inc. (DHI) on behalf of the Commission for Environmental Cooperation (CEC), which are intended to be referenced as a whole, and are outlined as follows:

- Co-Benefits;
- Monitoring Efficacy;
- Retrofitting Existing Infrastructure; and
- Monitoring Efficacy: Proposed Methodology and Indicators (this document)

This document differs from the *Monitoring Efficacy* report by providing more detailed approaches and methodologies for monitoring NBS.

1.1 Objectives and Scope

An intersectoral workshop series was hosted by DHI in spring, 2022 as part of a CEC project to support the broader implementation of NBS for coastal flood-risk management in North American communities (DHI, 2022). The workshop series consisted of seven sessions, with 95 specialists from Canada, Mexico, and the United States. Two of the sessions focused specifically on monitoring the efficacy of NBS. During these sessions, attendees participated in idea generation and identification of data gaps, barriers, and opportunities related to monitoring NBS.

This document addresses knowledge gaps identified in the workshop series, synthesizes existing information, and provides practical guidance to plan, evaluate, and implement meaningful monitoring programs associated with NBS used to address flood risks in coastal communities. It is part of a comprehensive set of guidance documents, which are intended to support decision makers in implementing NBS for coastal flood-risk management across North America.

More specifically, this document aims to:

- Summarize guiding principles and goals of monitoring;
- Provide best practices for monitoring program design;
- Establish core and additional (or optional) performance indicators for monitoring, drawing upon existing international references;
- Summarize specific considerations for various types of NBS and ecosystems;
- Summarize key considerations related to monitoring data analysis, access, and dissemination;
- Summarize key technical considerations for monitoring plans, including indicators, methods, varying physical environments, and time and spatial scales;
- Provide case studies related to the design and implementation of monitoring plans and how they aid in assessing the efficacy, performance, and resilience of NBS; and

- Where possible, address gaps and barriers identified during the previous intersectoral workshop series.

This document is intended to provide guidance and evidence to support decision makers in the commissioning and monitoring of NBS to address coastal flood risks in coastal communities. The guidance provided herein is intended to assist decision makers in all stages of the project process, from conceptualization through design and operation. The document does not provide in-depth technical guidance, nor does it provide an exhaustive review of the rapidly growing body of literature on monitoring methodology and NBS.

1.2 Guiding Principles

Monitoring seeks to inform whether a project is effective or not, and to what degree. Effectiveness (or efficacy) can be defined as "the degree to which objectives are achieved and the extent to which targeted problems are solved. In contrast to efficiency, effectiveness is determined without reference to costs" (Raymond et al., 2017, 6).

The document *Evaluating the impact of nature-based solutions: a handbook for practitioners* (Dumitru & Wendling, 2021) outlines three core elements of well-designed performance and impact evaluations for NBS based on extensive analysis of case studies in Europe. These core elements include that:

1. The impact evaluation addresses a concrete assessment question;
2. A robust methodology is developed that balances an understanding of the complexity and diversity of NBS outcomes, including trade-offs, with feasibility in relation to available resources and the specific socio-economic context; and
3. A transdisciplinary and multisectoral evaluation team is assembled depending on the types of NBS and outcomes of interest.

A key component of NBS is their ability to provide social, environmental, and economic co-benefits in addition to FrM benefits. It is therefore fundamental that monitoring protocols include performance indicators spanning all four interconnected benefit categories. It is also important to consider the synergies and trade-offs between different categories of impacts of NBS. Given the data gaps related to long-term effects of NBS, monitoring programs should also be as long as possible and include disservices (e.g., reduced sediment supply to downdrift shorelines) in the evaluation of NBS (Dumitru et al., 2020). Additional details can be found in Chapter 2 of the European Commission, Directorate-General for Research and Innovation, 2021 report: *Evaluating the impact of nature-based solutions: a handbook for practitioners* (Dumitru & Wendling, 2021).

Furthermore, there are a number of guiding principles that should be considered when developing and implementing a NBS monitoring plan (Skodra et al., 2021). Plans and indicators should follow these principles:

- Be scientifically sound and **SMART** (specific, measurable, attributable, realistic, and timely or time-bound);
- Be **practical** and straightforward but fulfill technical requirements;
- Be conducted at an **appropriate scale** (spatial and temporal) that considers the variability of the indicator to be measured, regional characteristics, changing climate and urban morphology;
- Be conducted at an appropriate scale (spatial and temporal) that **aligns** with different decision-making contexts, policy principles and **reporting obligations**;
- Clearly state and use **reference conditions** and **baseline** assessments;

- Facilitate rapid assessment of trajectories and adaptive management;
- Be based on a **transdisciplinary** approach; and
- Use c**ommon/standard** indicators (where possible) to facilitate comparison between sites and ensure that the results are **transferable** and **scalable**.

1.3 Key Definitions

Fundamental objectives, performance metrics, and performance indicators all play an important role in the monitoring programs. For this document, we will use the following definitions:

- ***Fundamental objectives*** are what the project is trying to achieve at its most basic level (e.g., reduce storm hazard impacts)
- ***Performance metrics*** are actionable targets which are specific to the site and the challenges that are present at the site (e.g., reduced flood hazard of a given event).
- ***Performance indicators*** are measurable or otherwise observable elements of the NBS project that indicate the advancement of the system towards the project goals and objectives (e.g., maximum flood extent or area).

1.4 Further Reading

Numerous guidance documents were reviewed and referenced in preparing this report. These documents – as well as the CEC's workshop series on NBS – served as the foundation for development of guidance, processes, and considerations outlined in this synthesis report. Key guidance documents are listed below and may provide the reader with further information and technical guidance. Additional key references specific to particular coastal environments are provided within Section 4 of this document.

- *Evaluating the Impact of Nature-Based Solutions - A Handbook for Practitioners,* European Commission (Dumitru & Wendling, 2021)
- *Increasing Infrastructure Resilience with Nature-based Solutions (NBS): A 12-Step Technical Guidance Document for Project Developers,* Inter-American Development Bank (IDB) (Silva Zuniga, 2020)
- *International Guidelines on Natural and Nature-based Features for Flood Risk Management,* United States Army Corps of Engineers (Bridges et al., 2021)
- *Nature-Based Solutions for Coastal and Riverine Flood and Erosion Risk Management,* Canadian Standards Association and National Research Council of Canada (Vouk et al., 2021)
- *An overview of monitoring methods for assessing the performance of nature-based solutions against natural hazards* (Kumar et al., 2021)
- *Introducing Indicators: A First Look At Using Indicators To Measure Adaptation Progress*, ICLEI Local Governments for Sustainability (ICLEI, 2022)

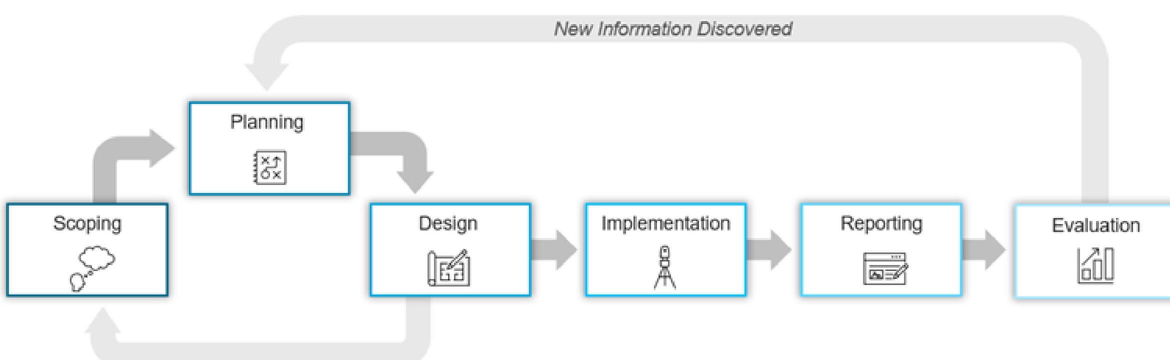
2 Proposed Monitoring Methodology

2.1 Monitoring Process

As stated in the *Monitoring Efficacy* report, NBS projects typically have five main phases: 1) scoping, 2) planning, 3) design, 4) implementation and 5) operations. These five phases are part of a cycle, and continuous reassessment and updates to the plan are required during the project development. Similarly, there are six overarching phases for monitoring, which are shown in Figure 1 and described below (De Looff et al., 2021). As with the NBS cycle, the monitoring process is iterative in nature.

- Scoping: Identify scale and scope of the monitoring and adaptive management plan, prioritize actions, define rightsholders and stakeholders, and develop funding strategies. Early and meaningful engagement should begin at this phase.
- Planning: Identify parameters of concern, establish performance metrics, make inventory of existing monitoring networks, identify data gaps, and identify potential resources and staff to conduct the monitoring program.
- Design: Develop a monitoring program that includes baseline monitoring prior to project implementation, determine the frequency of monitoring suitable for each performance metric and identify appropriate methodologies, establish data collection and data management protocols.
- Implementation: Conduct monitoring program(s), adapting as needed if ground conditions require.
- Reporting: Review, analyze and report data, communicate findings with the project team (including contractor during construction and operation phases) and inform other stakeholders.
- Evaluation: Using monitoring results, evaluate the NBS performance, propose modifications to the NBS (adaptive management) when required, and reassess and adapt the monitoring program based on learned information.

Figure 1. Monitoring Framework



While monitoring is often included only as part of the operation phase for FrM projects (often for determining compliance), for NBS projects it is crucial that monitoring begins early in the project, starting in the scoping and planning stages (prior to the implementation stage), and continues through to longer term monitoring. Integrating the full monitoring program design early in the project lifecycle ensures that sufficient budget and resources are allocated to monitoring and adaptive management activities, and the development of common definitions and working language. Further, baseline data is critical in determining project feasibility and informs which NBS method would be most appropriate for a particular site. Early monitoring will impact what is designed and how, which likewise influences planning (such as when each phase should be implemented), and how the project is implemented. Without this early knowledge, the overall success of the project may be jeopardized. This can be particularly crucial when a NBS project involves complexities such as endangered species habitat which requires sensitivity when working around certain life stages (e.g., nesting season). Consistency between baseline and post-construction data from a temporal, spatial and methodology standpoint is essential to evaluate project efficacy as well as to understand how climate change may shift baseline conditions. Therefore, for the greatest scientific rigor and to obtain the most useful information, baseline monitoring should be started on both the project and the reference sites prior to implementation.

The complete integration of monitoring throughout the project life cycle is also important to inform adaptive management. Adaptive management has been defined as "learning by doing" (Thom, 2000, PWA and Faber, 2004), and it is fundamental in the management of NBS to reduce the uncertainties in project design, to increase project flexibility and allow projects to evolve over time in response to changing environmental conditions (de Looff et al., 2021), and to correct unanticipated and/or undesirable developments (Thom 1997). As such, if it is determined that a project's performance has deviated from the acceptable range (a range which is determined on a case-by-case basis and compared to the respective reference site), adaptive management ensures that a plan is in place to adjust to a more acceptable trajectory. To effectively apply adaptive management, the monitoring requires (Thom, 2000):

1. Measuring the conditions of the system using selected indicators,
2. Assessing progress towards goals and performance indicators, and
3. Deciding on actions to take.

Appropriate actions that may be taken include doing nothing, taking corrective action, or changing the goal(s) (Thom, 2000). A more detailed discussion of adaptive management is included in the *Monitoring Efficacy* report.

2.2 Systems Thinking in Monitoring

When designing the monitoring program (as well as the adaptive management plan), it is key to consider the role of the site within the overall system holistically in context with the overall goals of a project. Coastal areas are at the interface between terrestrial and aquatic systems. They are highly dynamic. They are also generally socially, culturally, economically, and biologically important areas. As such, coastal systems are inherently complex and interconnected. It is important not only to consider the feedback loops within a system, but also those adjacent to the system. For example, when using managed dike realignment to restore a tidal wetland, it is crucial to understand the underlying physical processes which create and sustain the desired wetland functions. If a managed dike realignment project is within an estuarine system, the potential impacts from and to upstream areas need to be considered (e.g., is there critical infrastructure that could be impacted by the addition of a more natural hydrology, or conversely, are there potential upstream factors such as the decommissioning of a dam that may result in a higher freshwater input). The monitoring program, and the application of adaptive management, for such a project will therefore need to prioritize monitoring those wetland functions and the structures of interest or concern, as well as the freshwater input.

Importantly, this holistic approach does not just apply ecologically, it also applies socially and culturally. How humans use the project area, and what is socially and culturally important, may also significantly change the design, monitoring, and application of adaptive management. For example, if a project is tackling the degradation of a dune system, it is critical to consider how and why people use the dunes (foot traffic versus all-terrain vehicles, etc.). If the area is an important recreational area for the local community, potentially driving tourism and economic activity in the area, then it may be unrealistic to attempt to completely restrict the public's access to the area. Because dunes are particularly sensitive to human usage, an ecologically well-designed dune restoration project may be derailed if human usage is not appropriately accounted for. Instead of completely restricting access, it may be necessary to include public education (e.g., signs), as well as structures to contain or direct human usage (such as boardwalks, fences, etc.) in the project's design, budget, and goals. These considerations will also influence what is monitored (e.g., human usage will need to be monitored, as well as the integrity of the boardwalks) and how adaptative management is applied (e.g., it may also require a public outreach component).

By approaching projects holistically and using that lens to determine what to monitor and how to apply adaptive management, it also provides the opportunity for the site to naturally evolve; this results in more optimal environmental conditions, while optimizing resources required for design, implementation, and maintenance phases of the project. It is important to remember that the goal of adaptive management is not to replicate a historical system, but rather to allow the landscape to evolve naturally in balance and in step with present and future ecological conditions.

2.3 General Methodology

As stated in Section 2.1, monitoring should be incorporated throughout the entire NBS project cycle, and can include historical, baseline, compliance and operational (long-term) monitoring. When designing and choosing performance indicators for the monitoring program, the choice will be "project-specific, and will be influenced by project objectives, scale, associated risk, degree of innovation, budget, policy directives, and logistical factors" (DHI, 2024a). The design of the monitoring program and selection of performance indicators for the monitoring program should be carried out as early as possible in the project lifecycle, during the scoping and planning phases. While the performance indicators (see Section 3) may vary from project to project (with the exception of core indicators), the underlying causes of the ecosystem degradation/stressors need to be identified and addressed for the successful implementation of all NBS projects. To meet these needs and basic scientific standards, we recommend following one of these two general monitoring approaches:

- Before-After Control-Impact (BACI)
- Reference Condition Approach (RCA)

2.3.1 The BACI Approach

The BACI approach is useful when the treatment and control sites cannot be assigned randomly, which is predominately the case in NBS projects. In many NBS projects, the treatment location is often selected in response to an area of human interest/concern (such as eroding shorelines, or important infrastructure at risk from climate change caused impacts or the site is restrained by access requirements and land ownership). The BACI approach evaluates the impacts of natural or human-induced disruptions on an ecosystem while allowing for a statistically powerful experimental design (Conner et al., 2016; Smokorowski and Randall, 2017). The BACI approach is highly effective in isolating the impacts of the project/treatment from natural variability, making it one of the most favorable models for environmental effects monitoring programs. (Smokorowski and Randall, 2017). This is because BACI methodology is made up of two parts: (1) Before-After and (2) Control-Impact.

The Before-After sampling provides information on how the NBS process has changed temporally from its historical condition. It involves gathering baseline monitoring data before the "implementation stage" of a NBS project, to determine what the conditions are *before* the implementation of the NBS, and then *after* the NBS has been implemented to determine how the system has changed when compared to the baseline conditions.

The Control-Impact sampling requires a reference site or area (i.e., control site/area), which is then compared to the impacted site or area. This allows for the effects of the impact to be discerned from underlying environmental trends (such as sea-level rise or ocean acidification), natural variability, and stochastic processes. To ensure the most accurate results for the data analysis, it is ideal if monitoring for both the impact site and the control site begins at the same time prior to the implementation of NBS and continues for the same duration post-implementation, as well as be sampled at the same frequency, using the same methodologies, within the same timeframes. For example, if sampling for baseline monitoring at the impact site is from the years, 2022 to, 2028, sampling at the control site should also be from, 2022 to, 2028. If baseline samples were taken on September 3, then control samples should ideally also be taken on September 3 or as close as possible to that date. Ideally, monitoring each consecutive year would also take place on September 3. However, if pre-existing data is available from the control site it may be possible to use this data to define the initial condition for the control, thereby saving money and time by not sampling in the same starting year as the impact site. Likewise, it may be acceptable to sample less frequently at the control site for time and economic efficiency (e.g., every other year, while the impact site is still monitored every year). These options require scrutiny of the available data and knowledge of the inherent variability of the control system. If the scope of the project allows (or funding, manpower, environment, etc.), the addition of more control sites increases confidence in the ability to determine causation of the impact (i.e., the more control sites, the better the trends can be interpreted from the data). Case studies 2 and 3 feature monitoring programs that use BACI designs.

There are various ways to statistically analyze the data, which is project dependent, however all involve some manner of analysis of variance. Basic statistical analyses are outlined by Green (1979) and Hurlbert (1984). There is a growing body of work that supports using additional statistical testing, with the precise methodology dependent upon available data and preferences for how the data are presented (Conner et al., 2016; Stewart-Oaten et al. 1986, Underwood 1991). Additional considerations for data analysis, access, and dissemination are discussed in Section 5.

2.3.2 The RCA Approach

The RCA is a similar concept to the CI part of BACI, which is primarily focused on biological assessment; however, the concepts may also be extended to include other environmental, social, economic, or FrM indicators. The approach recognizes the diversity in biota and environmental features by defining the "reference condition" based on multiple sites that are known to exhibit varying expressions of good condition. This reference condition (defined by many sites) is then compared to the impacted site. The extent and manner in which the impacted site differs from the "reference condition" serve as a measure of the impact of stressors on the ecosystem. The key difference between the BACI and the RCA is that with RCA the impact has already occurred, and as such 'before-impact' sampling cannot occur. This is not ideal, and if possible, the BACI approach should be used. Another key difference is that it is focused on fauna. Any physical and chemical sampling is completed with the lens of how it relates to the fauna (usually invertebrates). This differs from the BACI in which fauna can be an optional indicator parameter. The steps in the RCA are outlined clearly and extensively in Bowman and Somers (2005), as well as the appropriate statistical analyses to use when using the RCA. While the RCA is traditionally a freshwater approach, in more recent years it has been applied to a broader set of ecosystems (Herlihy et al., 2019). In theory, any performance indicators (including social, environmental, and economic indicators) can be compared using an RCA approach, by summarizing the reference condition for each indicator using data from multiple sites (see Case Study 1).

Case Study 1. Converse Marsh Reference Condition Approach

Converse Marsh Restoration:
Converse Marsh Reference Condition Approach (RCA)

Missaguash River,
Nova Scotia, Canada

The Converse Marsh dike realignment and salt marsh restoration was instigated due to erosion affecting both the foreshore wetlands and a dike, which protected farmland and roads along the mouth of the Missaguash River (upper Bay of Fundy, Nova Scotia and New Brunswick, Canada). Due to increased costs for dike maintenance and repair, and the threat of flooding to adjacent lands, it was decided that a salt marsh restoration, following managed dike realignment, was the best approach for this site.

Baseline data on site history, geospatial attributes, hydrology, soils and sediments, and vegetation was collected in, 2017 and, 2018. Construction of 150 m of new dike was completed in fall of, 2018 and the old dike was breached in December, 2018 (Bowron et al., 2019).

The reference condition for the monitoring program was drawn from a regional database of tidal wetland habitat conditions including multiple reference sites for several BACI-designed projects. Each reference site was represented by replicated plots that covered the main elevation gradients present at each site. To determine appropriate reference plots from the database to compare with the Converse study site plots, sites were selected that were categorized as belonging to the same morphological class (i.e., the Tidal River Salt Marsh class). Within these reference sites, plots were chosen that matched elevation, inundation frequency, and hydroperiod such that the range of each variable across the reference plots closely overlapped with those of the study site plots. Plot size and sampling methods in the reference database are identical to those used in the study site monitoring program so direct comparisons could be made. Reference condition plots were used to compare vegetation cover and plant species composition over time at the Converse study site, with the range of values found across the reference condition plots.

Three years following realignment, the site is still in transition, but is on a positive restoration trajectory. The return of tidal flooding resulted in the dieback of agricultural communities and initially high sedimentation rates, followed by a decrease in subsequent years as sediments settled and consolidated. Seventy-four percent of the site was converted to bare ground in the first year of restoration, and bare ground has decreased to 40% of the site in the third year (Figure 2). Vegetation in the monitoring plots is beginning to match the species composition and diversity in the reference condition plots in some areas of the Converse site (Bowron et al., 2022).

Figure 2. Oblique aerial view of the Converse Managed Dike Managed realignment site on the Chignecto Isthmus

Source: Samantha Lewis, CBWES
Note: Photo taken on July 25, 2021 (~2.5 years post restoration), using a DJI Phantom 4 drone.

2.3.3 Other Approaches

While BACI and RCA monitoring methodologies represent best practices, it should be acknowledged that other methodologies may be employed when project impacts are well understood, during specific phases of the project lifecycle, or when project timelines or resources are limited. Rapid assessments, compliance monitoring, Before-After (BA), or Control-Impact (CI) designs may be necessary, for example where intense development precludes an appropriate control or where project timelines necessitate a limited baseline data collection (as in emergency response scenarios).

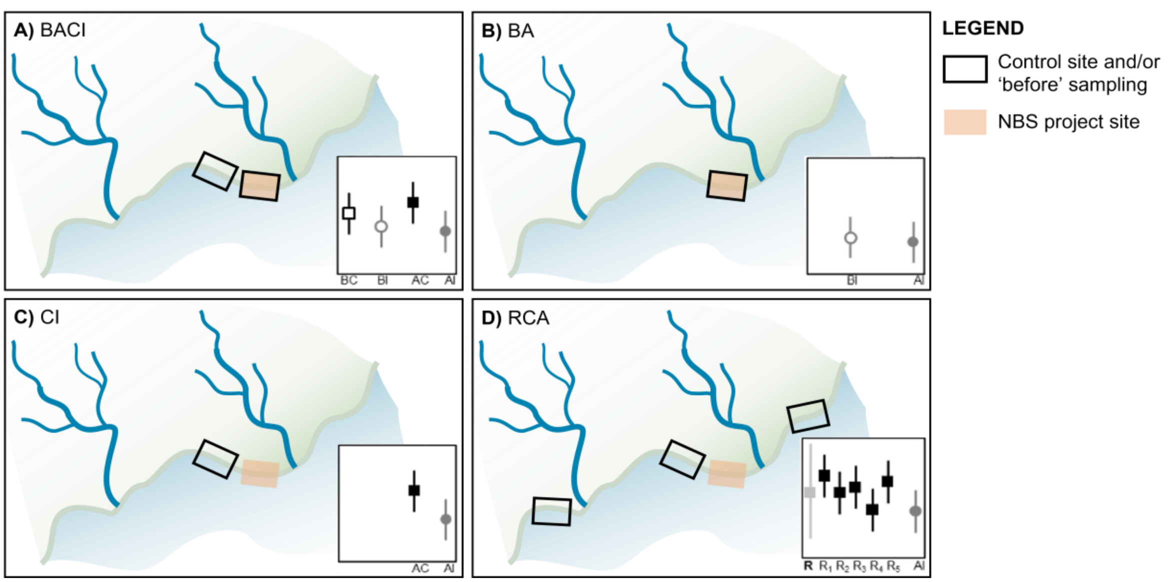
Rapid assessments are useful to preliminarily "scout out" the conditions of a site. The specific methodology of rapid assessment will depend on the goals of the project. The purpose is to record observations on the ground to attain a more in-depth understanding than what can be achieved on a desktop but without expending a lot of resources on a site that may not be viable. If the site is viable, then more extensive monitoring will be necessary.

Compliance monitoring, which can include construction monitoring, as-built surveys, and some or all long-term monitoring protocols, is carried out during project implementation as discussed in the *Monitoring Efficacy* report. This form of monitoring ensures compliance with the design plans and regulatory requirements, as well as informing any necessary design changes or adaptive management. Finally, compliance monitoring can serve as the starting point for long-term monitoring.

BA and CI are described above as part of the BACI approach, but it should be noted that when used individually, the BA and CI approaches have limitations. It is very difficult to determine to what degree observed changes are due to the natural background "noise" of the changing environment (which is expected to increasingly vary due to climate change), and to what degree the changes are due to the implementation of the project.

Figure 3 illustrates how BACI, BA, CI and RCA monitoring designs may be laid out and statistical analysis approached.

Figure 3. Examples of spatial and statistical analysis for BACI, BA, CI, and RCA monitoring plans



Source: Modified from Douglas et al., 2019
Note: Data plots are hypothetical data showing how comparisons are made between control and impact sites, and/or sampling periods. Gray points represent impact sites and black points are the control sites. Open points represent sites before impact and closed points represent sites after impact.

2.3.4 General Methodological Considerations

Regardless of the monitoring methodology approach selected for a specific project, the quality of experimental design and sampling techniques will greatly impact the results. The adage "garbage in, garbage out" is equally applicable to experimental design and field sampling. While some degree of error is unavoidable (e.g., two different people sampling the same thing will have slightly different results/judgment calls or techniques), it is best practice to try to identify potential error and plan ways to minimize that error in all parts of the project. For example, sampling bias could be introduced as simply as choosing the season or time in which the sampling occurs without properly understanding the system. If the purpose of sampling an area is to determine species diversity and usage, and the sampling coincides with a particular fish species' migration time, it will skew the results showing that the most abundant species that uses that sample area is the migratory species, when in actuality the most abundant species over the whole year may be a resident species. This would be apparent if the location was sampled multiple times throughout the field season and over a few years.

When deciding the quantity of sampling points, it may be useful to do a power analysis (a formal calculation that indicates the number of samples required to detect a statistically significant difference). Power analysis can be applied to both the quantity of repetitions of a single sampling location over time, and the quantity of samples within a zone to be statistically relevant (Brooks et al., 2002). If the sites are large, it may be useful to either use permanent transects (generally evenly spaced unless a feature of interest is important to capture), or to parcel the site into habitat zones with either transects or random sample point locations depending on the size of the zones. It is important that each habitat zone has enough sample points so that the data can be statistically analyzed. However, in many ecosystems, habitat zonation does not have clear boundaries, especially as seen from the ground, and therefore can be challenging to demarcate and monitor. Spacing—whether for random locations or along transects—can also be challenging due to access of stations or safety considerations of field technicians, which should also be kept in mind when designing the monitoring station layout. There may also be additional environmental considerations which are regionally specific (e.g., areas that have snow and ice during the winter), which could impact access or increase the risk of losing long-term installed equipment.

Another important consideration in the design of a monitoring program is the frequency of data collection. While many factors may influence this choice, the largest considerations are often project goals, budget, resources, and climate. It should also be noted that the magnitude and rate of change of a performance indicator may also be a consideration. For example, some performance indicators may progress slowly and at a magnitude that reduces the ability to reliably detect change (e.g., elevation in a microtidal setting). Other Indicators may change rapidly and dramatically (e.g., shoreline position following a large storm) and therefore need to have increased sampling frequency (see section 4.4 of *Monitoring Efficacy* report). In addition, frequency of data collection should consider alignment of the level of effort required to gather the data with the information that those data can provide and inform adaptive management.

Inherent in the International Union for Conservation of Nature's (IUCN) definition of NBS is the need for NBS to "address societal challenges effectively and adaptively, simultaneously benefiting people and nature" (Cohen-Shacham et al., 2016, 19). However, the potential impacts of NBS on environmental, social, and economic outcomes remain poorly understood, and, in particular, socio-economic impacts are often not systematically evaluated. Therefore, integrating socio-economic performance metrics and indicators within monitoring programs is key. To achieve this, it is therefore important to include multi-disciplinary and multi-sectoral teams in the design and evaluation process (Dumitru et al., 2021). See the *Monitoring Efficacy* report for additional information of roles and responsibilities for monitoring.

Once a monitoring approach has been selected (as part of the Planning phase), the next steps are to identify performance indicators and methodologies (as part of the Planning and Design phases). Section 3 introduces fundamental objectives, performance metrics, and performance indicators commonly used in NBS monitoring plans, drawing from sources identified in Section 1.4 and other relevant literature.

3 Performance Indicators and Monitoring Techniques

Performance indicators for a monitoring program are chosen based on their relationship to the fundamental objectives and overarching goals of the project (determined in collaboration with rightsholders and stakeholders) (Neckles et al., 2015). Fundamental objectives can be broken down into performance metrics (during the Planning Phase of the monitoring process), which indicate how the fundamental objectives will be achieved. Together, these guide which performance indicators are appropriate to achieve the metrics.

NBS for FrM projects are grounded in the biophysical and ecological conditions that are created to provide flood-risk management benefits. Therefore, many critical performance indicators for FrM projects on ecological systems (which NBS inherently include) are physical controlling factors or ecological response parameters (Neckles and Dionne, 2000; Neckles et al., 2002). Physical Controlling factors include elevation, morphology, hydrodynamics, soil characteristics, and hydrology. Biological parameters include vegetation communities and fauna usage. Performance indicators for other co-benefits include social parameters, such as usage, aesthetics and community wellbeing, and economic measures such as cost-benefit analysis. While performance metrics are actionable targets, performance indicators are what needs to be measured and sampled to determine if the performance metrics are being achieved.

For example, for a hypothetical FrM project which involves restoration of fish habitat (i.e., a tidal wetland) through managed dike realignment, the fundamental objectives could be to 1) restore floodplain area and connectivity to improve flood management, 2) restore coastal processes to improve the ecological health and function of the system, and 3) maintain biological diversity typical of the ecosystem type (sustainability). These three fundamental objectives can be broken down into performance metrics with performance indicators assigned to each. Table 1 provides a brief example of how the fundamental objectives—or goals—for this theoretical FrM project involving restoration of fish habitat will inform the potential performance metrics and performance indicators for that project.

Table 1. An example of fundamental objectives broken into performance metrics, which are directly correlated to selected performance indicators in the monitoring plan

Fundamental Objectives	Performance Metrics	Performance Indicators
Reduce storm hazard impacts	Reduce flood hazard area for a given event	Maximum flood level, flood duration (hydroperiod), maximum flood extent or area, hazard index, flood frequency, wave conditions, bedform measurements
	Reduce wave effects for target areas	Wave attenuation
	Reduce flood hazard exposure for a given event	Physical property (infrastructure, home, businesses) damage prevented
Ecological Health and Function	Restore natural tidal regime/hydrology	Tidal range, hydroperiod, inundation frequency, salinity

Fundamental Objectives	Performance Metrics	Performance Indicators
	Restore sediment dynamics	Positive change in marsh surface elevation, natural processes restored (storm disturbance/overwash)
	Improve water quality	Salinity, temperature, pH, dissolved oxygen consistent with reference site
Maintain Biological Diversity	Enhance natural tidal wetland vegetation communities and expand into encroaching uplands	% cover by species, increase in area, halophytic abundance and density, comparison with reference site
	Increase or maintain populations of natural fish communities	Fish community composition, relative abundance by species
	Optimize primary production of native vegetation	Species composition, height, density

Monitoring and evaluation protocols involve a range of indicators to measure the success of adaptation, including ecosystem-based adaptations (or NBS) particularly for resilience-related benefits and co-benefits (Rizvi et al., 2014). In general, there are two types of indicators: Process-based (i.e., input and output indicators) and performance-based (i.e., measuring outcome and impact) indicators (Ritzi et al., 2014). Performance-based indicators are also referred to as outcome-based indicators (ICLEI, 2022) or results-based indicators (Pearce-Higgins et al., 2022).

Process-based indicators are used to track or measure the progress towards achieving a particular target or goal (ICLEI, 2022; Pearce-Higgins et al., 2022). They seek to monitor the development and implementation of adaptation approaches (Ritzi et al., 2014). They can be particularly valuable for short- to medium-term time horizons, providing flexibility and alerting to potential adaptive management needs (ICLEI, 2022; Ritzi et al., 2014.).

Outcome-based (i.e., results-based or performance-based) indicators are used to measure the success or effectiveness of adaptation policies, activities, projects, and programs (ICLEI, 2022; Ritzi et al., 2014). They are generally used over longer time frames, and the outcome or success of an action can only be measured once it has been implemented or completed. For example, during a storm, successful erosion reduction or wave energy dissipation of a fully vegetated living shoreline may be considered a successful outcome for a specific NBS project. However, for many ecological or environmental indicators, identifying an end point may be challenging. Some define ‘success’ as species persistence, ecosystem functioning, and ecosystem service provisioning within the context of a changing climate (Pearce-Higgins et al., 2022).

Process-based and outcome/performance/results-based indicators share many of the same selection considerations as fundamental objectives and performance indicators presented in this report. This includes SMART criteria, establishing a baseline, and setting achievable targets (Ritzi et al., 2014; ICLEI, 2022).

3.1 Overview of Performance Categories

Broadly speaking, performance indicators may be split into four interconnected categories identified in the *Co-Benefits* report (from Bridges et al., 2021; Shiao, 2020), and listed below:

- Flood-risk management (FrM) (Section 2.2),
- Environmental (Section 2.3),
- Social (Section 2.4)
- Economic (Section 2.5).

These four categories are dynamic and interconnected. In practice, many performance indicators can be associated with more than one category, with the project's goals dictating both the measurement technique and results interpretation. An efficient and effective monitoring program often includes indicators that will do "double duty," assessing progress towards multiple objectives with one measurement. Table 2 summarizes potential performance metrics, which are commonly adopted for many monitoring programs across North America, organized by both ecosystem setting (shoreline type) and performance category. Within each performance category, potential performance metrics (i.e., project-specific goals) are identified. For example, structural components may be measured for all discussed NBS to determine stability (and sometimes to confirm permit compliance) as a FrM metric, while vegetation area and cover (a potential component of an NBS) also measure habitat value in the environmental category.

The following Sections will address core (i.e., primary, or necessary) and additional (i.e., secondary, or optional) metrics and indicators that should be considered when addressing each of the four categories identified above. **Core metrics and indicators are those that are considered most critical in the majority of NBS types, as well as achievable in a wide range of settings. Additional indicators may be included to meet project-specific objectives**. Additional indicators are also recommended for more complex sites, sites where the NBS in question has not been widely applied in that environment previously, or to inform future NBS implementation/research.

The following Sections will also address the types of techniques that may be applied to either quantitatively or qualitatively measure performance indicators. Any metric which applies to more than half of the identified ecosystem will be categorized as a core metric in Section 3.2, though they may be omitted in sites or shorelines where they are not critical or not applicable. In addition, the same performance indicators (e.g., surface elevation) may be associated with several different performance metrics. Consequently, in some cases, performance indicators are classified as both core and additional.

Identified techniques are modified from a National Wildlife Federation Workshop held in, 2017 (MARCO, 2017), which established a comprehensive monitoring framework relying upon community science for natural and nature-based features. Techniques are divided into methods led by subject matter experts or methods led by community scientists (which can also be applied in more resource-limited communities). However, it is important to recognize that both methods led by subject matter experts and community scientist methods exhibit considerable variation in difficulty, demanding differing levels of knowledge, funding, and resources. Community science methods often involve the use of proxies rather than direct measurement and typically include the need for capacity building and training to harness its full potential. These methods may also be coupled with higher resolution technologies for increased accuracy. For example, community members may photograph a flooded area and provide a temporary marker of flood extent. This marker can then be surveyed using high precision GPS once storm waters have receded and entered into mapping software to accurately delineate and calculate the flooded area. Identified techniques are also informed by findings of the intersectoral workshop series on NBS hosted by DHI on behalf of the CEC in the spring of, 2022 and the accompanying *Co-benefits* report. Additional material was sourced through the extensive review of monitoring methods by Kumar et al. (2021). For some indicators there are currently no known community science techniques, a limitation that should be addressed in future work.

Table 2. Performance metrics organized by performance category and project objectives for different types of NBS (✓ core metric; ? additional metrics; – not applicable)

Performance Category	Fundamental Project Objectives	Performance Metric	Submerged Features	Wetlands and Tidal Flats	Coastal Forests and Woody Areas	Beaches and Dunes	Islands	Hybrid Features
Flood Risk Management	Reduce storm hazard impacts	Reduced flood hazard area for a given event	–	✓	✓	✓	✓	✓
		Reduced wave effects for a target area	✓	✓	✓	✓	✓	✓
		Reduced flood hazard exposure for a given event	–	✓	✓	✓	✓	✓
	Maintain structural integrity and performance	Maintain stability of structural components	✓	✓	✓	✓	✓	✓
	Improve system resilience	Improved resilience of infrastructure or contingencies for failure	✓	✓	✓	✓	✓	✓
Environmental	Improve habitat value	Restore a more natural hydrological regime	–	✓	✓	✓	–	✓
		Increased or maintain critical habitat features and connectivity within a site	✓	?	?	✓	✓	✓
		Increased biodiversity and habitat usage	✓	✓	✓	✓	✓	✓
		Increased habitat connectivity to adjacent habitats	?	?	?	?	?	?
		Improved ecosystem resilience	✓	✓	✓	✓	✓	✓
		Soil productivity	?	?	?	?	?	?
	Climate mitigation and carbon sequestration	Reduced pollution	–	?	?	–	–	–
		Reduced carbon emissions	?	?	?	?	?	?

Performance Category	Fundamental Project Objectives	Performance Metric	Submerged Features	Wetlands and Tidal Flats	Coastal Forests and Woody Areas	Beaches and Dunes	Islands	Hybrid Features
		Carbon sequestration	✓	✓	✓	?	✓	✓
		Buffering capacity (water chemistry)	?	?	–	–	?	?
		Microclimate regulation	–	?	?	?	?	?
	Improved surface and groundwater water quality	Reduced sediment load	✓	✓	?	?	?	?
		Nutrient reduction	✓	?	?	–	?	?
		Groundwater recharge and storage	–	?	?	?	?	?
		Suitable aquatic habitat	✓	✓	?	?	?	?
		Toxin/pathogen removal	?	?	?	–	?	?
Social	Improved health and well being	Improved security and peace of mind	✓	✓	✓	✓	✓	✓
		Connectivity to green space and natural systems	✓	✓	✓	✓	✓	✓
		Noise abatement	–	?	?	?	?	?
		Food security	?	?	?	–	?	?
	Equity and justice	Inclusion and equity	?	?	✓	✓	✓	✓
		Poverty reduction	?	?	✓	✓	✓	✓
		Improved aesthetics	?	?	✓	✓	✓	✓

Performance Category	Fundamental Project Objectives	Performance Metric	Submerged Features	Wetlands and Tidal Flats	Coastal Forests and Woody Areas	Beaches and Dunes	Islands	Hybrid Features
	Esthetics and environmental stewardship	Increased community engagement and environmental stewardship	✓	✓	✓	✓	✓	✓
		Favorable public perception of project	✓	✓	✓	✓	✓	✓
	Alignment with cultural and religious values, heritage	Provides cultural, religious or spiritual amenity	✓	✓	✓	✓	✓	✓
		Improved participation and stewardship by Indigenous peoples or marginalized communities	✓	✓	✓	✓	✓	✓
		Foraging, gathering and traditional uses	✓	✓	✓	?	✓	✓
		Restoration of historic uses	?	?	?	?	?	?
	Recreation use and education	Broader recreation and gathering spaces	–	?	?	✓	✓	?
		Opportunities for education/scientific study	?	?	?	?	?	?
	Provides additional climate adaptation and mitigation benefits	Adaptation to or mitigation of poor air quality	–	✓	✓	–	–	–
		Adaptation to or mitigation of extreme heat	–	✓	✓	–	–	–
Economic	Provide monetary benefits	Reduced capital costs	✓	✓	✓	✓	✓	✓
		Reduced maintenance and operational costs	✓	✓	✓	✓	✓	✓
		Reduced costs to adjacent infrastructure (avoided flood losses)	?	?	?	?	?	?
		Decreased flood insurance premiums	?	?	?	?	?	?
		Increased land/property value	?	?	?	?	?	?

Performance Category	Fundamental Project Objectives	Performance Metric	Submerged Features	Wetlands and Tidal Flats	Coastal Forests and Woody Areas	Beaches and Dunes	Islands	Hybrid Features
		Increased tax revenues	?	?	?	?	?	?
	Positive impacts on local economy and communities	Improved fisheries, agricultural or artisanal livelihoods	✓	✓	✓	✓	✓	✓
		Local job opportunities	?	?	?	?	?	?
		Eco-tourism opportunities	?	?	?	?	?	?
		Reduced cost of living	?	?	?	?	?	?
		Reduced flooding impacts to communities	✓	✓	✓	✓	✓	✓

3.2 Flood Risk Management Indicators and Techniques

Flood-risk management (FrM) is a major concern for coastal urban and peri-urban areas, particularly when considering sea-level rise caused by climate change. When evaluating the performance of NBS in addressing FrM, indicators should be selected to inform how well the feature is reducing flood risk (system performance), as well as the physical condition of the structure over time (structure performance) (Science and Resilience Institute, 2020; Bridges et al., 2021).

3.2.1 Core

The fundamental objectives for FrM performance metrics outlined in Table 2 are as follows: Reduce storm hazard impacts; Maintain structural integrity and performance; and Improve system resilience. To achieve these three fundamental objectives, the core performance metrics are as follows (see Table 3):

- Reduced flood hazard area for a given event;
- Reduced flood hazard exposure for a given event;
- Reduced wave effects for target areas;
- Maintain stability of structural components; and
- Improved resilience of infrastructure or contingencies for failure.

The performance indicators—the factors that need to be measured and monitored to determine if the core metrics are being achieved—are summarized in Table 3 (along with potential measurement techniques) and include:

- Maximum flood level and water depth;
- Maximum flood extent or area;
- Hydroperiod (duration of flooding);
- Hazard index – depth-velocity;
- Flood frequency;
- Wave conditions;
- Bedform measurements;
- Physical property (infrastructure, homes, businesses) damage prevented;
- Wave attenuation;
- Elevation and location of features (survey);
- Measurements (dimensions) of features;
- Structural integrity of materials; and
- Sediment characteristics.

Water depths or flood levels, flood extents, and flood duration are critical in understanding the shoreline and the impacts of flooding and storm surge. Water marks such as ordinary high-water mark, and mean water level are critical in coastal processes such as erosion and distribution of biotic components such as vegetation and fish. Water marks such as high-water line (HWL), higher high water large tide, storm surge predictions, and wave run-up or overtopping are also the basis of many flood risk assessment protocols. Thus, these indicators are critical to most FrM projects. An example of an exception is 'reduction in wave effects', which may not be crucial or applicable for all projects (e.g., those aiming to create flood plains in upper reaches of the estuary) but is a core metric for many others. Along with wave conditions, it may also be important to measure wave attenuation where energy dissipation or erosion control is a primary goal. Wave effects may be inferred by measuring wave height, directly through measurement of overtopping volume or video monitoring, or indirectly through damage assessments or other appropriate indicators.

Reduction of properties' (including infrastructure, homes, businesses) exposure to the flood and storm hazard is a critical core metric. Indicators such as the number of properties that are not damaged after a storm event as a result of the implemented NBS should be considered core indicators and are easily measured using pre- and post-storm data (e.g., aerial imagery, topographic surveys, municipal mapping). Other indicators such as loss of life, impact to access to services, and impact to quality of life may be considered as additional indicators. Some indicators can be combined to create additional hazard indices. For example, depth-velocity matrixes are commonly used to indicate increasing levels of flood hazard and can be tailored or modified to account for differences in risk (e.g., the risk to an adult versus a child).

Core indicators related to the structural and shoreline stabilization components of the NBS (see above) include elevation/position of the NBS, dimensions of the NBS and its component, structural integrity, sediment characteristics, and rate of shoreline change. These indicators establish the initial conditions of the NBS and track its resilience over time. The direction and magnitude of change will depend greatly on the type of NBS implemented. For example, elevation change is expected to be positive for structures where sediment accretion is expected (for example wetlands and islands), and in line with predicted patterns if loss over time is expected (for example beaches where additional nourishment is expected). Monitoring of structural components is also important for adaptive management decisions—with the expectation that the dimensions will remain stable, decline at an expected rate (e.g., deterioration of gray components) or improve over time (e.g., development of green components).

Table 3. FrM core performance metrics with the corresponding performance indicator(s) and suggested monitoring techniques

Performance Metric	Performance Indicator	Method(s)	
		Methods led by Subject Matter Experts	Methods led by Community Members
Reduced flood hazard area for a given event	Maximum flood level and water depth	Water-level logging (HOBO, YSI)	Smartphone app; Community interview and generational memories; Graduated water-level staff and HWL manually logged;
	Maximum flood extent or area	Marsh area and porosity	Estimate marsh area; Community interview and generational memories
		Aerial imagery or RTK (HWL/flood mark)	Geo-tagged cell phone image
	Flood duration (hydroperiod)	Water-level logging & GIS	Observed ordinary high-water mark, observed flood duration
		Water volume (hydrodynamic change model)	Geo-tagged cell phone image
	Flood frequency	Long-term water level logging	Water-level recorder (graduated staff —manual logging or strip chart recorder)
		Repeat RTK surveys of flood marks	Community interview and generational memories

Performance Metric	**Performance Indicator**	**Method(s)**	
		Methods led by Subject Matter Experts	**Methods led by Community Members**
		Repeat high resolution satellite imagery (e.g., Sentinel)	Geo-tagged cell phone image
	Wave conditions	Meteocean wave buoys, ADCP	Leo forms
		Wave pressure sensors	Observations (e.g., videos) of boat traffic and storms, google earth measurements of fetch, visual or automated observation of vertical staff gauges of dyed ropes, anecdotal evidence from recreational fisherman/boaters
	Hazard index (depth-velocity metric)	Current profiler (ADCP, Acoustic Doppler Velocimeter)	Flow rates w/dissolution
		Water volume (hydrodynamic change model)	Time-lapse video
		Water-level logging	Water-level recorder (graduated staff – manual logging or strip chart recorder)
	Bedform measurements	Side scan sonar (SSS)—bedform morphology	N/A
Reduced wave effects for target areas	Wave attenuation	Wave height models	Movement of proxy material
		Pressure sensor array (ADCP or wave loggers)	
		Run-up	
Reduced flood hazard exposure for a given event	Physical property (infrastructure, homes, businesses) damage prevented	% reduction in property damage (buildings, infrastructure) attributed to NNBF	Comparison of Google Earth imagery, Google Streetview, open source data (e.g., open street maps).
Maintain stability of structural components	Elevation and location of features (survey)	RTK-GPS; Lidar DEM	Aerial drone photo only, no control points
		As built documents	
		Aerial drones with control points	
		Bathymetry/SSS	Kayaks/hikes with geotagged photos
	Measurements (dimensions) of features	Aerial imaging	Wide view photographs
		Photogrammetry of feature	Photographs pre- and post-storm
			Position relative to mean high water/mean low water
			Position relative to an existing natural feature
			Tie down distance (measures distance to fixed marks)
			Distance moved from original placement
			GPS structures based on as-built plans
			Ponding of water

Performance Metric	Performance Indicator	Method(s)	
		Methods led by Subject Matter Experts	**Methods led by Community Members**
			Measure buffer distance or setback distances
Improved resilience of infrastructure or contingencies for failure	Structural integrity of materials	Engineering survey-laser level	Photographs of structure or barnacle line
			Height/weight/length/volume
			Relative integrity (missing components, % missing components, soil loss, overtopping)
		Photogrammetry	Quadrant survey
	Measurements (dimensions) of features	RTK or laser scan of structure	Measure material size
			Observation of material condition
		Aerial Imagery	Visual damage assessment
	Sediment characteristics	Sediment particle size (coulter counter or laser diffraction)	Sediment texture analysis
			Rock/grain size
			Height/weight/length/volume

Source: adapted from MARCO, 2017

3.2.2 Additional

Depending on the particular nature of the NBS project, other indicators related to FrM may be important. To achieve the three fundamental objectives stated above, the following additional metrics should be considered (listed in Table 4):

- Reduced flood hazard exposure for a given event;
- Erosion reduction; and
- improved sediment management (supply and retention).

The performance indicators— the factors that need to be measured and monitored to determine if additional metrics are being achieved—are summarized in Table 4 (along with potential measurement techniques) and include:

- Loss of life;
- Impacts to access of services;
- Impacts to quality of life:
- Velocity or flow rate;
- Bedform measurements;
- Rate of shoreline position change over time;
- Elevation change over time; and
- Additional sediment characteristics.

Selection of additional performance indicators (Table 4) will depend on the type of NBS implemented, the project goals, and availability of resources (including instrumentation and trained personnel). Additional indicators associated with reduction of flood hazard exposure include reduction of loss of life, impacts to service access and impacts to quality of life. These indicators may be more challenging to directly attribute to the implemented NBS. Monitoring may involve repeat community surveys, comparison of vital statistics from health units, or media accounts. Geographic

Information Systems (GIS) may be used to identify and quantify length of roads flooded and duration of flooding that affects access to essential services.

Indicators which address storm surge and flood reduction goals, such as flow rate, velocity measurements and bedform measurements in the intertidal or offshore zones, may require more intensive techniques and are particularly important for large and/or complex projects. The rate of shoreline change may be measured over the short or long-term, depending on the objective of the project. Indicators can be assessed directly using in-situ equipment and modeling approaches, or indirectly by monitoring structures which play a role in energy reduction such as bedforms (bathymetry).

Indicators for erosion prevention beyond the measures identified above could include more specialized or complex methods of measuring elevation change and additional sediment characteristics such as bulk density, grain size, and bearing capacity. These characteristics are important to the stability of the shoreline as well as the ability of biotic components to establish and flourish.

Table 4. FrM additional performance metrics with the corresponding performance indicator(s) and suggested monitoring techniques

Performance Metric	Performance Indicator	Method(s)	
		Methods led by Subject Matter Experts	**Methods led by Community Members**
Reduces flood hazard exposure for a given event	Loss of life	Vital statistics, community agency or public health statistics	Obituaries, vital statistics, media reports
	Impact to access of services	GIS analysis of roads flooded and differences in timed access to essential services; community reports; service access statistics (e.g., hospital visits, etc.); pre- and post-surveys, polls, focus groups	Media accounts, social media, visual accounts of roads flooded
	Impact to quality of life	Pre and post Household surveys; community surveys; focus groups	Social media, community interviews
Reduced flood hazard area for a given event	Bedform measurements – dimensions and movement	Side scan sonar (SSS) – bedform morphology	Geo-tagged cell phone photos with physical object for scale in photo (e.g., ruler or notebook)
		Low altitude aerial surveys – 3D topography	
Erosion reduction	Rate of shoreline position change over time	RTK – GPS	Coastal erosion station - repeat measurement of distance from two shore perpendicular markers (to keep straight line) to shoreline or marsh edge
		Aerial imagery; GIS	Google Earth
		Engineering Survey	N/A
		Drone survey (measure feature change temporally/spatially)	Submit/share time-lapse, geotagged phone photos

Performance Metric	Performance Indicator	Method(s)	
		Methods led by Subject Matter Experts	Methods led by Community Members
Improved sediment management (supply and retention)	Elevation changes over time	DEM; elevation profile along transect (RTK-GPS); sediment transport models	Laser-level to benchmark;
			Recreational drone video or imagery
		Sediment elevation table	Feldspar clay markers
		Photographs	Photographs (pre- and post-storm)
		Marker horizon layers	Survey rod and transit;
			Feldspar markers (measures sediment accretion)
			Permanent monument (e.g., steel rod)
			Mobile or web application that collects phone GPS data
		Drone survey—topo (3D); LiDAR; Satellite derived bathymetry	Recreational drone video or imagery
		Nearshore survey—surface sonar	Movement of sediment surface relative to permanent benchmark
	Additional sediment characteristics	Bulk density	Fill volume known containers
		Bearing capacity (stability)	
		SSS – grain type (e.g., Lidar)	
		RTK-GPS survey	

Source: adapted from MARCO, 2017

3.3 Environmental Indicators and Techniques

3.3.1 Core

The fundamental objectives for Environmental co-benefits outlined in Table 2 are as follows: (1) Improve habitat value, (2) Climate mitigation and carbon sequestration, (3) Improved surface and groundwater water quality. To achieve these three fundamental objectives, the core metrics, listed in Table 5, are as follows:

- Restored a more natural hydrological regime;
- Increased or maintain critical habitat features and connectivity within a site;
- Increased biodiversity and habitat usage (flora and fauna);
- Improved ecosystem resilience; and
- Carbon sequestration.

The performance indicators are summarized in Table 5 (along with potential measurement techniques) and include:

- Water level;
- Flood extent;
- Hydroperiod (inundation ratio, inundation frequency, mean inundation time);
- Dimension and geo-position of key habitat features (e.g., dunes, reefs, eelgrass beds, etc.);
- Percent cover of flora and species diversity/composition;
- Percent cover of sessile taxa;
- Health of flora and fauna (condition and survival);
- Rate of post storm persistence and recovery;
- Abundance/density of indicator species;
- Plant density or height;
- Carbon stocks;
- Net carbon accumulation in biomass; and
- Net carbon accumulation in soil.

Coastlines are defined by their land-water interface, so hydrological variables are important environmental indicators. The relative elevation and position of land or submerged features can be an important indicator of success for projects where elevations have been raised to create habitat or enhance coastal protection (Table 3; Table 5); the area of land at or above a certain elevation is also a useful metric that can indicate how an NBS is performing (Table 3) (Wijsman et al., 2021). Water depths, extent, frequency, and duration of flooding are all important hydrological indicators relevant to both FrM and ecological dimensions of NBS projects.

Tracking changes in elevation over time is crucial to the ecological health of most coastal NBS projects (Wijsman et al., 2021). Elevations dictate what biotic components and habitats may occupy the area. Since coastlines evolve quickly in the face of change, checking visually for erosion or changes to flow patterns may be especially important in early project stages to inform adaptive management. Selection of a monitoring technique will depend both on the frequency of monitoring as well as the magnitude of change. Annual monitoring of elevation profiles using survey data, Lidar, or other elevation models is a common component of coastal NBS monitoring (Table 5). Related to elevation changes are processes of sediment transport and accretion. Monitoring sediment movement can take place using visual observations or by calculation of volumetric change (i.e., digital elevation model (DEM) of Difference) derived from Lidar or other elevation models over time. Projects where sediment accumulation is important can directly measure accretion using marker horizons and rod sediment tables (Table 5), which are able to differentiate above and below ground processes and detect change at a finer resolution (mm to cm) than other techniques. These techniques are typically repeated each year during the early phases of NBS project development.

Vegetation is another performance indicator that is fundamental to many key ecological functions in NBS projects (Table 2). Plants play an important role in shoreline protection, resilience, and erosion management. Plant cover and abundance can serve as indicators of the overall success of planted NBS. Cover simply represents how much surface area is covered by any type of vegetation (Wijsman et al., 2021), usually quantified as a percent score. High levels of plant cover often indicate important functions such as substrate stability and reduction of erosion rates. The simplest measure of species abundance is a (percent) cover value for each species or for a subset of dominant or otherwise significant species. It is important to identify the relative abundance and diversity of different vegetation species including invasive species which can have lasting negative impact on systems. Vegetation inventories can be used to identify species, including invasive, within a system.

Comprehensive plant species inventories are carried out via an attempt to detect all plant species occurring at the site or all species within sampled plots or transects. From such an inventory, species richness (the number of species detected in each area), or other biodiversity metrics can be calculated as well. Depending on site context, summarizing plant abundance data into functional categories of species can help assess indicators of site condition or ecological integrity (e.g., halophytes—salt-tolerant plants—can be key indicators of salt marsh vegetation recovery). In addition, surveys of flora and fauna pre- and post-storm (persistence, survival, recovery) and health over time can be used as indicators of ecosystem resilience.

Vegetation indicators change over time, especially in the context of a newly restored site, so repeated monitoring is extremely important. Most programs have yearly vegetation monitoring, and where habitat creation is a priority in NBS projects, comparisons with one or more reference sites are frequently incorporated into monitoring programs (Graham et al., 2021). Such comparisons allow for evaluation of how close various indicators match between the created or restored habitats in the NBS and those in natural reference sites.

For NBS projects involving submerged habitats such as oyster reefs or eelgrass beds, coverage, species relative abundance and richness indicators for submerged sessile organisms are also often useful and can follow similar protocols to those used for vegetation. These can also be divided into different functional groups that might indicate NBS performance (e.g., coverage of filter feeders). Likewise, the relative coverage of different kinds of substrates can be important in both submerged and land areas: wrack, debris, concrete, or other surface covers may be relevant to track, depending on the regional context of the NBS (Wijsman et al., 2021).

Coastal NBS, especially those involving wetland creation, can result in blue carbon sequestration and storage. If assessments of blue carbon are important, core performance metrics could include the density of organic carbon (per unit area) and the rate of its accumulation (per area, per year) (Howard et al., 2014). Key performance indicators could include both carbon stocks (an assessment of the amount of carbon currently held by the ecosystem), as well as sequestration rates (a measure of the rate of accumulation of carbon from the atmosphere or other sources) (Table 5) (Howard et al., 2014). To fully assess the role of NBS in carbon dynamics, net amounts of carbon or CO_2 equivalents are important to quantify, as losses due to decomposition or erosion need to be factored in for overall carbon or greenhouse gas budgeting. In habitats dominated by herbaceous plants, belowground carbon stocks and accumulation rates are targeted as the aboveground biomass does not represent a stable carbon sink, rather that biomass is replaced yearly. In habitats with woody plants, however, (e.g., mangrove swamps or coastal shrublands) an assessment of carbon stocks held both aboveground and belowground is important (Table 5).

Table 5. Environmental core performance metrics with corresponding performance indicator and suggested monitoring techniques

Performance Metric	Performance Indicator	Method(s)	
		Methods led by Subject Matter Experts	Methods led by Community Members
Restore a more natural hydrological regime	Water level	Water-level logging	Smartphone app
	Flood extent	Marsh area and porosity	Estimate marsh area
		Aerial imagery or RTK GPS (HWL/flood mark)	Geo-tagged cellphone photographs
	Hydroperiod (inundation ratio, inundation frequency, mean inundation time)	Water volume (hydrodynamic change model)	Observed high water mark
		Water-level logging & GIS	Geo-tagged cell phone image

Performance Metric	Performance Indicator	Method(s)	
		Methods led by Subject Matter Experts	**Methods led by Community Members**
Increase or maintain critical habitat features and connectivity within a site	Critical habitat feature dimensions, geo-position, and elevation (and change of elevation via sedimentation; coverage by debris)	Geotagged aerial survey (drone)	Measure features height/length/width/slope using measuring tape & simple laser-level, or clinometer
		RTK GPS	
		Numerical modeling	Tape measure survey
		3D laser scan (submerged features)	Measure submerged feature characteristics (i.e., height/length/width/rugosity) using chain-measure or photographs
		Sonar survey (SSS kayak or boat mounted)	Echosounding survey (single frequency) from kayak or boat
		Laser levels	Laser levels
		DEM; elevation profile along transect (RTK-GPS); sediment transport models	Laser level to benchmark
			Recreational drone video or photography
		Sediment elevation table	Feldspar clay markers
Increased biodiversity and habitat usage (flora and fauna)	% cover by plants	RTK GPS	Quadrat survey
		Georeferenced orthomosaic from drone	Google Earth or equivalent
	Species diversity	Shannon diversity and other absence, abundance, and richness measures	Transect or quadrat methods for species count and richness; Identify presence/absence of organism-groups/guilds; Bioblitz with cellphones for photo-capture and identification (e.g., iNaturalist); Benthic cores; Seining, dip net or sieving; Surveys collected from anglers, birders, etc.
	% cover of sessile taxa	Aerial imagery (ID, diversity, coverage)	Photo observation
		Benthic survey	CABIN survey
	Abundance/density of indicator species	Index of biological integrity or variations	N/A
		Acoustic/satellite tagging	N/A

Performance Metric	Performance Indicator	Method(s)	
		Methods led by Subject Matter Experts	**Methods led by Community Members**
	Increases in population size over time	Flora/fauna growth, reproduction and survivorship (e.g., floral resource surveys)	N/A
	Plant density or height	Image analysis	Plot sampling (count stems); Measure heights with tape measure
Improved ecosystem resilience	Health of flora and fauna (condition and seasonal survival)	quadrat and health condition surveys—density, health (e.g., healthy, stressed, dying); annual survival rate from RTK GPS tagged individuals (plants).	Repeat geotagged photos; quadrat survey photographs and comparison to health scale.
	Post storm persistence and recovery	Repeat low altitude aerial or quadrat surveys pre- and post-storm; % cover and individual plant tracking	Repeat geotagged photos, quadrat survey photography, % cover.
Carbon sequestration	Carbon stocks	Biomass measurements	Organic matter content (e.g., Loss on Ignition) and bulk density
		Standing stock (veg cover and conversion)	
	Net carbon accumulation in biomass	Change in below- and/or above-ground biomass	
	Net carbon accumulation in soil	Change in soil organic carbon	
		Organic matter x conversion	
		Lead 210 carbon dating to get a sequestration rate (P)	

Source: adapted from MARCO, 2017

Case Study 2. Dike realignment and tidal wetland restoration

Belcher St. Marsh:
Dike realignment and tidal wetland restoration

Belcher St. Marsh, Nova Scotia
Canada

This project involved reconstructing a failing dike farther inland and allowing restoration of tidal hydrology in front of the new dike (Figure 4) (Graham et al., 2021). Baseline assessment was carried out in, 2017; the site contained mainly abandoned pasture and freshwater wetland vegetation prior to realignment and is situated near the farthest inland point of tidal influence along the Jijuktu'kwejk River (Cornwallis River). Dike reconstruction was carried out in spring, 2018. The monitoring program took a BACI approach and involved several core indicators (Table 6), primarily in the Flood Risk Management and Environmental categories. After restoration of tidal hydrology, vegetation recovery was rapid after the initial influx of large amounts of sediment. Lessons learned include the importance of legacy impacts of heavy equipment on sediments during the realignment process; erosion occurred as a result of sediment compaction but was addressed via adaptive management (digging channels to direct flow and installation of living shoreline features).

Figure 4. (left) Post-construction unvegetated state (year 1), and (right) vegetated state (year 4)

Table 6. List of methods with performance indicators

Category	Performance Indicators	Sampling Method	Sampling Frequency
Geospatial	Critical habitat feature dimensions	UAS Orthomosaic; DSM; GNSS RTK surveying unit	As Required
	Elevation and location of features	Digital Elevation Model (DEM); G8 GNSS RTK surveying unit (or equivalent)	Annually
	Habitat map	Low-altitude aerial photography; Vegetation data	Annually
Hydrology	Hydroperiod; Water level	Automated water level recorders (5-minute intervals)	Minimum 29 day period
	Flood extent	DEM; Tide Signal	Annually
Soils & Sediments	Elevation change over time	Rod Surface Elevation Table (RSET); Marker Horizons (MH)	Annually
	Sediment characteristics	Bulk density, organic matter content, sediment type, water content	Annually
Vegetation	% cover by plants	Transect based, Point Intercept Method (1 m^2 plots)	Annually
	Species diversity		
	Abundance of indicator species		
Winter Walk	Winter Conditions	Structured winter walks & photo-documentation	Annually

3.3.2 Additional

Depending on the particular nature of the NBS project, other environmental indicators related to ecological functions may be important. To achieve the fundamental objectives identified in Table 2 the additional performance metrics, listed in Table 7, are as follows:

- Increased habitat connectivity to adjacent habitats;
- Increased biodiversity and habitat use (in terms of vegetation productivity);
- Increased biodiversity and habitat use (in terms of fauna usage);
- Soil productivity;
- Reduced pollution (improved air quality);
- Reduced greenhouse gas emissions;
- Buffering capacity (water chemistry);
- Microclimate regulation;
- Reduced sediment load;
- Nutrient reduction;
- Groundwater recharge and storage;
- Suitable aquatic habitat; and
- Toxin/pathogen removal.

The additional performance indicators are summarized in Table 7 (along with potential measurement techniques) and include:

- Increased access among habitats by sessile organisms;
- Height and number of plant stems (per unit area);
- Plant flowering/fruiting;
- Population densities;
- Nesting success (birds);
- Benthic habitats (fish);
- Water quality (fish);
- Soil nutrient concentrations;
- CO_2, CH_4, NO_2 gas measurements;
- Water pH;
- Water CO_2 concentrations;
- Carbonate;
- Dissolved oxygen;
- Shellfish health;
- Temperature (air, soil and water);
- Total suspended solids/Suspended sediment concentration;
- Nutrient concentrations in water;
- Number of discrete contamination events;
- Rate of groundwater recharge;
- Storage capacity;
- Bacterial levels in water; and
- Tissue concentrations.

Habitat connectivity may be an important driver of long-term resilience of populations of mobile organisms that use NBS sites (Wijsman et al., 2021). The value of NBS can increase if the site is connected to other high-quality habitats. Metrics to determine landscape scale connectivity can be as simple as assessing the extent of natural habitats versus artificial infrastructure adjacent to the site, with greater adjacent natural habitat implying greater connectivity (Sowińska-Świerkosz and García, 2021).

Additional biodiversity sampling may be indicated when rare species are targets of habitat creation. Many NBS projects aim to create or enhance habitat for breeding birds. Such projects typically require a suite of indicators that get at bird densities, nesting success or other variables. Monitoring in these cases is generally carried out yearly and must be completed with protocols designed to minimize harm or disturbance to nesting populations. Fish are also included in many monitoring programs to assess the role of NBS in providing or enhancing fish habitat. Like bird population sampling, fish sampling is usually done as a catch and release procedure, but there are also several other habitat indicators for fish habitat that may be included (area of different benthic habitats, water depth and velocity, water quality, temperature, etc.) (Braun et al., 2019). Water quality assessment can include sampling pH, dissolved oxygen and nutrients, suspended sediment concentration, salinity or other parameters and may be important indicators in situations where they can be limiting factors for aquatic organisms (Table 7).

Additional performance indicators involving vegetation may include height and number of plant stems (per unit area) (Table 7). These variables can be important to understand the overall health and productivity in plant communities but are also important determinants of the ability for vegetation to moderate wave height and energy (Denny, 2021). These variables tend to take more time to sample than cover estimates so the decision to include more detailed plant sampling needs to be evaluated carefully. Plant flowering or fruiting may also be an important indicator of system performance, if rare plant habitat is included as part of project targets; flowering is also important if the NBS is adjacent to agricultural lands and may support pollinators. Flowering can be monitored at a relatively low cost by visually estimating coverage, species composition or richness, and can also be included as components of photographic monitoring (Table 7).

Table 7. Environmental additional performance metrics with the corresponding performance indicator(s) and suggested monitoring techniques

<table>
<tr><th rowspan="2">Performance Metric</th><th rowspan="2">Performance Indicator</th><th colspan="2">Method(s)</th></tr>
<tr><th>Methods led by Subject Matter Experts</th><th>Methods led by Community Members</th></tr>
<tr><td>Increased habitat connectivity to adjacent habitats</td><td>Increased access among habitats by sessile organisms</td><td>GIS analysis of neighboring habitats</td><td>Google Earth or equivalent</td></tr>
<tr><td rowspan="2">Increased biodiversity and habitat use (in terms of vegetation productivity)</td><td>Height and number of plant stems (per unit area)</td><td>Height measurement and stem count survey</td><td>Measuring height, and stem count survey</td></tr>
<tr><td>Plant flowering/fruiting</td><td>Visual estimation of coverage
Species composition or richness
Photo observation (high resolution low altitude aerial photography)</td><td>Visual estimation of coverage
Species composition or richness;
Photo observation</td></tr>
</table>

Performance Metric	Performance Indicator	Method(s)	
		Methods led by Subject Matter Experts	**Methods led by Community Members**
Increased biodiversity and habitat use (in terms of fauna usage)	Population densities; nesting success (birds); benthic habitats (fish); Water quality (fish)	Species surveys (e.g., catch and release); CABIN (invertebrates); benthic surveys	Visual observation; eBird; CABIN; Photo observation
Soil productivity	Soil nutrient concentrations	Soil nutrient analysis (government or commercial lab)	Garden soil kits for basic nutrients
Reduced pollution (improved air quality)	Air quality index	Continuous monitoring (real-time, automated), non-continuous monitoring (discrete, manual), mobile monitors	Mobile monitor
	Ground-level ozone (O_3); fine particle matter ($PM_{2.5}$); carbon monoxide (CO); sulphur dioxide (SO_2); total reduces sulphur (TRS); nitrogen oxides (NO_x); volatile organic compounds (VOC)		
Reduced greenhouse gas emissions	CO_2, CH_4, NO_2 gas measurements	Portable GHG analyzer-with automated chambers	Handmade static chambers, syringe extraction of gas, sample sent to analytical lab
Buffering capacity (water chemistry)	Water pH	CTDs	CTDs
	Water CO_2 concentrations		
	Carbonate		
	Dissolved oxygen		
	Shellfish health	Shellfish surveys	Shellfish surveys
Microclimate regulation	Temperature (air and soil)	Real time weather station or temperature probe	Weather station
Reduced sediment load	Total suspended solids/Suspended sediment concentration	Water sample analysis for total suspended solids; Automated water sampler	Evaluation of water clarity (e.g., disappearance of Secchi Disk) Mail-in sample kit (e.g., chlorophyll A)
Nutrient reduction	Nutrient concentrations in water	Water sampling (large scale)	Observe occurrences of algal blooms
		Filtration capacity of shellfish (small scale)	Measure oyster density and size

Performance Metric	Performance Indicator	Method(s)	
		Methods led by Subject Matter Experts	Methods led by Community Members
		Nutrient load measurements (before/after or control/reference)	Mail-in sample kits
		Modeled reduction based on literature and/or approved protocols	*None known*
		N load modeling (e.g., land use in watershed)	*None known*
		Multimeters (e.g., YSI)	Multimeters (e.g., YSI)
	Number of discrete contamination events	Combined sewer overflow discharge frequency or volume	Report occurrence of combined sewer overflow discharges or sewage infrastructure issues; Report fish or wildlife kills
Groundwater recharge and storage	Rate of groundwater recharge	Hydrograph analysis and water table fluctuations	*None known*
	Storage capacity	Groundwater storage calculations/analysis	*None known*
Suitable aquatic habitat	Dissolved O_2	CTDs (direct sampling of water)	CTDs (direct sampling of water)
	Water pH		
	Water temperature		
Toxin/pathogen removal	Bacterial levels in water	Fecal coliform or entero sampling	Mail-in sample kits Reporting beach closures
	Tissue concentrations	Tissue samples of vegetation (toxics) Heavy metal analysis in fish/sediments	Submit plant samples Submit caught fish

Source: adapted from MARCO, 2017

3.4 Social Indicators and Techniques

3.4.1 Core

The fundamental objectives for social co-benefits outlined in Table 2 are as follows: (1) Improved health and well-being, (2) Esthetics and environmental stewardship, (3) Equity and justice, (4) Alignment with cultural and religious values, (5) Recreation use and education; and (6) Climate change adaptation and resilience. To achieve these six fundamental objectives, core performance metrics are as follows (Table 8):

- Improved security and peace of mind;
- Connectivity to green space and natural systems;

- Improved esthetics;
- Increased community engagement and environmental stewardship;
- Favorable public perception of the project;
- Provides cultural, religious, or spiritual setting;
- Poverty reduction;
- Participation and stewardship by Indigenous Peoples or marginalized groups;
- Equity and inclusion; and
- Provides additional climate adaptation and resilience benefits.

The performance indicators are summarized in Table 8 (along with potential measurement techniques) and include:

- Public perception;
- Physical health;
- Mental health and wellbeing;
- Sense of place;
- Cultural/tribal value;
- Social media use;
- News reports;
- Population living in poverty;
- Population demographics (gender, ethnicity, age);
- Change in littering/dumping;
- Usage rate;
- Community engagement; and
- Connectivity.

Social co-benefits are a fundamental component of NBS. Social uptake and perception of the NBS is therefore critical to understanding how the solution is performing. Measures of knowledge, awareness and engagement can be used to track progress in achieving certain communication objectives (Harley and van Minnen, 2009). These indicators are useful in gauging community interest and uptake in NBS. In addition, the climate change mitigation benefits of NBS are not evenly distributed among socio-demographic groups. Therefore, when designing monitoring and evaluation programs for NBS, it is important to select appropriate baseline measurements for performance indicators (Dumitru et al., 2020), which may vary according to community values. Additionally, NBS provide the potential to foster sustainable placemaking by enhancing green space, strengthening the bond between people and nature, promoting social cohesion, and improving overall individual wellbeing (Wendling et al., 2021; Dumitru et al., 2020). Core performance indicators are those related to the direct impact on or of the community from the project. These include perception surveys matching the intended performance goals of the project with public perceptions of the intended outcome. This can be accomplished using surveys or focus groups (Table 8) and can be used to focus targeted education campaigns and/or change communication and public messaging. Primary methods include surveys, focus groups, and community meetings. Alternatively, indirect measurements include monitoring social media platforms, news media and interviews with trusted leaders within the community. Additional details are provided in the companion *Co-benefits* report and expanded in *Evaluating the Impact of Nature-Based Solutions: Appendix of Methods* by Dimitru and Wendling (2021).

To increase the likelihood of sustainable and just management, a successful NBS project must respectfully and appropriately integrate the communities, cultures and knowledge systems that may be affected by a shift in management approaches (i.e., shift away from gray infrastructure to more NBS) (van Proosdij et al., 2021). This includes considerations of equity, inclusion and increased participation and stewardship by Indigenous peoples and marginalized groups. These can be considered core performance metrics. Performance indicators include socio-demographics (e.g., income, race, sex, gender, language, citizenship, age, and ability) variables that can be derived from census surveys. Statistical data, however, may not be available at the scale needed for small area considerations. Local government, planning or community development staff, or staff in service organizations, know their communities; they can often share their local knowledge through semi-structured interviews and surveys (van Proosdij et al., 2021)

Table 8. Social core performance metrics with corresponding performance indicator(s) and suggested monitoring techniques

Performance Metric	Performance Indicator	Method(s)	
		Methods led by Subject Matter Experts	Methods led by Community Members
Improved security and peace of mind	Public perception of safety	Pre/post surveys, focus groups, polls, interviews	Online surveys & polls, interviews
	News media – favorable reports	Automated monitoring of news feed including impacts of storm events; content analysis	# of media reports
	Social media – positive postings	Automated social media monitoring analysis	‘likes’ on social media platforms linked to community group
	Mental health and well-being	Pre/post surveys, focus groups, polls, interviews; self-reported mental health and wellbeing surveys	Online surveys and polls; social media posts - content
Favorable public perception of project	Public perception	Pre/post surveys, focus groups, polls, interviews	Online surveys and polls, interviews
	Social media – positive posting	Automated social media monitoring analysis	‘likes’ and shares on social media platforms linked to community group
Improved esthetics	Social media – photos	Automated social media monitoring analysis	Photo uploads, shares, and likes

Performance Metric	Performance Indicator	Method(s)	
		Methods led by Subject Matter Experts	**Methods led by Community Members**
Increased community engagement and environmental stewardship	Change in littering or dumping	Analysis of clean-up events; municipal waste services analytics; reports of illegal dumping	Tracking amount of trash gathered at clean-up events
	Usage rate	Willingness to pay surveys; people counts	# of volunteers and public participation at events; # of events
	Community engagement	NGO priorities for funding	donations
Connectivity to green space and natural systems	Connectivity between project to green space and natural systems	GIS analysis	Google earth, Surveys
Provides cultural, religious or spiritual setting	Sense of place	Interviews/focus groups/survey; art and creative expressions	Interviews/surveys; Art and creative expressions
Indigenous participation and stewardship	Cultural/tribal value	Interviews/focus groups/survey	Indigenous participation
Foraging, gathering and traditional uses	Traditional use	Traditional knowledge survey; interviews	Interviews, social media
Poverty reduction	Reduction in number of households below the poverty line	Census surveys, interviews, socio-demographic statistics	Publicly available census, interviews, surveys
Inclusion and equity	Diversity in socio-demographics	Socio-demographic census, surveys, interviews	Publicly available census, polls, surveys
Minorities or historically marginalized communities' participation and stewardship	Cultural/social value	Interviews/focus groups/survey	Minorities or historically marginalized communities' participation
Additional climate change or mitigation benefits: Adaptation to or mitigation of poor air quality	Perception survey	Expert panel interviews; adoption of NBS in municipal	Invited expert public lecture - # attendees; public perception and experience surveys

Performance Metric	Performance Indicator	Method(s)	
		Methods led by Subject Matter Experts	Methods led by Community Members
Adaptation to or mitigation of extreme heat		climate change adaptation plans	
	Physical health	Comparison of impacts of extreme events; hospitalizations & emergency room visits (heat & respiratory)	# air quality advisories; # of heat alerts; # of flood advisory warnings

3.4.2 Additional

Depending on the particular nature of the NBS project, other social indicators may be important. To achieve the fundamental objectives identified in Table 2, the additional performance metrics, are as follows (Table 9):

- Noise abatement;
- Food security;
- Restoration of historic uses;
- Broader recreation and gathering spaces; and
- Opportunities for education/scientific study.

The performance indicators are summarized in Table 9 (along with potential measurement techniques) and include:

- Noise level;
- Food availability;
- Current historic uses;
- Recreation use;
- Physical fitness;
- Scientific studies; and
- Education opportunities.

Additional measures of NBS performance and success include those related to building social capacity and community engagement in environmental education activities. Environmental education and stewardship play an important role in further engagement and support of NBS activities (Wendling et al., 2021) (Table 9). Engagement also relates to a community member's sense of place and attachment which is often associated with cultural values. Cultural value metrics can include restoration of historical uses and exploring sense of place or cultural/tribal value (Table 9). In addition, NBS projects can increase recreational use as well as provide important health and well-being benefits (Table 9) (Wendling et al., 2021).

Table 9. Additional social performance metrics with corresponding performance indicator and suggested monitoring techniques

Performance Metric	Performance Indicator	Method(s)	
		Methods led by Subject Matter Experts	Methods led by Community Members
Noise abatement	Noise level	Sound level meter and dosimeter	Number of noise complaints
Food security	Food availability	Surveys; food bank use; farmers markets	Polls, numbers of vendors selling local food; local interviews
Restoration of historical uses	Contemporary use of historical activities	interviews/focus groups/surveys	Social media posts; use surveys
Broader recreation and gathering spaces	Recreational use	Use surveys (type and amount); remote sensing counts; number of visitors; # of rentals; social media	Number of public access sites and observations of use; car counts; entrance surveys; social media
	Physical fitness	Fitbit metrics or automated fitness tracking	Posting on social media, fitness aps and groups
		Prevalence of cardiovascular disease or respiratory conditions	Surveys
Opportunities for education/scientific study	Scientific studies	# of peer reviewed and gray literature published; conference presentations	Number of scientific studies; media reports
	Educational opportunities	Integration of NBS into academic curriculum (all levels); educational signage	number of courses; field trips—public and school; outreach events

3.5 Economic Indicators and Techniques

What separates NBS from other approaches, such as the Ecosystem Approach or Ecological Engineering, is that it is essential to account for multiple perspectives for the links within and between ecological, social, and economic systems, as well as considering the various social and environmental consequences of any intervention (Nesshöver et al., 2017). While many costs associated with NBS have clear monetary values that can be quantified, there are many co-benefits (particularly ecological, environmental, or social benefits) that are less tangible or even intangible. However, these intangible benefits still hold real value for a community (van Proosdij et al., 2021). As with other categories, Economic indicators are summarized below in both core and additional categories. In addition, the System of Environmental-Economic Accounting Ecosystem Accounting (SEEA EA) is provided an alternative and powerful tool to help with the quantification and optimization of a NBS project's environmental and economic benefits in projects where fundamental objectives fall into both categories (Box 1).

3.5.1 Core

The fundamental objectives for Economic co-benefits outlined in Table 2 are as follows: (1) Monetary benefits, and (2) Positive impacts on local economy. To achieve these two fundamental objectives, the core metrics are as follows (Table 10):

- Reduced capital costs;
- Reduced maintenance and operational costs;
- Improved fisheries, agricultural or artisanal livelihoods; and
- Local job opportunities.

The performance indicators are summarized in Table 10 (along with potential measurement techniques) and include:

- Capital costs;
- Maintenance & repair costs;
- Economic revenue; and
- Employment statistics.

NBS may require large investment in materials and energy, and there is thus a need to acknowledge the potential for economic trade-offs that may be required to implement such strategies (for example, wetland restoration may provide flood protection and co-benefits such as water purification, but it could negatively impact local farming through the reclamation of high-quality farmlands). Therefore, to understand these trade-offs in economic terms, it can be helpful to use a common currency (e.g., US$) for evaluating different solutions. Solutions should be determined with the lens of linking the pillars of sustainable development, and evaluating social, environmental, and economic dimension equally (Nesshöver et al., 2017). Cost-benefit analyses are often useful tools for decision makers; however, achieving a robust cost-benefit analysis can be difficult when many of the co-benefits may not have a guideline to be clearly monetized (i.e., some co-benefits are intangible) or the data aren't available for certain regions. In addition, critical decisions about NBS design and costs will likely involve a wide range of stakeholders, and while the aim is to find a clear win-win that supports the triple-bottom line (i.e., the environment, society, and the economy), the reality is that there are often trade-offs which are difficult to quantify and have different associated costs, benefits, impacts, and risks (Eger et al., 2022, Halpern et al., 2013, Nesshöver et al., 2017). Valuation methods require guidance from experts as well as input from the community to capture the full value of a project's expected outcomes. Additional details are provided in the companion *Co-benefits* report and expanded in *Evaluating the Impact of Nature-Based Solutions: Appendix of Methods* by Dimitru and Wendling (2021).

Recognition of the service value of natural assets is growing, along with interest in incorporating ecosystem services into planning and decision-making (e.g., the Natural Assets Initiative). Ecosystem service assessments support identifying and quantifying ecosystem services and benefits. This process also provides a way to explore the broader societal implications of a project or decision and to examine the trade-offs, inequities, and intangible elements of human well-being (van Proosdij et al., 2021).

Table 10. Core economic performance metrics with the corresponding performance indicator(s) and suggested monitoring techniques

Performance Metric	Performance Indicator	Method(s)	
		Methods led by Subject Matter Experts	Methods led by Community Members
Reduced capital costs	Capital costs	Accounting of costs across the entire project life cycle	*None known*
Reduced maintenance and operational costs	Maintenance and repair costs		
Improved fisheries, agricultural or artisanal livelihoods	Revenue	Economic revenue	*None known*
Local job opportunities	Number of jobs	Employment statistics; Socioeconomic data or surveys	Employment statistics, job ads; case study review

Source: adapted from MARCO, 2017

3.5.2 Additional

Depending on the particular nature of the NBS project, other indicators related to economic co-benefits may be important. To achieve the fundamental objectives identified in Table 2, the additional metrics are as follows (Table 11):

- Reduced costs to adjacent infrastructure (avoided flood losses);
- Increased land/property value;
- Decreased flood insurance premiums;
- Increased tax revenues;
- Eco-tourism opportunities; and
- Decrease in cost of living.

The performance indicators are summarized in Table 11 (along with potential measurement techniques) and include:

- Capital, maintenance and repair costs;
- Perceived value;
- Real value;
- Cost/number of insurance claims;
- Ratings systems;
- Risk modeling;
- Tax revenue;
- Community perception; and
- Cost of living.

Table 11. Additional economic performance metrics with the corresponding performance indicator(s) and suggested monitoring techniques

Performance Metric	Performance Indicator	Method(s)	
		Methods led by Subject Matter Experts	Methods led by Community Members
Reduced costs to protected infrastructure (avoided flood losses)	Capital, maintenance and repair cost	Accounting of costs across the entire project life cycle Cost-benefit analysis	*None known*
Increased land/property value	Perceived value	Survey resident perceived value Interviews on perceptions of NNBF benefit to sense of protection	Online sharing Online hits
	Real value	Real estate transactions Real estate values	*None known*
Decrease in flood insurance premiums	Cost/number of insurance claims	Flood insurance claims	Case study review
	Ratings systems	NNBF-related CRS points attained	*None known*
	Risk modeling	Intensive numerical modeling	*None known*
Increased tax revenues	Tax revenue	Request data from relevant government authority	*None known*
Eco-tourism opportunities	Community perception	Interviews Willingness to pay polling or surveys	*None known*
Decrease in cost of living	Cost of living	Cost of living analysis	Observational analysis

Source: adapted from MARCO, 2017

Box 1. Special Case: System of Environmental-Economic Accounting Ecosystem Accounting

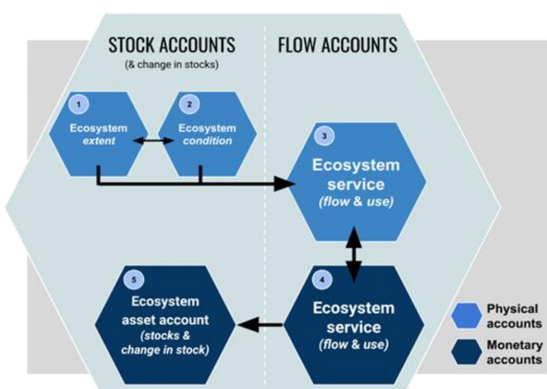
SPECIAL CASE:
System of Environmental-Economic Accounting Ecosystem Accounting (SEEA EA)

Because "economic co-benefits rarely provide significant environmental co-benefits, prioritizing economic co-benefits of a NBS may result in poor outcomes (i.e., trade-offs) for the environment." (DHI, 2024b). The System of Environmental-Economic Accounting Ecosystem Accounting (SEEA EA) is an alternative and powerful tool to help with the quantification and optimization of a NBS project's environmental and economic benefits in projects where fundamental objectives fall under both categories. SEEA EA is "a framework that integrates economic and environmental data to provide a more comprehensive and multipurpose view of the interrelationships between the economy and the environment and the stocks and changes in stocks of environmental assets, as they bring benefits to humanity" (United Nations, 2021). By using this ecosystem accounting framework, a comprehensive and statistical way of accounting can be achieved to help determine the full impact of a NBS project as well. The framework also provides a monetary number, which can be more easily understood by decision makers and compared to other goods and services. The SEEA EA therefore allows for a more standardized way to complete a cost-benefit analysis, more informed economic policy planning, and simple comparison of the capital costs and maintenance over the lifetime of a project. Hence, ecosystem accounting allows for the economic value of a system to be determined, and therefore may be used as a performance indicator of the contributions of a NBS project to the economy.

To account for the economic benefits, SEEA EA uses five core metrics and indicators (Figure 5):

1. Ecosystem Extent – Captures the total recorded area of each ecosystem and tracks how ecosystem types evolve over time;
2. Ecosystem Condition – Monitors and records the condition of selected ecosystem asset characteristics at defined points in time;
3. Ecosystem Services (co-benefits) – physical accounts – Records supply of ecosystem services by ecosystem assets and their utilization by economic units, including households;
4. Ecosystem Services (co-benefits) – monetary accounts – Captures the monetary evaluation of ecosystem services and their co-benefits; and
5. Ecosystem Asset Account – Records changes in stocks of ecosystem assets, and accounts for ecosystem degradation and enhancement.

Figure 5. Ecosystem accounts and how they relate to each other



Source: United Nations et al., 2021

4 Special Considerations for Ecosystems and NBS Type

The selection of performance indicators and related monitoring techniques is heavily influenced by the ecosystems where NBS are situated or with which they are closely integrated. This chapter outlines considerations which should be incorporated when developing monitoring plans for a range of ecosystems and NBS types. Special considerations have been broadly grouped into: Beaches and Dunes, Wetlands and Tidal Flats, Islands, Coastal Forests and Woody Areas, Submerged Features, and Hybrid features. A brief description of each habitat type and how their characteristics may impact monitoring plan design and implementation is provided below. Case studies are included to highlight key concepts.

4.1 Beaches and Dunes

Beaches and dunes are sandy coastal systems that occur on coasts within Canada, the United States and Mexico. They are more extensive on trailing edge coasts with wide continental shelves of the eastern seaboard, which are characterized by barrier islands, spits, and beaches (Bird and Schwartz, 1985; Luijendijk et al., 2018). Extensive dune fields also exist on the western coasts of the United States and Mexico, with the longest expanse of coastal dunes in Oregon State and largest dune fields in southwestern desert areas (Sherman, 2021). They occur in many settings including mainland, barrier, headland, and estuarine coasts where there is adequate sediment supply (Lodder et al., 2021). Beaches and dunes are inherently dynamic systems, shaped by both marine (wave and tides) and terrestrial (aeolian) processes (Davidson-Arnott et al., 2019). They also serve protective functions with environmental and high amenity (e.g., tourism) benefits (Lodder et al., 2021).

NBS with beach and dune systems mimic characteristics of natural environments to provide specific services such as coastal protection, recreational use, or habitat for species at risk (Lodder et al., 2021). NBS for sandy systems may include for example, beach nourishment (including mega nourishments) or dune restoration using a variety of techniques (Bridges et al., 2021). It may also include hybrid systems which include buried revetments that provide additional protection during high energy storm events, for example (Lodder et al., 2021). Beaches and dune systems are discussed further in the *Retrofitting Existing Infrastructure* report.

Some key drivers for these types of NBS are to restore, maintain or enhance coastal processes to increase resiliency. Coastal resiliency refers to the ability of a system to recover following impact, which will vary depending on system specific characteristics and the level of impact. NBS to improve resiliency will therefore be site-specific and may include adding sediment and native vegetation which can increase beach, dune and shoreface volumes. This can enhance the existing buffer against erosion and decrease inundation risk (e.g., to assist in flood-risk management) (Lodder et al., 2021). These projects require flexibility in design and maintenance, since coastal environments are dynamic and evolve through interconnected processes and feedbacks. It is therefore important to consider downdrift impacts both from an ecological/environmental and an economic perspective. For example, the addition of sediment through nourishment will need to consider the ecological effects and resultant changes due to habitat transition. Additionally, monitoring programs will need to consider both updrift and downdrift effects as the NBS and beach/dune systems evolve. For example, a mega-nourishment updrift will exert an influence on benthic organisms at the site (warranting additional environmental monitoring, as outlined in Table 7). In all cases, it is important to reserve space for natural landward migration (Lodder et al., 2021).

Effective design and monitoring of beach and dune NBS requires a cross-disciplinary approach. Essential disciplines include engineering, coastal geomorphology, ecology, governance, and social science. Evolution of beach nourishment practices now includes considerations of human safety and water recreation (e.g., rip currents), groundwater dynamics and ecosystem impacts (de Schipper et al., 2021). These expand the scope of conventional monitoring of physical and ecological elements such as beach width, slope, dune dimensions and vegetation cover to beach user surveys, real estate values, benthic invertebrate, and bird surveys.

Case Study 3: Playa Hermosa Dune Restoration

Playa Hermosa Dune Restoration:
Increasing Social Fundamental Objectives by Restoring a Dune and Beach System

Ensenada, Baja California, Mexico

Playa Hermosa is located in Ensenada, Baja California, Mexico. While the beach is in the city, about 3 km from downtown, the access to the beach was via a dirt road, and the beach was seldom used. Sections of the beach had maintained dunes while other sections had degraded dunes. In, 2009, the construction of a main road started, together with a beach recuperation plan. As a result, the municipality did a project in, 2010 to restore the degraded dunes, create access to the beach using boardwalks to preserve the dunes, and restrict all construction on the seaside of the road.

Figure 6. Changes in the beach and dune system pre-(2006) and post-restoration efforts (2011)

Source: Google Earth, 2022

The beach, while still suffering water quality issues due to the arroyo discharges on the northern end, is now frequented by locals, who use it heavily for exercise and recreation. The project had been threatened by new proposals that would have removed the dunes to create a skate park. But social pressure has helped maintain the dune restoration project and, in, 2023, the skate park was constructed at an alternative location.

Figure 7. New boardwalk installation over dunes to provide access to the beach

Source: courtesy of Lorax, S.A. de C.V.

The increased availability of high-resolution digital elevation and surface models, derived either from LIDAR or repeated low altitude aerial surveys with control points surveyed with high precision, have allowed for accurate, volumetric measurements of the beach sand to be calculated at low tide (see Table 5). Coupled with repeat bathymetric surveys of the nearshore zone, a sediment budget (sediment inputs and outputs) can be calculated and can track changes over time (Davidson-Arnott et al., 2019). Changes in the sediment budget will translate to a continuum of changes in foredune characteristics, beach width, and ability of the nearshore to recover from disturbance events such as hurricanes (Ciarletta et al., 2021). Important considerations for accurately calculating a sediment budget include the selection of a relevant spatial and temporal scale to match the performance criteria; an understanding of the coastal system in question and its dynamics and consideration of long-term trends and natural variability observed in coastal state indicators (e.g., erosion, progradation) (Lodder et al., 2021).

Sandy beach and dune systems are inherently very dynamic, with large morphological changes occurring seasonally (e.g., the beach profile in winter versus summer) and after significant storms. Therefore, the timing and frequency of surveys need to be carefully considered. Seasonal and annual assessments of sedimentation and erosion can be performed along transects using a combination of real-time kinematic global positioning system (RTK GPS) or lidar surveys with single beam echo-sounding data. Care must be taken to convert bathymetric depths (commonly relative to chart datum) to a terrestrial vertical datum. Annual surveys should be taken at the same time of year. Profiles can then be compared to a reference coastline—a technique commonly used in the Netherlands to inform nourishment schemes (Elias et al., 2012). In addition, surveys can be conducted after large storms to quantify impacts and track post storm recovery. In northern climates, snow and ice cover including presence (or absence in the case of warming winters) of an ice foot will impact sediment transport processes and morphological changes. In southern climates, beaches and dunes used primarily for tourism will also respond to and be impacted by coastal management activities (e.g., beach raking, burial or removal of wrack) and human activity (e.g., foot traffic through dunes, use of recreational vehicles) which will influence the monitoring program. Inclusion of social components such as type of beach use, frequency of activity and public safety (e.g., number of days closed to swimming due to dangerous rip currents) will be important to distinguish between natural and anthropogenic drivers of change.

4.2 Wetlands and Tidal Flats

Wetlands and tidal flats occur in the intertidal zone and play an important role in the coastal system. They can be incorporated into different types of NBS with differing effects. For example, foreshore wetlands adjacent to dikes or levees can reduce wave energy and thus the risk of overtopping and flooding while those incorporated into living shoreline structures function to stabilize the shoreline, decreasing erosion and retreat rates. Occurring in low and moderate energy environments where the accretion of sediments leads to the establishment of vegetation, these critical habitats can vary in form depending on climate, geography, sediment characteristics, hydroperiod, salinity regime and many other factors. Protective functions and ecosystem services likewise vary based on the type of wetlands and tidal flats present, but often include wave reduction, improved flood capacity, water treatment services, carbon sequestration, biodiversity support, and recreation. Coastal wetland types include (but are not limited to) salt marshes, brackish marshes, tidal freshwater marshes, mangrove swamps and bottomland hardwood swamps. While many tidal marshes and coastal wetlands are dominated by grasses and rushes in the *Sporobolus (Spartina)* and *Juncus* genera, the presence of shrubs and large tree species such as mangrove (Box 2) and tupelo can require different approaches when monitoring methodologies are considered (see *Section 4.4*). Wetlands and tidal flats are discussed further in the *Retrofitting Existing Infrastructure* report.

Three primary characteristics distinguish wetlands from uplands: hydrology, vegetation, and soils/sediments. These indicators appear in multiple co-benefit categories identified in *Section 2*, as they focus on the biophysical functions that form the foundations of wetland systems – making them a good place to begin when selecting a monitoring program's components. The addition of other indicators, such as public usage (social), monetary assets (economic), or species diversity can greatly improve the value of the monitoring program.

The primary control on the morphology and structure of wetland and tidal flats is hydrology, which directly impacts soil and sediment processes and vegetation community composition. Hydrology parameters can include hydroperiod, water depths and flows, flood extent mapping, wave height, and water quality and can be associated with ecological and structural dimensions of the monitoring program (Science + Resilience Institute Jamaica Bay, 2020). Methodologies are summarized in Tables 3, 5 and 6, and can range in both complexity and cost. For example, visual assessments (e.g., presence of wrack lines, Ordinary High-Water Mark, or erosional areas) may be recorded with a low level of effort and cost while hydrodynamic modeling (typically needed in complex and/or higher risk scenarios) is costly, time consuming, and requires a high level of expert input.

Vegetation plays a critical role in protective functions of wetlands by reducing wave energy, as well as providing critical habitat and ecosystem services (Table 2; Table 5). Vegetation can be measured at various scales and methods may differ depending on the focal scale (Table 5). Species density, diversity, and biomass are often important components of monitoring programs as they serve to measure both wave dampening capacity and biodiversity (Table 5). At larger scales, activities such as cover mapping can contribute to understanding co-benefits such as rare species habitat.

Soils and sediments are important for wetlands and tidal flats in terms of productivity (soil characteristics relate to vegetative growth and elevation to zonation) and their ability to survive sea level rise. The ability of tidal wetlands to keep pace with sea-level rise is tied directly to their ability to increase in elevation, primarily through sedimentation and sub-surface processes (Nolte et al., 2013). While elevation surveys, often along transects to derive profiles, and elevation models (DEM, digital surface model) are important to identify landscape-scale changes in the intertidal area morphology (Table 5), they are often unable to adequately capture small but important changes in elevation over the short term, particularly in areas with low suspended sediment concentrations and small tidal ranges. One of the desirable characteristics of tidal wetlands for NBS is its ability to vertically keep pace with sea-level rise and grow vertically within the tidal frame (Cahoon et al., 2006). Specialized equipment such as Rod Surface Elevation Tables and Marker Horizons which measure both below and above ground processes can be used to detect change in elevation at sub-centimeter resolutions (Webb et al., 2013; Lynch et al., 2015). These measurements can be used to assess if the tidal wetland platform is keeping pace with relative sea level rise or subsiding. It can also be used to determine if addition of thin layers of dredged sediment is required as an adaptive management approach. Techniques to classify soil conditions can vary in both cost and complexity, ranging from rapid field protocols to classify soil texture and color as per functional assessment or wetland delineation (New Brunswick Department of Environment and Local Government, 2018), to long-term carbon sequestration studies employing static greenhouse gas chambers and soil coring (Bartolucci et al., 2021).

Box 2. Special Case: Mangroves

SPECIAL CASE:
Mangroves

Mangrove forests are increasingly being integrated into flood management strategies in low elevation coastal zones (Menéndez et al., 2020; Gijsman et al., 2021) and in hybrid-engineering solutions (Sutton-Grier et al., 2015). Similar to tidal wetlands, they reduce surge levels and attenuate wind waves; however, they do so via characteristic above-ground aerial root systems. These root systems and the compact physical form of mangrove forests can make it very challenging to monitor these systems using conventional methods. Access and navigation can be challenging. In addition, successful implementation and monitoring requires a "mechanistic understanding of mangrove functionality and persistence" (Gijsman et al., 2021, 1). Similar to tidal wetlands, this includes hydrodynamic, morphological and ecological processes taking place across various temporal and spatial scales. These multi-scale interactions encompass the tree scale (focusing on local short-term dynamics around trees and tree patches), the forest scale (involving dynamics of complete transects along elevation gradients through mangrove forests), and the ecosystem scale (Gijsman et al., 2021).

Field monitoring typically focuses on tree- and forest-scale processes whereas remote-sensing techniques can provide valuable insights on forest- and ecosystem-scale processes and identify forest structure changes. Measurement of hydrodynamics, morphology and ecological parameters are similar to those already reported. Note that it is generally difficult to obtain topographic data in mangrove forests because dense vegetation hampers RTK GPS and direct measurements (Gijsman et al., 2021). Many remote sensing methods are also affected by the tree canopy. Direct measurements are performed at the tree-scale, involving assessment of tree density, tree species, tree stem diameter, tree heights, and tree roots along a transect to representatively analyze the ecosystem.

In addition to contributors to surface elevation changes already mentioned for tidal wetlands, mangroves exhibit additional contributions, including the growth of algae and microbial mats, as well as the accumulation of leaf litter and detritus (Cahoon et al., 2006). Field surveys typically encompass various tree-scale processes, such as root growth, tree growth, microbial mat or algae growth, and the buildup of detritus and leaf litter. Tree growth is evaluated through manual measurements or dendrometer bands (stainless-steel bands placed around the tree stem) (Lovelock et al., 2011) or by tagging and remeasuring select trees (Feller et al., 2015). Root growth may be measured with root ingrowth bags, which are nylon mesh bags filled with natural sediments, buried within the site, and later collected to measure the produced-root biomass (Lovelock et al., 2011). The contribution of leaf litter or detritus to surface elevation changes can be gauged using litter baskets (Steinke and Ward, 1989). The growth of algae or microbial mats may be measured by constructing surface screens (McKee, 2011) or from cut pneumatophore roots (Steinke and Ward, 1989).

Case Study 4. Cheverie Salt Marsh Restoration

Cheverie Salt Marsh Restoration:
Restoring Ecosystem Services and Coastal Protection

Cheverie, Nova Scotia, Canada

In the fall of, 2005, the Nova Scotia Department of Transportation and Infrastructure Renewal and CBWES Inc. undertook restoration works for tidal flow and fish passage to Cheverie Creek, NS, Canada, restoring 43 ha of salt marsh habitat. At the same time the Cheverie Crossway Salt Marsh Society formed, providing strong community support for the project, and eventually leading to the construction of a hiking trail, interpretive signage, and a camera obscura (Nova Scotia: Off the Beaten Path, 2019).

Figure 8. New culvert installation in, 2005

The monitoring program was primarily focused on ecological indicators and intended to:

- Document the efficacy of the compensation being undertaken,
- Determine the nature, extent and direction of change, and
- Document restoration progress and determine project success.

A BACI approach was taken, with both baseline and reference site conditions used to quantify change. Baseline data were collected from, 2002 to, 2005 by the Ecology Action Centre, Saint Mary's University, and CBWES. CBWES established and executed a comprehensive, long-term post-restoration monitoring program covering years one through three (2006–2008), five (2010), and seven (2012). During years four and six, the monitoring activities were limited in scope. The monitoring program needed to be designed for the unique conditions of the Bay of Fundy—a macrotidal estuary with exceptionally high tides, high suspended sediment concentrations, and variable winter conditions. To this end, the program was adapted by CBWES from the Gulf of Maine Regional Monitoring Protocol (Neckles et al., 2002). Parameters sampled included:

- Hydrology (water levels, hydroperiod, groundwater);
- Soils and sediments (accretion, elevation, characteristics);
- Vegetation (composition, abundance, height, habitat mapping);
- Nekton (Composition, species richness, density, length);
- Invertebrates (abundance, species richness); winter condition (visual assessment).

Figure 9. Cheverie Marsh 15 years post-restoration

Source: CBWES Inc.

Methodologies used included low-cost/low-tech approaches and more complex and costly measures. Monitoring over the seven years following restoration indicated that the Cheverie Creek system was meeting restoration goals as anticipated. The development of new marsh exceeded the predicted extent of tidal wetland habitat, while existing wetland had characteristics (vegetation, soils) which aligned well to the reference site. The new hydrological regime was sufficient to flood the entire 43 ha marsh with tidal waters on spring high-tide events.

4.3 Islands

Islands are typically characterized by relatively high wave energy environments and exposure to coastal processes. Sea-level rise and increased storm severity require particular attention to shoreline changes that can affect the overall resiliency of an island. Islands often function as barriers protecting the mainland coast and provide numerous benefits to regions that have them including recreation, maintenance of routes for boat navigation, commercial opportunities, and habitats for rare species (Gallani et al., 2021). An island as a whole can represent a NBS due to its coastal protection functions for the mainland, but islands may also provide opportunity for the deployment of multiple kinds of NBS on a smaller scale, such as wetland creation or restoration, or the creation of oyster reefs. NBS implementation can involve creation of entire islands using dredge material, or the restoration or enhancement of key features of existing islands. Due to their isolation from the mainland, some islands can afford unique opportunities for NBS such as habitat creation to support rare seabird colonies that may be impossible on the mainland (Babcock and Booth, 2020; Bracey et al., 2022) (Box 3). NBS involving islands are discussed further in the *Retrofitting Existing Infrastructure* report.

The key drivers of island resilience include wave and wind exposure, sediment transport, and vegetation. Design of NBS involving islands requires assessment of prior wave/wind conditions, sea levels, tides, and the availability of sediments. Monitoring programs for islands thus emphasize indicators that drive the stability and resilience of an island in the face of continuous and episodic coastal effects including climate change. NBS implementation on and around islands often involves addition or movement of sediments, so monitoring programs need to include specific indicators for sediment transport. These may include repeated bathymetric and elevation surveys (Table 3), mapping of subsurface or temporarily submerged features, such as mudflats, and/or periodic assessments of regional sediment supply via monitoring coastal erosion similar to Section 4.1 as well as suspended sediment concentrations in rivers and changes in bathymetry (Tables 3-4). Beyond the large-scale distribution and movement of sediments, the characteristics of the sediments themselves are very important to foundational island processes such as soil building; particle size, bulk density and organic matter content should be quantified and compared to reference or target values (Tables 3–4).

Elevation surveys, often along transects, to derive profiles are important to identify how the island is changing relative to tidal range, water levels or storms. The amount of island area at different elevations, as well as the island crest height, may be important indicators in some cases (Table 3). Wave energy and height (including during storms), current speeds, erosion rates, wave run-up elevations and the frequency, duration, and area of inundation or overwash are all key indicators that can be included in island NBS monitoring programs (Tables 3–5). In northern environments, ice coverage in winter may also be an important variable to include in monitoring programs as ice can have both positive and negative effects on sediment transport and coastal erosion.

Water quality indicators such as salinity, suspended sediment concentrations, dissolved oxygen content and temperature (Table 7) may also be important if NBS targets include wetland or subtidal habitat (Gallani et al., 2021). Vegetation surveys are important to document vegetation cover and composition; cover of shorelines by various kinds of debris is also an important indicator that can influence NBS success (Table 5).

Construction costs can be substantially higher on islands compared with mainland installation of NBS, therefore, it is crucial to closely monitor any construction-related factors that could potentially affect the performance of NBS during the construction phase. This proactive approach can help mitigate the necessity for expensive interventions after the NBS installation is completed, while also ensuring minimal environmental impact (Gallani et al., 2021). Monitoring for construction impacts may include visual inspection to help detect areas where equipment has caused compaction of sediments or alterations of flow patterns (Tables 3–4). For islands that are relatively isolated from human populations, after installation of NBS, periodic site visits should be incorporated to detect any changes caused by sudden events; post-storm visits should also be planned.

Islands can be categorized into three groups: barrier islands, deltaic islands, and in-bay islands (Gallani et al., 2021). Barrier islands are generally long and narrow, and often protect mainland coastlines from storms. Barrier islands often migrate away from the open ocean due to the removal of sediments from the front (open ocean side) and deposition on the backshore (Gallani et al., 2021). This natural process should be monitored to assess the overall resilience of barrier islands. Their narrow shape makes vegetation cover a very important indicator of the integrity of a barrier island in the face of increased storm activity and sea-level rise (SLR). Deltaic islands form in estuaries and result from processes of sediment deposition and wave/current action. Human activities often alter or reduce sediment supply in estuaries, hence, critical indicators for monitoring include sediment supply and elevation changes. It is important to note that barrier and deltaic islands, particularly in sandy systems, are dynamic and should be expected to move and migrate over time as part of natural coastline processes. In-bay or in-lake islands tend to have a rounder shape than barrier islands but can also experience landward migration.

Box 3. Special Case: Bird Habitat Islands

SPECIAL CASE:
Bird Habitat Islands

Island creation or habitat enhancement is occasionally undertaken to support bird species-at-risk (SAR) (Babcock and Booth, 2020). Substrate cover characteristics (e.g., vegetation vs. open gravel) may be important to particular bird species and are often incorporated into monitoring programs (Rock et al., 2007). Since seabirds typically access benthic or other marine resources, sometimes at considerable distances from the colony, it may be worth incorporating surveys of these other resources, such as fish stocks, to monitor food availability as this can be affected by many elements of coastal change (Pratte et al., 2021). Additionally, the effects of large seabird colonies on islands can result in changes to substrates such as nutrient enrichment; potential shifts in vegetation due to such nutrient subsidies should be carefully monitored as should soil nutrient levels in cases where negative effects are likely (Table 7). Likewise, while islands can play an important role in bird SAR conservation, seabird colonies can completely kill off terrestrial vegetation leading to habitat destruction, erosion and loss of island area (Hebert et al., 2014). In regions where species like cormorants can cause these effects, monitoring of island use by such species is recommended in order to assess the risk of new colony formation.

Case Study 5. Poplar Island

Poplar Island Environmental Restoration Project: Bird Habitat and Wetland Restoration

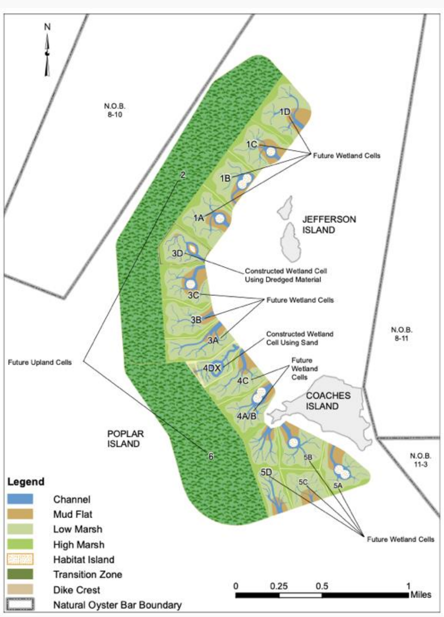
Chesapeake Bay, Maryland, USA

The Poplar Island Environmental Restoration Project is located in the Chesapeake Bay, Maryland, USA. The project used dredge material to restore 460 ha of habitat. The NBS interventions began in, 2003 with a demonstration wetland cell (13 ha), and subsequent installations involved completing additional cells over the last, 20 years. Habitats created include 230 ha of tidal marsh (80% low marsh, 20% high marsh). The island was originally over 400 ha in the 1800s but had been reduced to approximately 2 ha by the 1990s due to erosion (Erwin et al., 2007).

The project is a partnership among federal and state government agencies. Interventions began with a 6.1m rock-armored exterior dike in, 2006 with several interior dikes defining smaller cells that were to be filled with dredge material at later times for habitat creation. Project targets included 80% low marsh and, 20% high marsh in wetland areas, and other habitat features such as open mudflats, open water and small nesting islands were also added. Target species for habitat creation included terns, American black duck, osprey and egrets.

The detailed monitoring program is linked tightly with project objectives (Derrick et al., 2007). Each indicator ("attribute") is associated with a quantitative target and an acceptable range of values, e.g., the species composition indicator specifies a target of >80% cover of *Spartina alterniflora* in created low marsh habitats with an acceptable lower bound of >20% (Derrick et al., 2007). Size (area) of habitats is an indicator as is coverage by wetland flora. These targets were determined by assessing the habitat needs of target bird and other species. Other biodiversity indicators and metrics include use of marshes by fish, birds, invertebrates and herpetofauna, with the metrics being presence/absence of the target groups. For nesting habitat areas, size (area of island above high tide line), vegetation cover, nesting (presence/absence), and fledging success (no. young per nest) were the key indicators used. Most indicators were assessed annually (Derrick et al., 2007).

Figure 10. Poplar Island site plan



Source: Derrick et al., 2007

Predator presence is a key determinant of the viability of many species of seabird colonies, so monitoring is important for early detection. On Poplar Island, infrared video cameras to determine owl presence were installed. Other ongoing interventions required to maintain the restored habitats include removal of vegetation from areas that are supposed to be vegetation-free, or addition of shells, sand or gravel (Erwin et al., 2007).

The monitoring program was augmented in, 2014 by aerial image analysis (Prosser et al., 2022). This was used to generate habitat maps and shows that approximately 16 ha of high marsh and 43 ha of low marsh had been created by, 2014 (Prosser et al., 2022). Black ducks and muskrat are breeding in some of the created cells. The island now supports the main nesting colony of common terns in Chesapeake Bay.

4.4 Coastal Forests and Woody Areas

Trees and shrubs differ from herbaceous species in that they have long-lived woody tissues and can accumulate substantial aboveground biomass that is relatively stable over time. Mangroves are trees that can be important components of tidal wetlands in the tropics and are discussed separately in Section 4.2. Many plant communities considered important in NBS are herbaceous, such as salt marsh dominated by grasses, but woody vegetation is often present just inland from tidal wetlands or dunes, at higher elevations. Riparian habitats can also support forest and shrub communities. These coastal forests or shrublands provide important coastal protection functions via wind attenuation, wave attenuation during extreme storm events, and deep roots that act to stabilize soils. Trees and shrubs may also offer significant habitat features including potential for bird perching and nesting, and shelter for terrestrial vertebrates. Shrublands and coastal forests also contribute to plant diversity at the landscape scale and may host rare species. Other co-benefits of woody vegetation include carbon storage, local microclimatic cooling, and improved aesthetics. Coastal forests and woody areas are discussed further in the *Retrofitting Existing Infrastructure* report.

Monitoring programs for sites that include coastal forests and shrublands incorporate many of the same indicators used for herbaceous vegetation, such as cover or species diversity. If coastal forest or shrubland is a major component of an NBS or is the target of restoration, larger quadrat sizes are often used to capture representative samples of plant communities composed of larger individuals (e.g., 5 m x 5 m or, 20 m x, 20 m plots). For NBS where erosion control is a key goal, the amount of bare ground not covered by litter, woody debris or plants is a key driver of erosion so tracking coverage by bare substrate is very important, especially on slopes or cliffs (Ellis et al., 2022) (Table 5). In areas where coastal effects are harsh and can limit the size and composition of woody plants, a 'treeline' can be present on the coast; the treeline is expected to move inland under scenarios of increased storm activity and SLR. The height of woody plants is often an indicator of coastal exposure effects (including wind, salt spray, etc.). Slope may also be an important indicator of shrubland or forest stability, as the large aboveground biomass can promote toppling in windstorms, which in turn can lead to root uplift and substrate erosion, not to mention death of trees and shrubs.

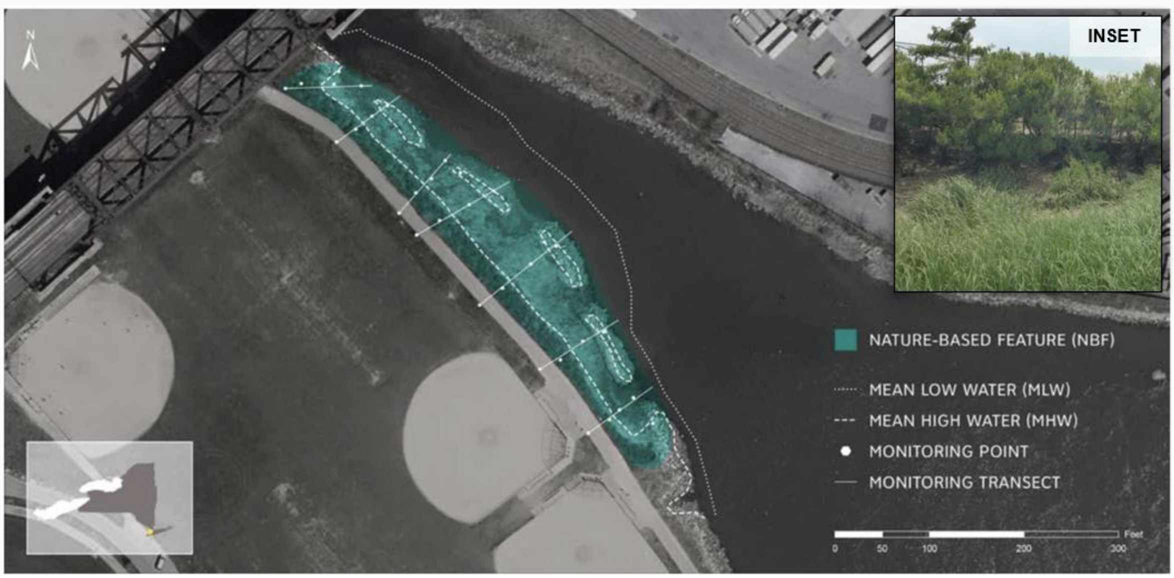
Case Study 6. Bronx Kill Nature-Based Shoreline Feature

Bronx Kill Nature-Based Shoreline Feature: Urban Shoreline Restoration

Harlem River, East River, New York, USA

This project involved salt marsh habitat creation behind a rock sill, as well as scrub shrub habitat adjacent to the salt marsh on the landward side (Science + Resilience Institute Jamaica Bay, 2020). The site originally had a degraded shoreline protected by riprap and was devoid of native vegetation. NYC Parks created five rock sill islands within a salt marsh for coastal protection. The scrub shrub habitat created consisted of two native species of salt tolerant shrubs (*Iva frutescens* and *Baccharis halimifolia*) that require a higher elevation than the *Spartina alterniflora*-dominated salt marsh. Researchers used seven profile lines (transects) with elevations recorded via an RTK GPS with assessment points on each transect in each of the three features (rock sill, salt marsh, shrubland). Social assessment was carried out via interviewing people using the site (bikers, birders, shellfish harvesters, etc.). Local stewardship and site monitoring are carried out by the Randall's Island Park Alliance. Monitoring has revealed that vegetation growth has been strong in both created habitats, native mussels have colonized within the salt marsh, and use by people has increased since the restoration, mainly for recreation.

Figure 11. Bronx Kill site: shoreline features and monitoring point locations. Upper right inset shows restored salt marsh and shrub scrub habitats, facing inland



Source : Science + Resilience Institute Jamaica Bay, 2020

4.5 Submerged Features

Submerged features are those that are below the intertidal zone. This primarily includes restoration of critical submerged flora (e.g., eelgrass beds, kelp forests, coral reefs), creation of submerged breakwaters/reefs (e.g., artificial reefs and sandbars), and/or the installation of wooden kickers (structure projecting from shoreline at an angle to the direction of flow; the angle determines in what direction the flow is diverted away from shoreline). Each of these features have different benefits and co-benefits. While wooden kickers are traditionally freshwater features, it can be adapted to the bidirectional flow of tidal rivers to redirect the current and hence the main benefit is that it can control the location of erosion. Restored eelgrass beds and kelp forests, and created/restored reefs, however, have been used extensively in coastal systems and are critical coastal features and habitats that support a large diversity of biota, and hence increase fisheries production, while protecting the shoreline from erosion and flooding by attenuating wave energy and trapping sediment (Oreska et al., 2021, Orth et al., 2020, Mora-Soto et al., 2021, Fabian et al., 2013). Other co-benefits also include improved water quality and habitat creation, for submerged flora carbon and nitrogen sequestration, and for submerged breakwaters coral and/or shellfish reef recovery (Oreska et al., 2021, Kroeger, 2012). Submerged features are discussed further in the *Retrofitting Existing Infrastructure* report.

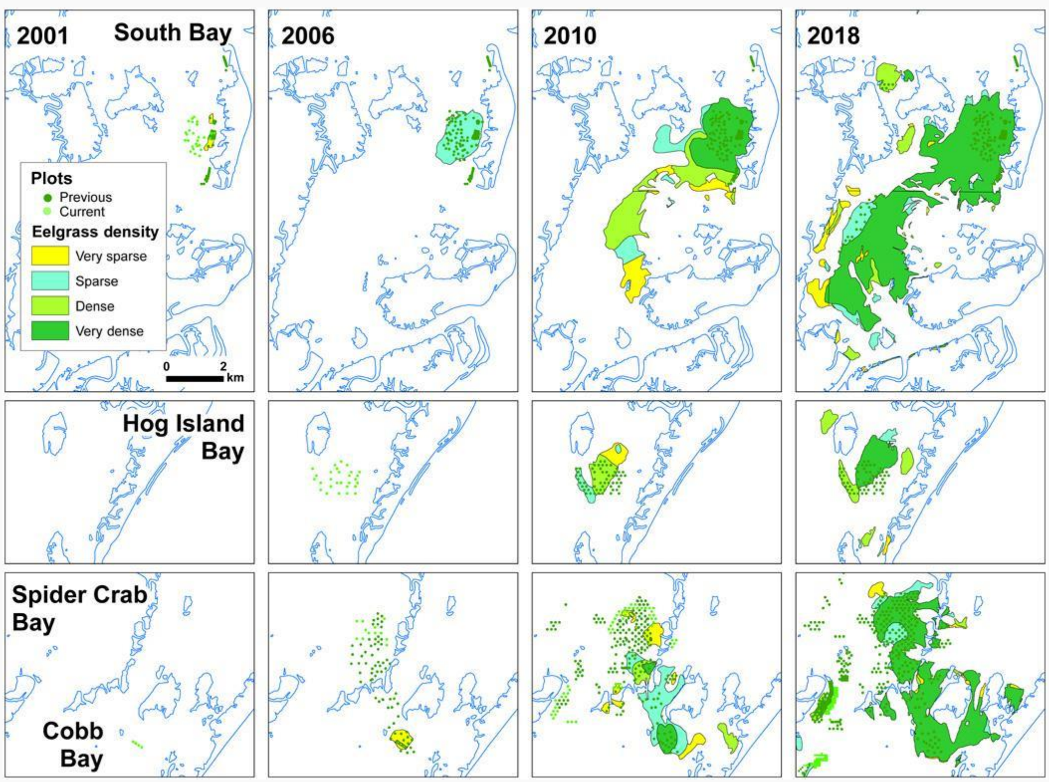
For successful monitoring and project implementation of restoration of submerged flora and reefs, the stressors that resulted in the degradation need to be identified, mitigated, or compensated for prior to restoration, and then monitored post-restoration to ensure recovery (Orth et al., 2020). Some of these stressors can be environmental stressors acting over long periods of time, such as climate change or ocean acidification, and therefore it is best practice for the long-term success of a project to consider not only the single habitat but the entire ecosystem (Orth et al., 2020, Oreska et al., 2021). This includes bathymetry (particularly crucial for placement of artificial reef structures), substrate condition and composition, water quality, fetch distance, water temperature, depth, sediment grain size, and adjacent ecosystems (which are important for seed or shellfish larvae supply) (Table 3, 4, 5, and 7). It is also important to consider the materials used for the projects, and that the appropriate materials for the conditions are chosen, with care taken to avoid the unnecessary use of plastics (Walters et al., 2022). Monitoring submerged flora uses many of the same indicators outlined for herbaceous vegetation (see Section *4.4 Coastal Forests and Woody Areas*) including vegetation quadrats, and recording habitat attributes such as plant species diversity, biomass, areal coverage, and/or shoot density (Orth et al., 2020, Oreska et al., 2021, Mora-Soto et al., 2021). Monitoring reefs/submerged breakwaters include the biological attributes, such as diversity and abundance of fish species or early life history stages and recruitment patterns of fish, and physical attributes, such as changes in reef shape, flow velocity, depth, and substrate over time. An aspect that can be overlooked, although it is important for a reef's long-term success in promoting biodiversity (if that is one of the goals of the project), is monitoring invasive species, accumulation of algal mats and sedimentation, and the wave and current velocities that are being received by the reefs (if the energy is too high, fish eggs can be damaged) (McLean et al., 2015, Hylkema et al., 2021).

Case Study 7. Virginia Eastern Shore Eelgrass Bed Restoration

Virginia Eastern Shore Eelgrass Bed Restoration: Virginia, USA
Large-Scale Restoration of Critical Habitat for Culturally and Socially Important Species

This project is the world's largest successful eelgrass bed restoration project. A stretch along Virginia's Eastern Shore had the eelgrass beds wiped out in the 1930s due to hurricanes and disease. It resulted in the near complete collapse of the ecosystem with bay scallops disappearing and finfish and crabs becoming scarce. In the late 1990s, seeds began to be harvested from the York River and dispersed in a Seaside Bay, which resulted in successful germination. This success allowed the expansion of the project goals to include the promotion of ecotourism and infrastructure construction, removal of invasive reeds, research on shorebird habitat, predator removal for shorebirds, implementation of aquaculture best management practices, conducting oyster inventory and reef construction, public outreach initiatives, and the reintroduction of bay scallops to seagrass beds. Over the past few decades, in an area that had completely lost all eelgrass coverage, there are now 9000 acres (approx. 3,642 ha) of eelgrass. This was achieved with significant involvement from volunteers that collected and broadcasted 37.8 million eelgrass seeds in four bays, spanning 309 acres (approx. 125 ha). Key parameters monitored included spatially intensive water quality sampling as well as fixed-location continuous, eelgrass density and spatial coverage, chlorophyll, and turbidity levels.

Figure 12. Seagrass cover in the four bays for four time periods: 2001, 2006, 2010, and, 2018



Source: Orth et al., 2020
Note: Cover estimates (very sparse, 1 to 10%; sparse, 11 to 40%; moderate, 41 to 70%; dense, 70 to 100%) indicated by color in each polygon. Small squares in each box represent restoration plots.

4.6 Hybrid Features

Hybrid features may utilize a wide array of both gray and green elements, creating diverse ecosystems. NBS are considered "hybrid" when gray elements, such as oyster shells, logs, biologs/biomats (made of natural, biodegradable materials—often coconut husk), or rocks are used to enhance the function of green shore elements such as vegetation, sand, and gravel. Hybrid features may also result through retrofitting or amending existing gray infrastructure using NBS, effectively resulting in a new hybrid feature. Many—or even most—retrofitting projects will not necessarily utilize NBS alone (resulting in a return to fully natural processes) and will therefore be categorized as hybrid features. See the *Retrofitting Existing Infrastructure* report for more information on retrofitting using hybrid features.

For hybrid NBS, gray elements should be used where they support system processes and can enhance the function of green shore elements. In general, this means that they should be minimized in size and extent, and carefully designed to limit their impact on coastal processes. An example would be the construction of a living shoreline with sill which is a common approach on the eastern seaboard of the USA and starting to be implemented in Canada. In the Yucatán, researchers from the National Autonomous University of Mexico (UNAM) have also implemented and are monitoring the use of a novel bamboo and rope structure to promote dune growth (Case Study 8).

Gray elements can also be buried below the green shore to provide additional protection during extreme events. For example, a buried revetment within a dune system can provide additional protection during large storm events but are designed to allow natural sand transport and dune processes (including recovery) after smaller storm events. In some cases, buried sand-filled geotextiles have also been used.

Hybrid solutions are often considered when asset managers are trying to improve the co-benefits (e.g., the habitat suitability) associated with existing gray infrastructure, or when there is significant uncertainty surrounding the performance of NBS—particularly along shorelines with greater fetch and/or higher energy coastal processes. Because of the many potential benefits of hybrid solutions, there is often a tendency to introduce gray elements into otherwise natural systems, even when it is not entirely necessary. This practice limits the potential co-benefits of the project and fails to take advantage of learning and research around the usage of NBS. Consequently, hybrid solutions may be associated with more environmental impact to the coastal zone than green shore protection and natural, undisturbed shorelines (Green Shores for Homes, 2022).

Monitoring hybrid NBS needs to consider both the gray engineered component and natural elements and performance indicators of the system as a whole. Therefore, hybrid NBS may require the inclusion of additional performance indicators (in comparison to NBS with less components), which should be considered on a project-specific basis. Monitoring should assess the current and future value gained for both the protective and nonprotective (ecological, social, economic) benefits (Suedel et al., 2021). It is particularly informative to compare the hybrid option with a natural analog to determine if the structural (gray) elements were truly needed. In addition, the interaction and potential feedback between gray and green elements of the hybrid NBS need to be monitored (e.g., scour). At the onset of the project, a monitoring framework needs to be co-created by a multi-disciplinary and multi-sectoral team. A key element of this process is the development of a common working language for discussion, collaboration, and reflection between practitioners on the project (Wijsman et al., 2021).

Case Study 8: Sisal/Chelem Beach novel dune fencing

Sisal/Chelem Beach:
Promoting and monitoring dune growth front: a novel hybrid fence technique

Yucatán, Mexico

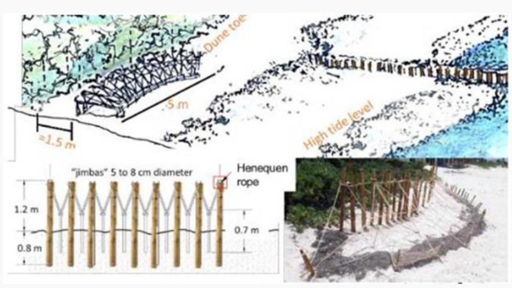
The beaches of Sisal and Chelem are situated on the northern coast of the Yucatán Peninsula, located approximately 30 km from each other. The beaches in Chelem are heavily urbanized and have undergone numerous modifications over the years, such as the construction of groynes (Leija and Lomas, 2018). Although Sisal is less developed, it is experiencing rapid urbanization, which makes it more prone to extreme events. Due to its low-lying dune elevations and a lack of dune vegetation, Chelem is now more vulnerable than ever to erosion and flooding. Sisal is at risk of suffering coastal squeeze which is the loss of natural habitat due to new developments preventing landward transgression, which could lead to significant dune loss.

While the coastal squeeze in Chelem limits the space for dune restoration, the lower urban density in Sisal allows for better restoration and conservation of coastal dunes. Students from the National Autonomous University of Mexico (UNAM) received a grant from the Bepensa Foundation to restore the dunes in Sisal using recycled materials. Through their project, titled "Recycling Dunes" (https://www.reciclandodunas.org/), the team successfully planted over 13,000 native dune plants, covering an area of 5,500 square meters. The project implemented a monitoring program using drone flights to track land cover changes. Although the monitoring program was not funded as part of the project, the team was able to utilize available resources and expertise through the university to undertake the monitoring program. Unfortunately, the program was prematurely halted due to pandemic-related restrictions and only one drone flight was performed before lockdown.

The Chelem and Sisal cases show that securing funding for monitoring programs can be challenging. However, collaborating with research institutes can provide additional resources and expertise to support these efforts. In the case of the Sisal project, the monitoring program is expected to restart using resources from the UNAM. The monitoring program is expected to be composed of the following characteristics:

- *Performance indicators*: Vegetation cover (m^2), number of species, biodiversity (Shannon index), number of invasive species removed, volumetric change (m^3/m), granulometric change.
- *Duration and frequency*: 24 months, with surveys every 4 months
- *Techniques*: quantification of vegetation cover from drone images, monitoring using 2m x 2m squares randomly placed along the strip of coastal dune.

Figure 13. Sketches and photo of the dune biomimicry structure



Source: Leija and Lomas, 2018

4.7 Further Discussion on Techniques

As described in the previous Sections, performance indicator selection will depend on NBS type, climate, monitoring program design, project goals, access to expertise and equipment, and budgetary constraints. Many indicators have multiple possible methodologies (e.g., habitat characterization through habitat mapping or statistical analysis) and corresponding techniques and technologies (e.g., drone imagery versus a species list or vegetation indices). Many possible techniques identified in Section 3 involve trade-offs in cost, accuracy, or intensity and must therefore be carefully considered. Table 12 provides examples of some possible considerations in technique selection for three indicative and theoretical, tidal wetland projects in Canada, Mexico, and the United States. The table highlights the need for project considerations of the climate, NBS type, and regulatory context, amongst other considerations. It should also be noted that monitoring techniques are continuously changing, and this guide is a living document.

Table 12. Possible consideration and implications for technique selection in a tidal wetland monitoring program

Wetland Type, Region	Example Considerations for Monitoring Techniques	Implications
Salt Marsh, Eastern Canada	Typical salt marsh zonation (*Sporabolus alterniflorus* low marsh and *Sporabolus pumilus* high marsh).	Typically, low species diversity (beneficial for species ID, problematic for some vegetation indices, and onerous for stem counts).
	Winter conditions with variable temperatures and ice/snow cover.	Equipment failure and site access possible due to weather.
	Canadian regulatory framework (e.g., Canadian Aviation Regulations for drones, DFO Scientific License).	Sampling efforts requiring permits must be acquired early.
Brackish Marsh, Southeast United States (Gulf of Mexico)	Salt marsh zonation driven by Salt and Freshwater mixing (*Sporabolus pumilus* and *Juncus roemerianu).*	Species diversity may be high. Saltwater intrusion due to climate change may cause unpredictable changes in ecosystem.
	Impacts resulting from heavy shipping and industrial activities (e.g., oil extraction).	Risk to equipment and access, may be a driver for adaptation or disruption.
	United States regulatory framework (e.g., Environmental Protection Agency Wetlands Regulations).	Sampling efforts requiring permits must be acquired early.
Mangrove Swamp, Southwest Mexico	Mangrove Swamp zonation (*Rhizophora mangle* intertidal, *Avicennia germinan* at higher elevations).	Large woody species require larger sampling areas. Access in standing water may be challenging.
	Warm climate with adequate rainfall.	Access restrictions due to poor weather unlikely.
	Lack of infrastructure and skilled labor, low population density.	Monitoring program must address program continuity and resource availability. Use of low-tech and participatory approaches (e.g., community science) may help.

5 Considerations for Data Analysis, Access, and Dissemination

At a time when we are all impacted and affected by climate change, it is of utmost importance that we work collaboratively to find solutions to this very complex and large problem. One of the most important ways to achieve this is through sharing information. The best way to ensure information can be accurately understood when it is shared is to establish a framework (a roadmap of the protocols for specific indicators and performance parameters for a specific project), and to use recognized, evidence-based sampling protocols, and adopt standardized reporting as much as possible. Standardized reporting can help ensure that the lessons learned in past projects inform new projects (Eger et al., 2022). There is great variability in NBS project types and objectives, however, if the reporting is standardized and determined from the beginning of the project then the data/results will have a greater potential to be comparable to other projects. It will also reduce reporting bias which is the selective presentation of successful results. We recommend that reports include at a minimum:

- Introduction of project, project goals, and timelines.
- Description of all sites, study and control(s), and any relevant historical information of the sites (e.g., the tidal wetland control site had agricultural activity 100 years ago, however, had lain fallow and unused for the past 75).
- Thorough description of methodologies, protocols, and analyses.
- Results and discussion of results.
- Conclusions.
- Metadata – appendix containing information such as survey datums used, geographical coordinates, data licenses, ownership and restrictions, additional information about the data including file names and format. This information can also be contained as a 'Read Me' text file which accompanies the data (instead of attached to the project report). Readers should be directed to this file within the written document.

Reporting should include, as much as possible, information such as successes ***and failures*** of a project (Dumitru et al., 2021). Reporting failure is important so that others can learn from past mistakes and avoid wasting precious resources. Ideally, social, cultural, and economic indicators, not just the ecological indicators of a project, would also be reported to help determine if a project supports the 'triple bottom line': environment, society, and the economy (Eger et al., 2022; Dumitru et al., 2021; Halpern et al., 2013).

Data analysis is essential to understanding the trajectory and "success" of a project. There are a wide range of possible data analyses and manipulations possible: from basic to sophisticated statistics or mapping. Some degree of statistics and mapping is essential for reporting and understanding the results of the data collected. Mapping is a particularly useful way to visually compare the ecological changes pre- and post- implementation of a NBS project. With the popularization of Remotely Piloted Aircraft Systems (i.e., drones), aerial mapping has become increasingly accessible and useful in data collection. The degree of sophistication of data analysis will greatly depend upon the expertise and resources available for the project. Regardless of the degree of sophistication for data collection and analysis, it is important to have quality assurance and quality control protocols established and incorporated into the monitoring plan from the beginning. Where possible, it is best practice to use standardized and established techniques and methodologies. This includes the storage of all relevant information and metadata, documenting all forms of data manipulation, and ensuring the data is an accurate representation of the conditions observed. **It is essential to have transparency and reproducibility in the results.**

For data management, it is recommended that projects adopt the FAIR approach (Findable, Accessible, Interoperable, and Reusable), as outlined by Wilkinson et al. (2016). To be findable, established repositories are useful, such as figshare, Knowledge Network for Biocomplexity (KNB), etc. Part of this is ensuring that the data are accessible, Accessibility can be accomplished by ensuring the data are machine-readable and in file formats that don't require proprietary software to open (e.g., of accessible file format: .csv). To ensure the data are interoperable (can be exchanged with others) and reusable, the data must be understandable. This means that the data must have complete descriptors (i.e., unit specifications, abbreviation definitions, and column headings), clear organization (i.e., if using excel, all tabs in the workbook must be clearly labeled and all column headings/variables labels must be consistent between tabs), standardized formatting (e.g., not including color coding in cells), consistent column headings and variable labels (including in the associated report), all data/data labels must be in a single language, and include detailed metadata (e.g., descriptions of column headings, abbreviations, units, what figures and/or analyses corresponds to what data, etc.). Quality control should always be performed (Roche et al., 2015). Roche et al. outlines a list of best practices for data management which is summarized as follows:

- Be mindful of public data archiving,
- Make your data discoverable,
- Provide detailed metadata,
- Use descriptive file names,
- Archive unprocessed data,
- Use standard file formats,
- Facilitate data aggregation,
- Perform quality control,
- Choose a publishing license, and
- Decide on an embargo.

One of the ways of reducing error and ensuring consistency in assessment between sites is to use standardized monitoring field sheets that can be tailored to the particular NBS project or organization conducting the monitoring program. The development of the monitoring sheet can also be used as a process for gathering feedback from other subject matter experts and community members. Examples of monitoring sheets can be found in *Monitoring Habitat Restoration Projects: U.S. Fish and Wildlife Service Pacific Region Partners for Fish and Wildlife Program and Coastal Program Protocol* (Woodward and Hollard, 2011).

Additional discussion on data analysis, access, storage, and dissemination, is provided in the *Monitoring Efficacy* report.

6 Future Directions and Opportunities

There is widespread acknowledgment that community science is a beneficial movement to empower people without professional expertise to contribute to environmental monitoring. Involvement of local residents in NBS monitoring is also an excellent way to spread awareness of the benefits of NBS projects and can foster a sense of ownership and connection. Many of the key monitoring indicators listed above have straightforward techniques that can have widespread and inexpensive application with minimal training, however, some indicators are more difficult to implement without specialized equipment or subject matter expertise and professional involvement (Box 4). Combined approaches that link experts and community members, can be one way of fostering greater local empowerment and engagement with communities. Some options include open-source natural history data sharing and mapping platforms like iNaturalist and eBird which anyone can contribute to, but also allow easy expert vetting of species identifications. Inexpensive sensor networks are also being developed to allow greater access to powerful technologies (Mao et al., 2019); other developments have made technologies like remote piloted aircraft systems cheaper and more accessible to community members. Some economic indicators (e.g., additional economic indicators provided in Table 11) may be challenging for community-science or community-led projects to incorporate into monitoring programs. More research needs to be conducted on how communities might engage with these important components of monitoring projects (Box 4).

If more scientific evidence accumulates documenting how to develop and implement successful NBS, then it is likely to promote the appropriate use of NBS and increase project uptake. It is important, however, to provide more integrative methods and approaches in multidisciplinary teams to address the wide range of performance objectives. There is also a need for more outreach from scientists and engineers who are designing and assessing NBS to make their findings accessible to a broader public, for example, by engaging with communities via social media, preparing policy briefs or plain-language summaries of research, and working with community scientists on monitoring programs. Landscape architects, for example, have a long history of preparing publicly understandable and accessible visual materials that can be used to communicate the benefits and future conditions of FrM and NBS projects. For example, *the Living with Water* project bring together a multidisciplinary and diverse team to help communities living on British Columbia's South Coast prepare and adapt for sea-level rise and flooding, many solutions of which involve NBS.[1] The project team includes academics, practitioners, First Nations, nongovernmental organizations (NGOs), government staff and decision-makers from various levels of government and is developing new planning, design and decision-making tools that "foreground community values, Indigenous knowledge and perspectives in coastal adaptation planning"; "broadens the solution space" by including NBS and "provide recommendations for regional governance arrangements to guide integrated solutions to coastal flood adaptation."[1]

[1] https://www.livingwithwater.ca/

Box 4. Opportunities and future directions related to monitoring methodologies and indicators for NBS and the type of barrier that the opportunities address

	Type of Barrier Addressed			
Opportunities and Future Directions	**Social**	**Technical**	**Environ.**	**Institutional**
1. Host or fund sessions, workshops, training sessions, and seminars on monitoring methodology	✓	✓	○	✓
2. Encourage diverse stakeholder engagement (i.e., policy makers, Indigenous Peoples, social groups, etc.) for entire project life cycle.	✓	✓	○	✓
3. Combine approaches that link experts and community members to foster greater local empowerment and engagement in communities.	✓	✓	○	✓
4. Encourage open-source data sharing and mapping.	○	✓	○	✓
5. Further research on how communities might engage with monitoring projects.	✓	○	○	✓
6. Increased outreach from scientists and engineers that design and assess NBS (e.g., increase social media usage).	✓	○	○	○
7. Encourage and highlight case-studies with long-term results.	○	✓	✓	✓
8. Work to make existing/historical monitoring data publicly available.	✓	✓	○	✓
9. Establish or identify industry standard technical guidance for monitoring methodology (for use by practitioners).	○	✓	○	○
10. Require project teams to commit to data distribution (including failures).	○	✓	○	○
11. Distribute existing monitoring methodology guidance to government, and other applicable organizations.	○	○	○	✓
12. Make funding for monitoring commensurate with capital funding for projects.	○	○	○	✓
13. Continue ongoing initiatives to value natural capital assets provided by NBS, and the value of long-term monitoring for NBS.	✓	○	○	✓

7 Conclusions

Monitoring is a crucial component of any FrM project, including NBS projects. A monitoring program should be designed during the scoping phase of the project so that the overall feasibility can be evaluated, the design can be informed by evidence from early monitoring, and baseline conditions can be established for later comparisons. The monitoring program needs to include indicators of project success to enable adaptive management after implementation. Monitoring programs generally include some kind of reference site(s) that represent target conditions, and periodic comparisons with the reference conditions to assess NBS performance. Two recommended best practice methodologies for this assessment are BACI (Before-After Control-Impact) and RCA (Reference Condition Approach). It is important to also recognize that these baseline conditions may shift over time due to climate change, therefore ongoing monitoring of reference conditions in tandem with the NBS project site is advised. Furthermore, post storm monitoring is recommended to examine the resilience of the NBS project to disturbance events.

Performance indicators for NBS project success can be grouped into four categories:

- **Flood-risk management** indicators typically address the primary goals of coastal NBS: reduction of flooding likelihood and improved sediment management. These indicators are also concerned with compliance with structural or other criteria for the NBS features. The other categories can be viewed as co-benefits but are often primary criteria for success on their own, depending on the project. There are eleven core performance indicators, and eight additional indicators which were identified and can be found in Section 3.2.
- **Environmental indicators** include biodiversity and other considerations about the quality of habitats created or restored. This category also includes indicators of carbon storage and climate change mitigation. There are thirteen core performance indicators, and twenty-two additional indicators were identified and can be found in Section 3.3.
- **Social indicators** address the effects on people from interacting with NBS and may include estimating changes in behavior, perceptions of the NBS or surrounding areas, or less tangible qualities such as sense of place. There are thirteen core performance indicators, and seven additional indicators were identified and can be found in Section 3.4.
- **Economic indicators** attempt to assess changes in local economies related to NBS implementation, including changes to recreational or subsistence activities, changes in insurance claims, or broader economic impacts. There are four core performance indicators, and nine additional indicators were identified and can be found in Section 3.5.

The ecosystem contexts for NBS implementation vary greatly depending on whether the project is wetland-focused, subtidal (e.g., oyster reef creation), taking place on or near islands, a hybrid approach including gray engineering structures or a combination of ecosystems. The regional climate may also require incorporation of additional indicators such as ice cover into monitoring programs. This document provides an overview of different ecosystem types and the special criteria that may inform monitoring programs.

Because monitoring NBS results in data that is important, not just to the project at hand, but other groups who may want to implement NBS in their region, data management needs to be carried out such that datasets are easily accessible, usable and replicable by others. Fortunately, there are established protocols for data archiving and sharing that can be adopted by NBS proponents. Finally, while many appropriate monitoring protocols exist for a range of NBS situations, cost can be limiting, especially for community groups. More research is required to develop cheap and accessible monitoring solutions for many indicators that to-date require substantial technical expertise and expense to assess.

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