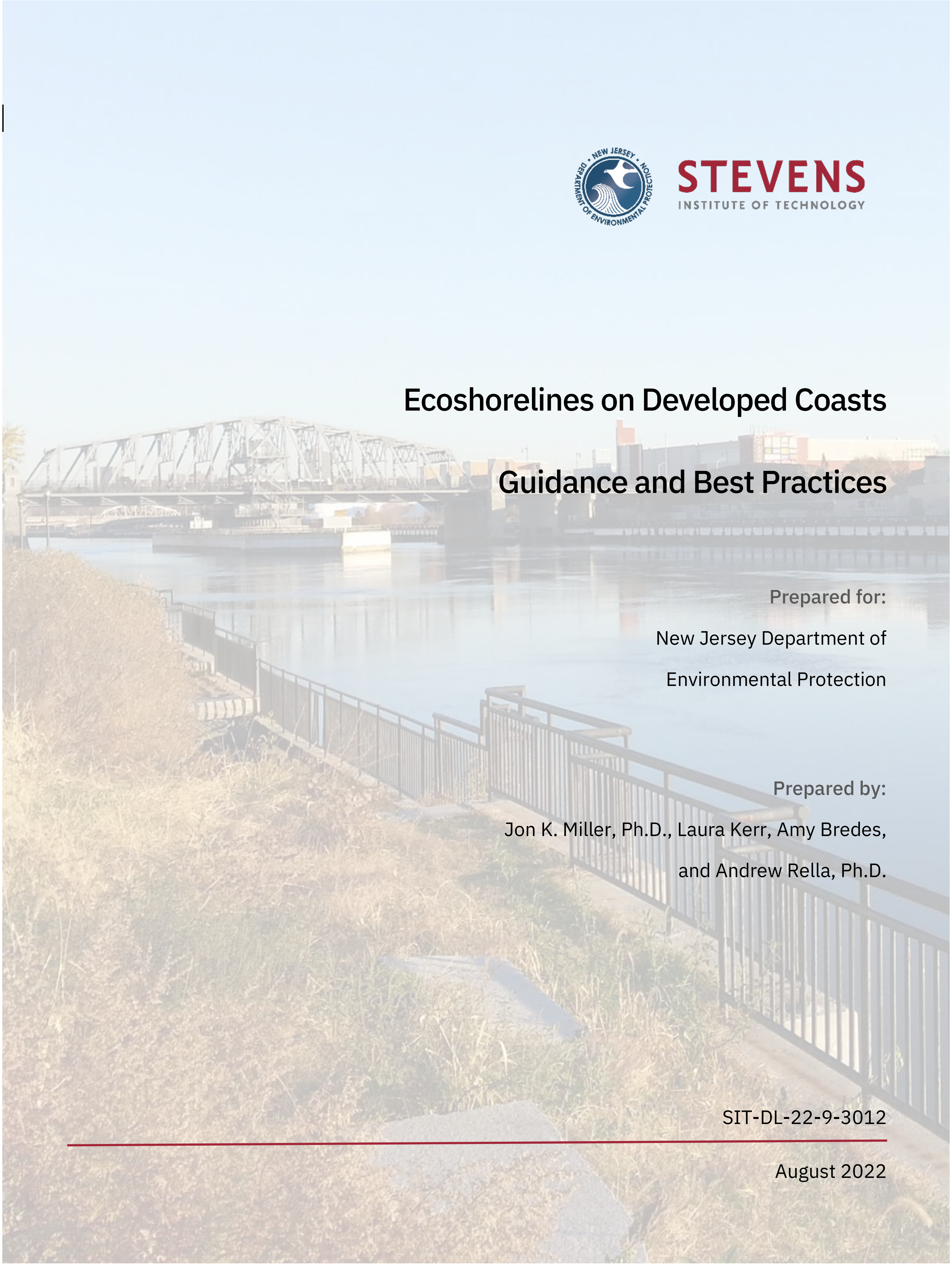

Ecoshorelines on Developed Coasts

Guidance and Best Practices

Prepared for:

New Jersey Department of
Environmental Protection

Prepared by:

Jon K. Miller, Ph.D., Laura Kerr, Amy Bredes,
and Andrew Rella, Ph.D.

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Contents

Introduction

In the past decade, the State of New Jersey has fully embraced the concept of living shorelines. According to the state definition, living shorelines are "a shoreline management practice that addresses the loss of vegetated shorelines, beaches, and habitat in the littoral zone by providing for the protection, restoration or enhancement of these habitats." To accelerate the rate of implementation of living shoreline projects the state adopted coastal general permit 24 (N.J.A.C. 7:7-6.24) in 2013. Although the permit deals more broadly with habitat restoration activities, it quickly became known as the living shorelines general permit. Seeking to provide guidance to the regulatory and design community, the state funded the development of a document outlining the engineering design of living shorelines (Miller, et al. 2015; Miller, et al. 2022). The resulting document was completed in 2013 (and updated in 2015 and in 2022) and summarizes the design process. Since its creation, the New Jersey *Living Shorelines Engineering Guidelines* (LSEG), have been used to guide the design and permitting of dozens of New Jersey projects, and have even served as the inspiration for the development of guidance documents for coastal programs in other states. Unfortunately, while many living shoreline projects have been proposed in "natural" coastal areas, only a relatively small number have been proposed along New Jersey's much more common developed shorelines. Developed shorelines vary greatly from "natural" shorelines, both in form and function, creating a need for different guidance to create robust sustainable living shoreline options for these environments.

Along developed shorelines, the traditional response to problems of erosion, storm risk, flooding, and sea level rise (SLR) has been to harden the shoreline. Within the United States, 14% of the overall shoreline is hardened. However, this percentage dramatically increases in urbanized areas. Manhattan has almost 100% of its shorelines hardened, while the rest of New York/New Jersey Harbor has between 25 and 75% of its shoreline hardened (Gittman, et al. 2015). Although humans have been structurally altering shorelines for centuries, the rate and extent of shoreline hardening has dramatically increased since 1900. These activities do not come without consequence. Shoreline hardening degrades coastal ecosystems and disrupts coastal habitat in a variety of ways. Seawalls and bulkheads steepen and shorten shallow intertidal habitat and often completely destroy wetlands. Even when wetlands are not directly destroyed, storms, erosion, and SLR can eventually cause the loss of wetlands through coastal squeeze. Along many developed coastlines, the majority of nearshore ecosystems have been drastically altered as a result of shoreline hardening. In order to help restore these damaged ecosystems, scientists and engineers have begun to apply living shoreline principles on developed shorelines. Known as "green shores" or "living shores" or "nature-based shorelines", these ecoshorelines attempt to balance the needs of the natural and built environment. When successful, these ecoshorelines often create not only ecological benefits, but also recreational, aesthetic, educational, monetary, and even structural benefits. One of the factors limiting the widespread implementation of ecoshorelines along developed coastlines is a general lack of knowledge and guidance. While there are several excellent examples of ecoshorelines, there are only a few examples where the projects have been objectively monitored and the results effectively communicated.

Although there are many overlaps between traditional living shoreline design and the design of ecoshorelines for developed coasts, there are a few key differences. One key difference relates to space. Ecoshorelines are nearly always space constrained. Above water, the value of land often dictates that every available area is built out to maximize profit. Below water, consideration must be given to water dependent uses. Recreational and commercial boat traffic must be considered, and channels and waterways must be maintained. The result is that intertidal shorelines are often squeezed and artificially steepened using structural measures. Another key difference between working in developed and natural areas is the number of stakeholders that need to be considered. Often, ecoshorelines require a blend of "green" and "grey" to achieve structural, recreational, and commercial goals in addition to the ecological goals. Stakeholders typically include numerous local community organizations, residents, governmental agencies of multiple levels, and commercial entities. Balancing these stakeholder needs requires extensive planning and communication amongst all stakeholders.

Specific guidance is needed for ecoshorelines due to these and other unique requirements for working on developed coasts. The objective of this document is to, firstly, interrogate existing design guidance for techniques applicable to space-constrained regions that may be transferable to New Jersey and, secondly, compile developed living shoreline case studies and extract relevant information that is transferable to future New Jersey projects. Note that while ecological enhancements such as floating islands and vegetation baskets are used in developed settings, these and similar techniques are not included in the scope of this document. Instead, the focus is on space-constrained shoreline edge design. Relevant techniques and lessons from each case study relating to the design of the edge are extracted and contextualized for application in New Jersey.

Existing Design Guidance

Unlike more traditional living shorelines, for which a number of guidance documents exist, there is relatively little in the way of guidelines for urban or developed living shorelines. In fact, there's often a debate about whether living shoreline techniques can even be applied in these environments. Two documents that do include developed shorelines, with information relevant and potentially transferable to New Jersey's developed coast, are the *Waterfront Edge Design Guidelines (WEDG)* (Waterfront Alliance, 2018), and the *International Guidelines on Natural and Nature-Based Features for Flood Risk Management (IGNNBF)* (Bridges, et al. 2021). Whereas WEDG is specifically focused on developed coasts, the IGNNBF considers all coasts, but has specific chapters dedicated to fluvial/riverine environments. A summary of the information contained in these documents is provided below, along with a discussion of some of the key elements relevant to the design of ecoshoreline projects in New Jersey.

Waterfront Edge Design Guidelines

Figure 1: Core WEDG principles

The Waterfront Edge Design Guidelines (WEDG) are a science-based set of guidelines created by the Waterfront Alliance as a means of encouraging sustainable waterfront design. WEDG is focused around three core principles: Resilience, Access, and Ecology. Originally created for New York City's developed shorelines, the program has expanded in recent years to take on a national focus and has expanded to include a wider array of waterbodies and shoreline types. Currently there are three elements to the WEDG program: WEDG verification, WEDG professionals, and WEDG neighborhoods. WEDG verification is the original credit-based project certification program that incentivizes waterfront design based around WEDG's core principles. Similar to the LEED certification for buildings, WEDG awards credits in a variety of categories, each relating back to the guiding principles. The six categories are **Site Assessment and Planning** (28 credits), **Responsible Siting and Risk Reduction** (40 credits), **Community Access and Connection** (52 credits), **Edge Resilience** (18 credits), **Natural Resources** (61 credits) and **Innovation** (16 credits). In order to be WEDG certified, projects must achieve at least 115 out of a total of 215 possible points. While the certification process is specific to WEDG, embedded within it are a number of design principles which have broad application to sustainable resilient waterfront design.

The **Responsible Siting and Risk Reduction** category awards credits for avoiding or reducing the risk from coastal hazards and siting development in a way that considers the ecology of the site, public access, and industrial water dependent uses. Points are awarded under this category for minimizing the exposure to risks such as coastal erosion and flooding, and for accounting for factors such as sea level rise. Specific strategies discussed include structural modification and the integration of natural and nature-based features. Either 4 or 6 points are awarded for siting structures outside the 100- or 500-year future (sea level rise adjusted) flood plain. For structures located within the flood plain, 4 or 6 points are awarded for ensuring structures and utilities are protected or floodable and structurally sound to the 100- or 500-year future flood condition. Additional points are awarded for creating a buffer between structures and sensitive habitats. For structures sited near beaches, it is suggested that a buffer 100 feet from the vegetated edge plus an additional amount determined by multiplying the annual erosion rate by the expected design life of the structure be added. A minimum design life of 40 years is suggested. Recommended buffers for other settings are provided in WEDG in a table which is reproduced here as Figure 2.

Credits are awarded under **Edge Resilience** for designing a resilient waterfront edge that is appropriate for the given conditions and is also sensitive to the local ecology. Specific strategies focus on maintaining or emulating natural shorelines, protecting working edges, and ecologically enhancing structural components. The approach suggested involves first determining if shoreline stabilization is needed, then selecting the most appropriate, minimally impactful method of stabilizing the shoreline. If a natural shoreline is to be maintained, points can be attained by developing a monitoring and maintenance plan for the site which considers adaptability over time. The greater the extent of natural shoreline maintained, or natural/nature-based methods used, the greater the number of points awarded under this credit. Up to two points can be awarded for maintaining or emulating the natural shoreline shape. One point is awarded for increasing shoreline sinuosity, or reducing slope, while two points are awarded for maintaining or enhancing an existing natural shoreline. On shorelines where structural stabilization is necessary (*i.e.*, bulkheads, seawalls, revetments) points can be obtained for ecologically enhancing the structural components. Enhancements can take the form of changes to the material specifications, modifications of the micro- and macro-scale roughness of the features, incorporation of natural materials (*i.e.*, oysters/mussels), or the inclusion of water retaining features.

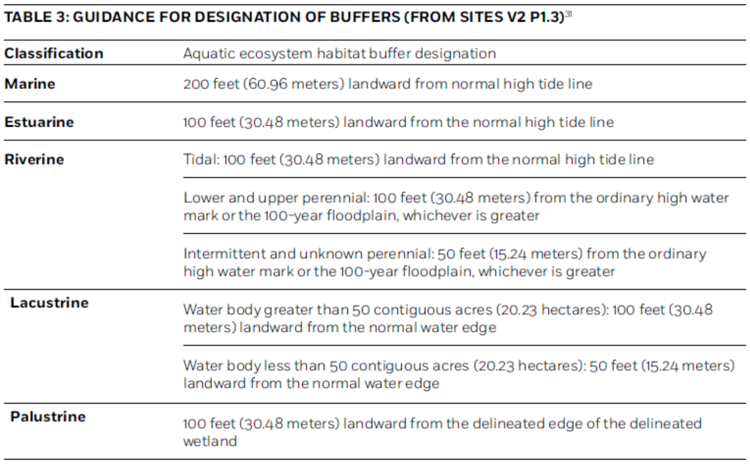


TABLE 3: GUIDANCE FOR DESIGNATION OF BUFFERS (FROM SITES V2 P1.3)[31]

Classification	Aquatic ecosystem habitat buffer designation
Marine	200 feet (60.96 meters) landward from normal high tide line
Estuarine	100 feet (30.48 meters) landward from the normal high tide line
Riverine	Tidal: 100 feet (30.48 meters) landward from the normal high tide line
	Lower and upper perennial: 100 feet (30.48 meters) from the ordinary high water mark or the 100-year floodplain, whichever is greater
	Intermittent and unknown perennial: 50 feet (15.24 meters) from the ordinary high water mark or the 100-year floodplain, whichever is greater
Lacustrine	Water body greater than 50 contiguous acres (20.23 hectares): 100 feet (30.48 meters) landward from the normal water edge
	Water body less than 50 contiguous acres (20.23 hectares): 50 feet (15.24 meters) landward from the normal water edge
Palustrine	100 feet (30.48 meters) landward from the delineated edge of the delineated wetland

Figure 2: Setback recommendation table reproduced from WEDG (Waterfront Alliance, 2018)

Credits are awarded in the **Natural Resources** category for actions which conserve, manage, restore, and improve biodiversity and ecosystem function. Under this category, points are awarded for avoiding, minimizing, or mitigating impacts to critical habitats during design and construction. As a part of this strategy, fill beyond the exiting pier-head/bulkhead line should be avoided and wherever possible beneficial re-use of material should be considered. For sites where habitat restoration is planned, WEDG supports increasing the diversity of habitats, restoring the continuity of ecosystems, and reducing fragmentation using native species. In terms of water quantity and quality, WEDG provides up to 10 credits for reducing the overall volume of stormwater discharged into the waterway and another four points improving the quality of storm water discharge. The last credit provides up to four points for partnering with an academic or scientific institution to study/monitor the site.

The final category, **Innovation**, awards credits for significantly exceeding the existing guidelines or developing new ways of improving resilience, ecology, or access. Inventive designs that use new materials and methods can achieve up to eight points, as can exemplary performance.

Key Takeaways

Although originally written with New York City's heavily developed urban shorelines in mind, the WEDG document itself embodies the principles of resilience and adaptability. Much of the information contained in WEDG is applicable to developed waterfronts in a variety of settings. At the philosophical level, principles such as designing for **resilience**, promoting ecology and public access, supporting diversity equity and inclusion, creating multi-disciplinary teams, communicating with stakeholders, and **measuring success**, are all compatible with concepts already being used in New Jersey. At the implementation level, WEDG awards points for practices such as **maintaining existing natural shorelines, increasing shoreline curvature, reducing slope, increasing surface roughness, using alternative materials,** and **including water retaining features**. These practices represent a set of foundational principles which are broadly applicable to the design of ecoshorelines on developed coasts and are considered appropriate for New Jersey.

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

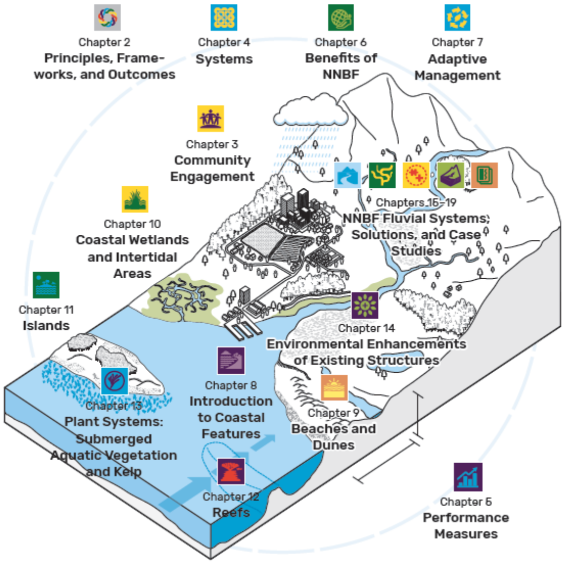


Figure 3: Organization of the IGNNBF

The International Guidelines on Natural and Nature-Based Features (NNBF) for Flood Risk Management (IGNNBF) were motivated by a need for a comprehensive guide to planning, designing, engineering, constructing, and operating NNBF. The project was initiated and led by the US Army Corps of Engineers Engineering with Nature group with significant contributions from the Rijkswaterstaat Ministry of Infrastructure and Water Management in the Netherlands and the Environment Agency in the United Kingdom. The final product was the culmination of a 5-year effort that included working meetings and knowledge sharing by partners around the world. The guidelines are divided into three main sections. Section 1 (chapters 1 through 7) covers topics that are broadly applicable across a range of landscapes and NNBF project types. Section 2 (chapters 8 through 14) covers topics related to coastal applications of NNBF. Section 3 (chapters 15 through 19) covers fluvial and riverine environments. A summary chapter (20) provides a perspective on the future of NNBF. The complete document is over 1,000-pages long and contains a wealth of information relevant to ecoshorelines along developed coasts.

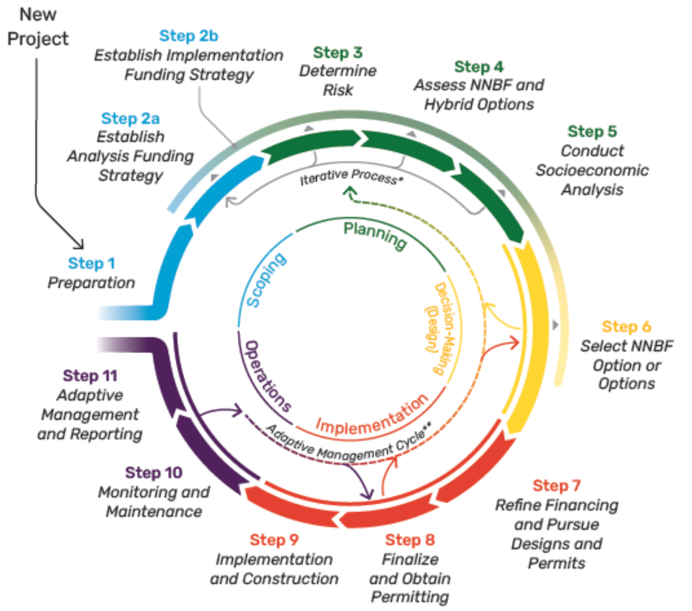
Section 1 of the IGNNBF contains an overview of NNBF that includes coastal and fluvial/riverine applications. Five foundational principles critical to the success of NNBF projects are outlined

1. expect change and manage adaptively,

2. identify sustainable resilient solutions that produce multiple benefits,
3. use a systems approach to leverage existing components and projects and their interconnectivity,
4. engage communities, stakeholders, partners, and multidisciplinary team members to develop innovative solutions,
5. anticipate, evaluate, and manage risk in project or system performance.

A framework consisting of five phases — scoping, planning, decision-making, implementation, and operations — is recommended, with outcomes assessed at each phase. Notably, the framework is not linear and often iteration is required.

The IGNNBF identify the importance of using a systems approach during the planning and implementation of NNBF projects that includes multi-disciplinary teams. A systems approach is recommended both to deal with inherent uncertainties, but also as a means of coping with the dynamic nature of living projects. Consistent with this, it is recommended that a systems approach be used to assess NNBF projects such that all of the physical and ecological processes can be evaluated properly. Specific to the engineering performance, it is recommended that two aspects be considered. The first is the system performance or the effect of the system on the inherent hazard, and the second is the structural performance or the effect of the hazard on the NNBF.

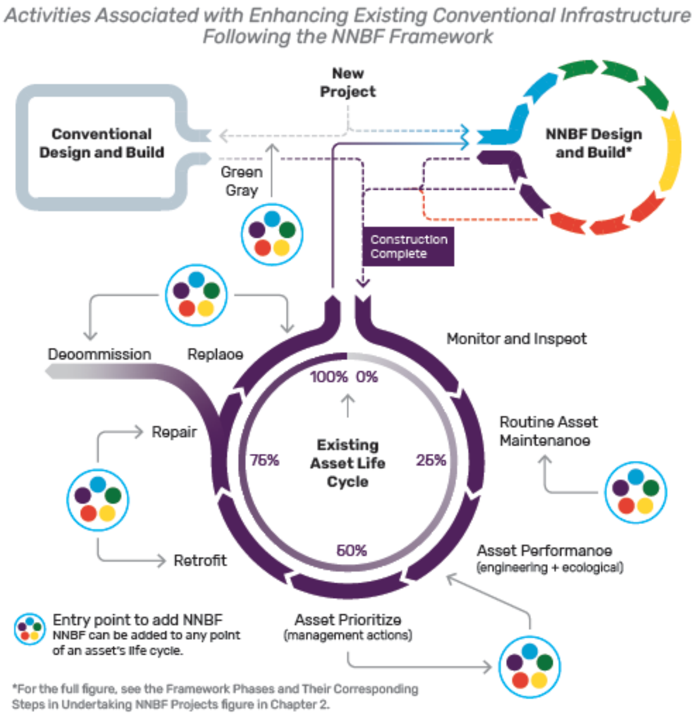


*Iterative process to identify practical and preferred NNBF options

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

Figure 4: IGNNBF process for identifying and implementing the preferred NNBF alternative

Assessment of NNBF is identified as critical for two specific aspects. The first is the establishment of the benefits and costs associated with NNBF. The IGNNBF note that traditionally NNBF have not been valued in the same way as traditional gray infrastructure, and that a fair evaluation of NNBF must include all of the co-benefits associated with the approach. It is also noted that all benefits need not have a monetary value associated with them. The other reason assessment is deemed critical is for adaptive management. The IGNNBF identify adaptive management as an iterative decision-making method that can and should be used to reduce levels of uncertainty and risk in predicting and achieving desired results by using NNBF or structural solutions. Specifically, adaptive management is identified as a way of enabling project designers to avoid "overbuilding" to account for uncertainty because the adaptive steps (measure and monitor, refine and adapt) facilitate future adjustments or enhancements, as necessary. One such uncertainty is sea level rise, where adaptive management can be used to design structures that are effective today and for the near future and then adaptively managed to account for future sea levels for which there is a higher degree of uncertainty.



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

Figure 5: Diagram illustrating the incorporation of NNBF at various phases of the design process

Section 2 of the IGNNBF addresses coastal systems which are covered in detail in the existing Living Shorelines Engineering Guidelines (Miller, et al. 2015). Section 3 addresses fluvial and riverine systems and the application of NNBF on developed coasts. Specifically for developed coastlines in fluvial/riverine environments, NNBF fall along a spectrum of project types ranging from retrofits of existing projects to full on integration of NNBF at the design phase. As such, opportunities for NNBF may arise at any phase of a project lifecycle from conception to initial construction, to rehabilitation and maintenance. The lack of documentation of successful fluvial/riverine NNBF, and hence awareness, was identified as one of the impediments preventing more widespread use of NNBF along developed shores. The need for education, training, and technical transfer-related needs including the documentation of case studies, development of webinars and workshops for disseminating information on best practices was identified as a key need. When implemented as a flood reduction measure, the IGNNBF stress the need to consider processes at the watershed scale. Often this means considering projects that implement multiple NNBF techniques (some potentially taking place well inland) or combinations of green and gray infrastructure. Long-term monitoring (>10 years) is identified as the key to documenting the success of NNBF in fluvial/riverine

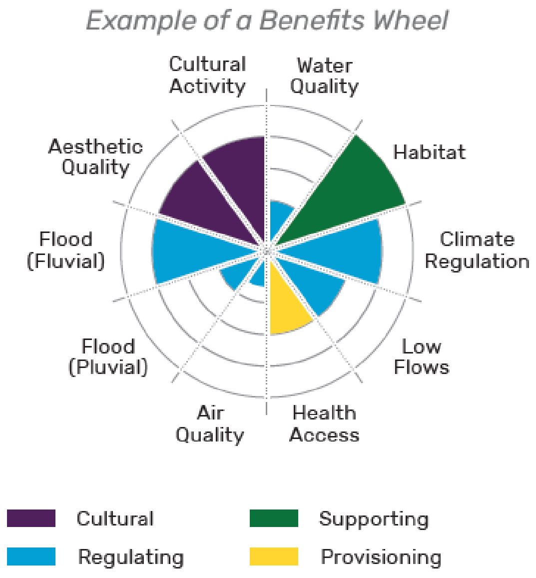


Figure 6: Benefits wheel concept for visualizing benefits and comparing projects

systems. The IGNNBF introduce a “benefits wheel” as a method of visualizing the services provided by NNBF in a way that is objective and reproducible. With respect to fluvial/riverine systems, the IGNNBF identify the need for additional research on:

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

The final chapter in the IGNNBF (Chapter 20) provides a perspective on the future of NNBF. Progress in three areas – **developing and delivering, communicating and collaborating, and elevating and educating** – is identified as the key for advancing NNBF to handle current and future flood risk management challenges. **Developing and delivering** refers to delivering the “right” projects that provide sustainable and resilient solutions over the long term and being more deliberate about learning from these projects so that policy and technical practice can be advanced. Under **communicating and collaborating**, the ability to communicate the non-monetized benefits of NNBF and the dynamic and hence less predictable nature of working with natural features are emphasized. Adaptive management is stressed as a means of dealing with nature’s unpredictability. Finally, under **elevating and educating**, the IGNNBF identify the importance of education for expanding public awareness of NNBF, sharing information on emerging technical approaches, and engaging communities and future professionals. Ultimately, all of the above are dependent on a commitment to monitoring and analysis and a willingness to embrace innovation.

Key Takeaways

The IGNNBF is an expansive document that covers the breadth of NNBF from initial design philosophy through monitoring project outcomes and includes information related to both traditional coastal and non-traditional fluvial/riverine projects. Embedded within the document are a number of concepts which are transferable to New Jersey’s developed coast. Consistent with WEDG, the IGNNBF promotes **preserving natural areas**, designing for **resilience**, supporting diversity equity and inclusion, creating multi-disciplinary teams, communicating with stakeholders, and **measuring success.** The IGNNBF places particular emphasis on long-term monitoring for the purpose of assessing performance, documenting benefits, and informing **adaptive management**.

Case Studies

Although guidance documents specifically focused on living shorelines for developed coasts are fairly limited, there are a plethora of projects which demonstrate sustainable, resilient, ecologically focused design principles which are appropriate for New Jersey. These projects range in size, scope, and setting from a $372 million seawall replacement in downtown Seattle, to a smaller $100 thousand project to install a living shoreline at a park along New York's Harlem River. Five case studies – Harlem River Park, Sherman Creek, Brooklyn Bridge Park, Seattle Seawall, and Lardner's Point Park – are described below. Specific attention is given to the design principles and practices expected to be relevant and transferable to New Jersey's developed shorelines.

Harlem River Park

Location: 40.816307, -73.933854

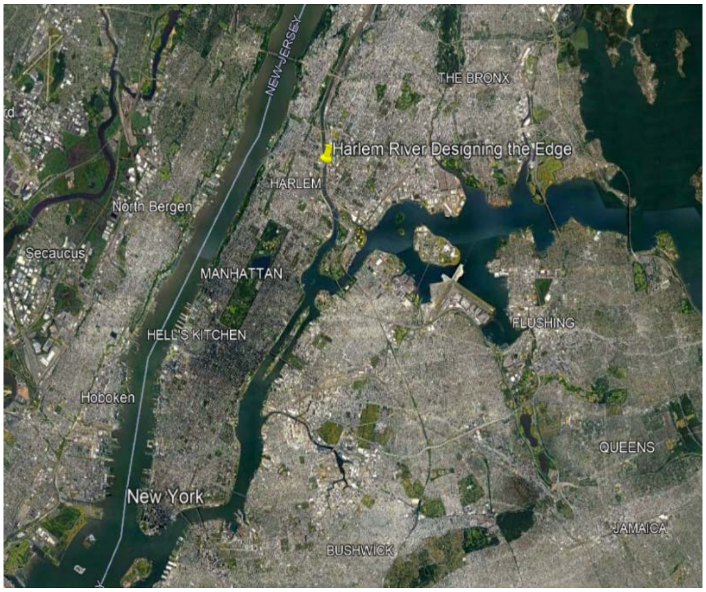
Date constructed: 2009

Website: https://harlemriverpark.weebly.com/designing-the-edge.html

Budget: $2.5 million

Techniques used:

- Tidal pool development
- Introducing curvature
- Surface roughness
- Gabions with oyster shells
- Porous material



Harlem River Park is located along the 9.3-mile tidal strait separating the Bronx and Manhattan known as the Harlem River. The park consists of 20-acres of Manhattan Harlem waterfront that begins east of Harlem River Drive and extends from 132nd Street to 145th Street. Over time, the original course of the river was modified through realignment, landfilling, dredging, and bulkheading, to serve as a shipping channel. Modern re-envisioning of the area recognized the opportunity to replace degraded steel sheet pile walls with a structure promoting the local ecology and reconnecting the community to the water.

With increasing demands for the public to gain access to the waterfront in the late 1970s and early 1980s, many public urban waterfronts developed paved esplanades along the waterfront. At Harlem River Park, a paved esplanade was constructed behind a vertical steel sheet pile bulkhead and steel railing designed to keep the public away from the water. While the esplanade allowed the public to admire the waterfront, it prevented them from touching the water and provided no ecological benefits. As more and more industrial waterfronts were replaced with residential/recreational waterfronts in the 1990s, the desirability of reconnecting people to the water, and restoring the local ecology became apparent. In the late 1990s, the deterioration of the bulkhead and esplanade at Hudson River Park provided the opportunity to research and implement an ecologically enhanced alternative to a traditional seawall.

Figure 7: Harlem River Park site. Source: Google Earth

Initiated in 2002 and completed in 2009, the Harlem River Park project involved many partners including: New York City Parks and Recreation, New York State Department of State Division of Coastal Resources, Metropolitan Waterfront Alliance, Harlem River Park Task Force, Economic Development Corp., and a multitude of other community members and organizations. There were five main goals for the project

1. to provide an ecologically advanced alternative to hard seawalls,
2. to improve public access to the waterfront,
3. to allow use of the water for recreation,
4. to provide ecological benefits for shore zone species, and
5. to enhance stormwater capture

The project was split into three phases. Each phase evaluated different seawall approaches in different locations along the same stretch of river. Construction on phase one began in 2001 and was completed in 2002 and included the shoreline from 132nd Street to 138th Street. Phases two and three were begun in 2007 and were completed in 2009. Phase two included the shoreline from 139th to 142nd Street, while phase three included the shoreline from 142nd to 145th Street. Each shoreline segment had its own unique design requirements; therefore, a different type of seawall was used in each area.

Figure 8: Harlem River Park ecoshoreline. Source: NYC Parks and Recreation Designing the Edge Report (2010)

During phase 1 of the project, the existing rusted industrial steel sheet pile seawall was replaced with a new steel bulkhead, and additional recreational amenities were provided at the request of the public. A new bike lane was constructed, and many benches were restored and added. Most importantly, for the first time, the neighborhood of East Harlem was provided with access to the waterfront and a path to the esplanade.

In 2002, Harlem River Park received a $40,000 grant as a part of the "Designing the Edge" competition. The Designing the Edge program was initiated to encourage innovative approaches to waterfront design that provided public access to the waterfront, enhanced stormwater capture, and restored habitat. In order to optimize the design of phases two and three, the community was invited to give input, and several innovative seawall designs were tested at Webb Institute and Stevens Institute of Technology. A total of three new techniques were tested and compared to a traditional steel sheet pile wall. The three techniques that were tested included:

- rectilinear gabion terraces with tide pools,
- sloped serpentine round gabions, and
- stacked staggered green walls.

After evaluating the three models, it was decided to incorporate the promising components from each into the final project design. This final project was completed using $2.5 million budget for the final construction and design.

The final Harlem River Park ecoshoreline design successfully balances the needs of a heavily developed shoreline on an active waterbody with the needs of the community while providing valuable ecosystem enhancements. A number of the design features are illustrated in Figure 8. Although the edge remains vertical, a more natural slope was created by carving into the shore and creating pockets of sloping shoreline. The terraces within these pockets allow for the growth of vegetation and create diverse microhabitats due to their varying size, shape and slope. The irregular, staggered, curved form of these pockets reduces nearshore tidal currents and creates small eddies along the river's edge which protect the edge from scour and creates habitat. Small fish seek refuge from the strong river currents in the pockets during high tide, and they serve as tide pools during low tide. Even the underwater portion of the seawall was designed with nature in mind. Gabion baskets filled with rock and oyster shells were used instead of steel sheet pile to attract algae, mussels, and oysters. The intention was to create a "living crust" that would filter the water and provide habitat

Figure 9: Gabion baskets used at Harlem River. Source: https://harlemriverpark.weebly.com/ gallery.html Photo by: Thomas Lunke

while protecting the shoreline from erosion. Salt marsh grasses were even planted within the gabion stones and access was created for the public.

Key Takeaways

The Harlem River Park project illustrates several innovative design strategies with application to New Jersey projects. Through the use of terraces, the project was able to recreate **sloping** shoreline in an environment where nearly all of the shoreline has been modified and is vertical. By creating pockets, **curvature** was reintroduced along the artificially straightened water body. These pockets also serve as **water retaining** tide pool features. The stone and oyster shell gabions used to create the tide pools allow for a more natural porous shoreline with the potential to recruit additional invertebrates. These in turn can protect the structure from ice and wake scour and improve water quality.

Sherman Creek

Location: 40.856944, -73.921906

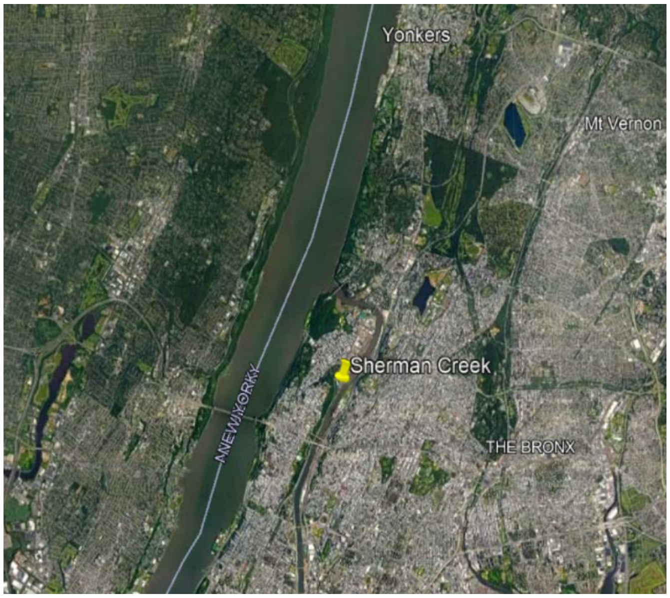
Date constructed: 2020

Website:
https://www.nyrp.org/en/blog/understanding-sherman-creeks-living-shoreline/

Budget: $100,000

Techniques used:

- Ecological Concrete
- Shellfish restoration
- Coir logs
- Marsh mats



In addition to the living shoreline at Harlem River Park, Inwood's Swindler Cove, along the Harlem River, is home to another urban living shoreline. Swindler Cove is a 5-acre park in northern Manhattan. The land on which the park sits was originally an illegal dumping ground but was transformed into a public park by the New York Restoration Project (NYRP) in 2003. NYRP planted and restored the park to include marshes, gardens, forests, walking paths, and vegetable gardens. The park was designed for community use and serves as an important educational resource for local school children.

In 2017, thanks to a $100,000 award from a local state senator, a living shoreline project was proposed to address an ongoing erosion problem at the site. During the project design it was determined that boat wakes were undercutting the shoreline and transporting sediment away from the park. Exacerbating the problem was the fact that water level changes resulting from sea level rise, were causing marshes to transition into tidal flat, and upland forests to transition into marsh. On an undeveloped coastline, this transition might be encouraged; however, in a heavily developed urban environment with limited space, these transitions threaten vital habitat and public space. The living shoreline project constructed at the site contains several elements including a high marsh with sand in-fill, a stone sill, a low marsh with Spartina alterniflora and a ribbed mussel colony, and a series of Oyster Castles, a structure made of ecological concrete that encourages bivalve colonization. The Oyster Castles were designed to provide wave attenuation for the features placed behind them. The individual Oyster Castle units were stacked to create pyramid shaped structures which were placed in a staggered pattern with irregular gaps to mimic a natural shoreline and provide space for animals to move between the marsh and subtidal zones. Community volunteers were recruited to help replant the low marsh behind the oyster castles using marsh mats and coir logs. The project preserved a valuable habitat in an area where natural marshes are limited and created a unique and recreational and educational opportunity for the area's urban residents. Post-installation project monitoring has revealed that native oysters have begun to colonize the oyster castles.

Figure 10: Sherman Creek site. Source: Google Earth

Key Takeaways

The Sherman Creek project is unique in such a heavily developed environment. Living shoreline techniques typically applied along more natural shorelines were used to preserve an existing, critically endangered **natural** habitat. Applying these techniques presented a unique educational opportunity through the incorporation of public space in the site design and the creation of volunteer opportunities.

Brooklyn Bridge Park

Location: 40.702051, -73.996612

Date constructed: 2010

Website: https://www.brooklynbridgepark.org/

Budget: $350 million

Techniques used:

- Sediment reuse
- Shellfish restoration
- Regrading
- Marsh development
- Ecological concrete
- Increased light penetration

Brooklyn Bridge Park is an 85-acre park set along the tidal strait connecting Long Island Sound to New York Harbor known as the East River. According to promotional material, this once industrial area is now home to a "world class park" that combines recreation, culture, and environmental benefits in a redeveloped urban setting. The park itself is located on a 1.3-mile stretch of East River shoreline that extends from Atlantic Avenue to Jay Street and includes six redeveloped piers supporting park amenities and residential developments.

Beginning in the mid-1600s, the area that is now Brooklyn Bridge Park, was used as a ferry landing. The trade associated with this ferry landing led to a prosperous economy in the small town located there. The site was also a critical strategic location for the Continental army during the Revolutionary War. By the end of the 1700s, additional ferry services were added, and the area became known as Fulton Ferry Landing. The neighborhood grew and by the 1850s, rail lines were installed, and brick warehouses dominated the waterfront. The ferry and rail system prospered until the opening of the Brooklyn Bridge in 1883. The bridge provided an easier passage between Manhattan and Brooklyn, making the ferries obsolete. Eventually Fulton Ferry Landing was closed in 1924 and many of the old warehouses were abandoned. In the 1950s the New York Dock Company built new piers and redeveloped the area for large cargo ships. As the nature of trading changed throughout the 20th century, the area became unusable and neglected, with cargo shipping operations ending in 1983. With the warehouses largely abandoned, they were demolished, and construction of the reimagined Brooklyn Bridge Park began in 2008.

Acquiring and developing the land to create Brooklyn Bridge Park was a decades long endeavor that began in 1985 with the creation of the not-for-profit organization Friends of Fulton Ferry Landing (now the Brooklyn Bridge Park Conservancy). Through the 1980s and 1990s, various developers attempted to buy the piers and adjacent upland properties to create commercial and/or residential developments. In 1998, then Brooklyn Borough President, Howard Golden, established the Brooklyn Waterfront Local Development Corporation which was tasked with "create(ing) and maintain(ing) a world class park that is a recreational, environmental and cultural destination enjoyed by residents of, and visitors to, New York City." The project was completed with a budget of $350 million in 2009; funding sources included both City and Port contribution, as well as private donations.

Figure 11: Brooklyn Bridge Park site. Source: Google Earth

Brooklyn Bridge Park was designed with resilience in mind. Design elevations were based on NOAA (National Oceanic and Atmospheric Administration) water level predictions for 2045 with a 1.32 ft increase of mean high water (MHW) and a 100-yr storm surge of 7.8 ft. All trees were planted at an elevation of 8 ft or higher to protect them from all but the most severe storm surges. Upland areas were elevated using locally sourced fill to both protect the park itself and to serve as barrier to future sea level rise and storm events. For Pier 1 alone, approximately 106,000 tons of soil and debris were imported from New York City projects such as the East Side access excavation. The highest point on the site reaches an elevation of nearly 30 ft. The park's effectiveness as a resilience feature was proven during Hurricane Sandy, as the elevated topography prevented flood waters and debris from moving further inland.

To manage stormwater and runoff, Brooklyn Bridge Park has a vast underground water storage system which recycles stormwater for irrigation purposes. Water is captured through freshwater ponds and is naturally filtered through the ground and finally stored in underground tanks until needed. Over 100,000 gallons of stormwater can be stored under Pier 1, while tanks at Pier 2, Pier 3, Pier 6, and Empire Fulton Ferry have even larger capacities.

To support native species and create habitat, ecological features were incorporated into the designs of Pier 1, Pier 2, Pier 4, and Pier 6. This included the use of ecologically enhanced concrete, the planting of native species, the removal of unnecessary piers to increase light penetration, and the construction of a beach, nature preserve, tidal marsh, and salt marsh. The majority (over 4,000 linear feet) of the Brooklyn Bridge Park shoreline is lined with rip rap. Sloping rip rap was chosen over vertical bulkhead walls for its wave attenuating characteristics and durability. Some softer edges were also incorporated, for example, at the salt marsh at the southern edge of Pier 1 where smooth cordgrass was planted. As a reminder of the previous use of the waterfront at this location, the existing relic pile field was retained. These piles also attenuate waves and protect the salt marsh from erosion and provide habitat for cormorants, terns, and gulls. A tidal marsh was constructed at Pier 2, John Street, as well; here, two bridges span a tidal marsh designed to minimize storm surge from the East River.

Ecologically enhanced concrete was used at two locations in Brooklyn Bridge Park. At Pier 4, coastal armor units designed to mimic natural rock pools were installed to provide shoreline stabilization, tidal habitat, and an opportunity for the public to enjoy and observe local marine life. At Pier 6, ecologically enhanced concrete pile jackets were installed to reinforce an existing pier. In both locations, a combination of special mixtures, molds and texture agents were used to create conditions favorable for marine growth. Post-installation monitoring of both sites has shown a high degree of biodiversity, including many native species, and continued structural stability.

Pier 4 designs include a habitat island (Bird Island) offshore of a beach allowing visitors to get to the water's edge and launch human powered watercraft. Bird Island is an inaccessible nature preserve built from the remains of a railroad float transfer bridge. There are a variety of salt-tolerant flora located on the island and an osprey platform to attract the migratory birds. This area on Pier 4 is also where the ECOconcrete ecological concrete tide pool armor units are located. Pier 6 flower fields provide a half-acre of native wildflowers to attract pollinators. Milkweeds, asters, and goldenrods were planted to attract monarch butterflies and other species.

Brooklyn Bridge Park’s design also attempts to reduce the overall amount of over-water shade structures. Historically, the large pier structures built along the waterfront in the mid-20th century were as large as five acres in area. These piers shaded the water along the shoreline. The absence of sunlight in the water column has been documented to have adverse effects on many fish species. Five acres of marine decking that was deemed unnecessary for park enjoyment was removed from Pier 1 to reduce water shading. All added over-water structures were kept as narrow as possible to allow for maximum light penetration.

Figure 12: ECOncrete tidepool units. Source: https://econcretetech.com/projects/brooklyn-public-park-renovation/

In addition to the constructed design elements of the park, Brooklyn Bridge Park partnered with the Billion Oyster Project to help restore oyster populations in New York Harbor. In 2020, thirty SEAPA brand cages filled with hundreds of oysters were installed at the park as a “community reef” where monitoring is performed by community groups, middle and high school students, and volunteers. These oyster reefs will filter the Harbor's water and provide habitat for marine life while also providing an opportunity for community engagement.

Key Takeaways

Urban projects are presented with the unique challenge of balancing community, commercial, and ecological needs in a limited amount of space. This challenge is especially evident in the choices made in the design of the Brooklyn Bridge Park. Overall, this project presents a great example of a well-thought-out ecologically conscious city park, however, it falls short in the restoration of the shoreline. While riprap is better than a traditional bulkhead, it still does not provide as much natural habitat as other alternatives may have. Improvements were made however to allow for greater **light penetration** into the water column. Still several large piers remain and shade a portion of the water column. The **ecological concrete** used in this project, while not extensive, can serve as a case study for the effectiveness and structural stability of these materials in the use of pilings and shore armor. Brooklyn Bridge Park shines in its ability to outreach to the community and provide opportunities for the public to interact with native species and more natural landscapes within a largely urban setting. Finally, the **resilience** of designing to NOAA's predicted 2045 water levels and constructing with beneficially reused materials to prepare the shoreline for storm surges and sea level rise should be commended. While the Brooklyn Bridge Park design is not perfect, it serves as an example that the more "novel" ecologically focused aspects of the design enhance the park, making it more beautiful, resilient, and enjoyable for visitors.

Seattle Seawall Project

Location: 47.604515, -122.339300

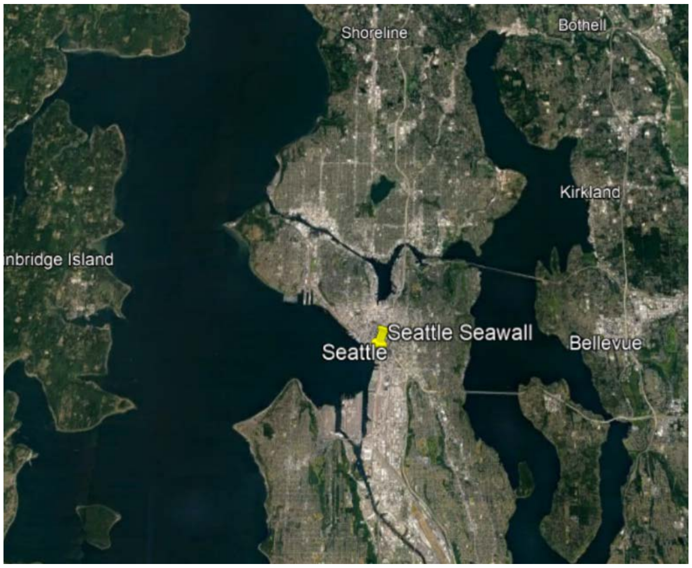
Date constructed: 2017

Website: https://waterfrontseattle.org/waterfront-projects/seawall

Budget: $410 million

Techniques used:

- Zee panel
- Light penetration
- Surface roughness
- Habitat shelves
- Marine mattress



The Seattle Seawall Project was completed in 2017 with the construction of the new Elliot Bay Seawall. This seawall replaced the original damaged and degraded Alaskan Way Seawall which ran approximately 1.3 miles along the Elliot Bay waterfront southwest of downtown Seattle from Bay Street to South Washington Street.

Figure 13: Seattle Seawall site. Source: Google Earth

In 2001, the City of Seattle, which is located along Elliott Bay, was struck by the magnitude 6.8 Nisqually earthquake damaging the existing seawall and nearby Alaskan Way Viaduct. The investigations that followed predicted that the existing seawall structures had a one in ten chance of failing over the course of ten years. The original seawall, completed in the 1930s, was not designed for earthquake loads. Additional degradation of the structure had occurred from salt water and marine borers that ate away portions of the wooden piles that supported the waterfront. These issues presented an urgent need to replace and modernize the seawall. Environmental impacts due to the existing engineered shoreline were also of concern. Leading up to the replacement of the seawall, it was found that 29% of the salmon population in the surrounding water had become extinct, with 27 other species threatened. The degradation of the local fish and wildlife population was attributed to 68% of the once natural shoreline being extensively modified from its natural characteristics through seawalls, piers, and docks.

The seawall replacement project involved many stakeholders: local businesses, city residents, multiple Native tribes, the U.S. Army Corps of Engineers, the U.S. Fish and Wildlife Service, the University of Washington School of Aquatic and Fishery Service, Washington State Department of Natural Resources and Ecology, arts & culture organizations, the Department of Transportation, engineering consultants, and many more.

After gathering input from academic and scientific studies, consultant recommendations, and community forums, several project goals emerged. The first goal was to protect public safety by designing the new structures to meet the most updated seismic standards. The second was to create a strong foundation for development along the waterfront to increase economic value; this included walking and bike paths and improved piers for businesses, recreation, and community building. The last design objective was to improve ecosystem productivity by promoting algae growth and restoring the juvenile salmon migration corridor.

The Seattle Seawall Project consisted of dozens of individual projects, spanning over a decade, all aimed at redeveloping and improving the waterfront. One interesting observation is there were no design elements that responded directly to the effects of sea level rise due to climate change. Tide projections indicated that the waterfront did not need to be raised over the next 100 years, as the mean higher high water (MHHW) elevation would still be several feet below the existing seawall. The new seawall, built to comply with seismic code, is also capable of withstanding a tsunami caused by a magnitude 6.7 earthquake on the Seattle Fault. However, the largest possible Seattle Fault earthquake predicted is of magnitude 7.3 with a recurrence interval between 200 to 12,000 years, according to the United States Geological Survey. At that magnitude, the seawall would be overtopped with up to 6.5 feet of inundation in the area along the waterfront. This case study focuses primarily on the environmental challenges of redesigning the seawall to promote ecological diversity, mimic natural habitats, and restore the migration corridor. The project was funded through a bond measure approved by Seattle voters and cost $410 million, about $60 million over the originally estimated cost.

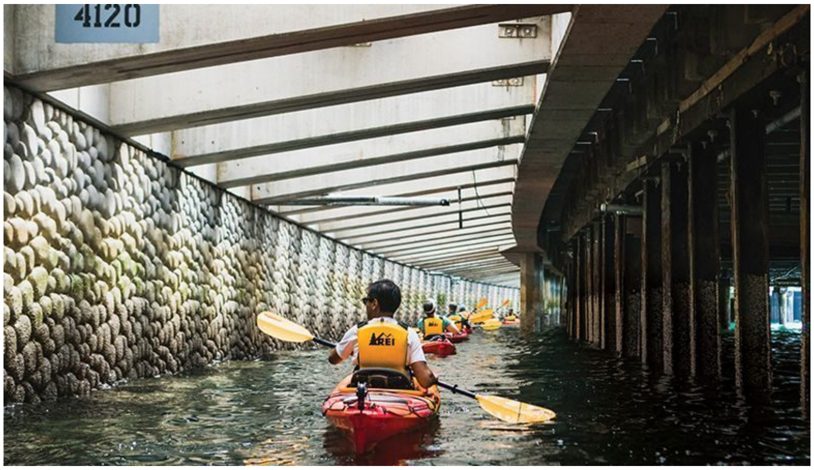


Figure 14: Kayakers kayaking under the Seattle Seawall's translucent panels. Source: https://waterfrontparkseattle.org/pier-62/ Photo by: Rhoades Clark courtesy of Downtown Seattle Association

The original seawall created conditions that deterred salmon from feeding and traveling in their natural habitat, the intertidal zone along the shoreline. Overwater structures such as piers and docks created dark environments along the deep water due to the vertical seawall. This forced salmon to travel farther offshore where exposure to predators, limited food sources, and delayed travel to the sea all posed risks to the species. The new seawall was engineered to incorporate the natural ecological features of intertidal zones that were missing due to the heavily modified shoreline. New design features included a zee panel, light penetrating surfaces, textured face panels, habitat shelves, and a marine mattress.

Installation of zee panels allowed the seawall to be shifted back 10 to 15 feet by supporting an overhanging pedestrian corridor above the water and seawall. The additional space created by the landward shift of the seawall left more room for habitat enhancement along the wall. Space alone was not enough to solve the main issue - a lack of light and food sources underneath pier structures. Therefore, light penetrating surfaces were incorporated into the overhanging sidewalk. Since the construction of the light penetrating surface, levels of juvenile salmon traveling and feeding under the piers have increased to levels seen at nearby areas of uncovered shoreline (Munsch, et al. 2017).

Another design feature was textured face panels and habitat shelves. The purpose of these features were to promote the presence of salmon prey that thrived in intertidal environments. Studies performed by the University of Washington indicated that textured face panels and shelves increased the abundance of algae, invertebrates, mussels, and overall salmon prey. Researchers came to this conclusion by testing, prior to construction, multiple different textures and types of marine shelves in comparison to the original seawall. They waited until all the test panels reached the same level of organism diversity then measured the density. The textured wall and benches consistently showed higher levels of ecological productivity when compared to the control. (Cordell, et al. 2017).

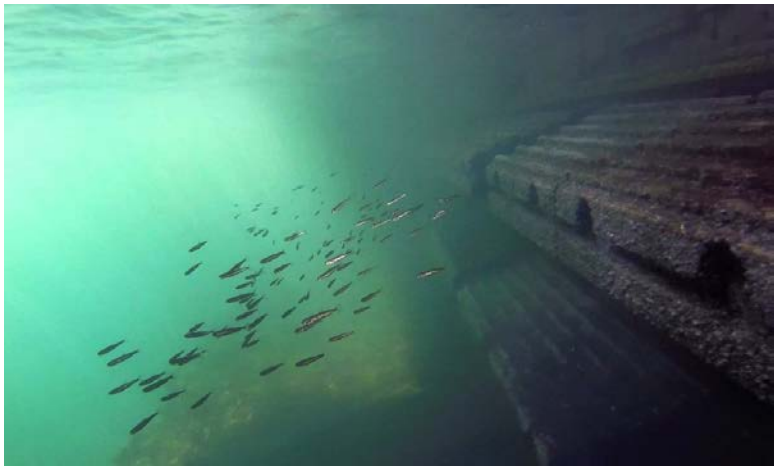


Figure 15: Salmon swimming near the habitat shelves. Source: Mike Caputo, University of Washington

Figure 16: Textured seawall surface and marine mattresses. Source: http://haddad-drugan.com/seawall-strata

The marine mattress was another design element of the replacement seawall that aimed to mimic a more natural shoreline. The mattress was placed in the salmon corridor, below the light penetrating surface, to offer shallow and complex areas for fish and organisms to take shelter. This is not the only function of the marine mattress though. According to a report from the U.S. Army Corps of Engineers, a more common use for marine mattresses is wave protection and erosion prevention. A marine mattress is made of a durable geogrid filled with stones that can be laced together or stacked to form a blanket or bed-like surface. It is versatile, easy to install, has high strength, is contained, and dissipates wave energy.

Replacing the seawall was only one component of the waterfront redevelopment. Other projects replaced the deteriorating piers, the Alaskan Way Viaduct, and created a walkable waterfront.

One additional project with similar goals and functions as the seawall replacement was the Habitat Intertidal Zone Project, meant to work hand in hand with the seawall project to provide suitable habitat and food sources. The zone acts as an intertidal "staging" area for salmon first traveling from the Duwamish River and directly connects to the seawall salmon corridor.

Key Takeaways

The Seattle Seawall Project has been highly regarded among international engineering communities. It combined research and engineering, as well as public input through a large outreach program, to successfully reach its project goals. Public amenities were expanded and significant improvements were made to the marine ecosystem, previously degraded from urban and industrial development. Throughout construction, innovative management technology was utilized for surveying and reporting while safety and environmental considerations were revered. Researchers at University of Washington have noted that geographical regions, local conditions, and native species should be considered when managing urban waterways. While the environment and species native to New Jersey differ, site-specific solutions were key to the success of this seawall replacement. Not everything from the project in Seattle can be translated to all waterways; however, the results of the redesign and various research projects corroborate that **gently sloped** surfaces and **complex surfaces** can be used to improve the ecology of developed shorelines.

Lardner's Point Park

Location: 40.014164, -75.046663

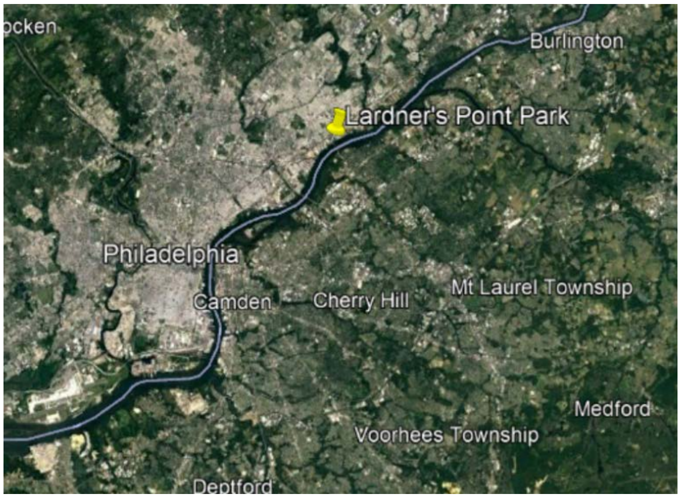
Date constructed: 2012

Website:
https://riverfrontnorth.org/learn/

Budget: $750,000

Techniques used:

- Live branch layering
- Marsh sill
- Root wads
- Regrading



Lardner's Point Park is a 4.5-acre riverfront park in northeastern Philadelphia. Set along the Delaware River, the park forms part of the North Delaware Riverfront Greenway, a more than 10-mile section of the Delaware Riverfront. Once a neglected industrial shoreline, Lardner's Point was transformed into an ecologically rich, sustainable, resilient public park in 2012.

Lardner's Point Park is located just west of the present day Tacony-Palmyra Bridge. Prior to construction of the bridge in 1929, Lardner's Point Park was the location of the Tacony terminal of the Tacony-Palmyra ferry route. Following construction of the bridge, ferry service was terminated and the City of Philadelphia assumed ownership of the land. Prior to its redevelopment, Lardner's Point was nothing more than a barren industrial brownfield consisting of deteriorating concrete, dilapidated docks and boat ramps, and sparse invasive species. In 2004, the tanker M/V Athos I ran aground while preparing to dock at a refinery in nearby Paulsboro, New Jersey, spilling 265,000 gallons of crude oil. Oil from the ruptured tanker spread 115 miles downriver and impacted 280 miles of shoreline. In 2010, NOAA and a team of natural resource trustees from Pennsylvania, New Jersey, and Delaware were awarded $27.5 million for restoration projects designed to benefit the environment, communities, and economy in the impacted areas. These projects included oyster reef restoration, dam removals, habitat restoration, and the redevelopment and restoration of Lardner's Point.

Figure 17: Lardner's Point site. Source: Google Earth

As part of the redevelopment of Lardner's Point, the existing industrial structures were demolished and a portion of the property became a section of the East Coast Greenway, a mixed-use bike and walking path. The remaining brownfield was partially replanted but little consideration was given to the erosive forces of the river. Over time, erosion destroyed the shoreline and the water's edge began encroaching on the bike path; in some areas, the shoreline was within two feet of the trail. A living shoreline was constructed to help further restore habitat and to reduce erosion. A total of 0.9 acres of intertidal marsh and wet meadow were restored. The design of the living shoreline at the park includes, from the river moving upland, a rubble/rock toe sill, marsh fill, marsh plantings, live branch layering, and, finally, plantings along the riverbank. This park also provides safe and attractive access to the Delaware River for recreation.

Various novel techniques were used in construction of the living shoreline at Larder's Point Park. The sill on the edge of the shoreline has a core of 24-to-36-inch rocks. Root wads (the bottom 15 feet of a dead tree) were imported and buried with fill material just landward of the sill to provide a carbon and nutrient source for the flora and fauna in the area as they decayed. In the high marsh portion of the site, two approaches were used, live branch layering, where live branches from shrubs like willows and dogwoods are buried, and live staking, where plant material is larger and planted vertically. In both approaches, the intention is for some of the branches to take root and grow in place and help provide stability to the shoreline.

In January 2017, a severe Nor'easter hit Lardner's Point Park with winds gusting up to 50 mph. The wind conditions created an extremely erosive wave climate for the majority of the storm which caused significant damage to the park. Areas saw significant scour of sand and silt leaving only coarse pebbles and cobble in the intertidal zone. The rock sill was also damaged; several areas were breached and resulted in loss of finer stone and sediment fill between the sill and coir log. Behind the sill several of the washed-out areas had exposed root mats as a result of this erosion; these exposed roots confirm that plant growth had occurred, but exposure is hazardous to plant health. Multiple planted shrubs were washed away or had exposed root balls. The silt and sand scoured from the project appeared to wash down to the inlet, south of the marsh sill. An approximately two-foot-tall dune formed around three to five feet from the base of the concrete wall located at the south end of the site.

After the Nor'easter, plants were reinstalled, and small dams of medium-sized rocks were placed downhill of exposed plants to encourage the accretion of sediment. The damaged sill was also rebuilt and repaired. Fill was added over plants with exposed root balls and root mats.

Key Takeaways

This project succeeds in creating a park that allows for recreational activities, river access, and **natural habitat**. However, while the living shoreline design at Lardner's Point established habitat effectively, it did not prove to be resilient to a large winter storm. Design considerations should be made for larger storms if living shorelines are truly considered to be resilient. This is even more important along developed shorelines, where habitat and sediment are already limited, making it more difficult for regrowth of desired flora after storm damage.

Port of San Diego

Location: 32.7355, -117.1772

Date constructed: 2021

Website:
https://econcretetech.com/projects/port-of-san-diego/

Budget: Unknown

Techniques used:

- Tidal pool development
- Surface roughness
- Reduce slope
- Ecological Concrete

Harbor Island is a 44-acre peninsula created in the early 1960's from material dredged from San Diego Bay, in San Diego, California. The island is located between Shelter Island and Downtown San Diego, directly across Harbor Drive from San Diego Airport. The property is owned and operated by the Port of San Diego. A small area of shoreline was selected to test various living shoreline designs to improve habitat value on the shoreline of this industrialized island. Pilot studies are ongoing as funding continues to become available.

In 2019, the Port approved a two-year pilot project with ECOncrete, an eco-engineering company developing ecological concrete infrastructure. The project included a multidisciplinary team of marine biologists, industrial designers, coastal engineers, as well as Port officials and other stakeholders. The aim of the project is to provide an example of inclusive design for coastal protection and port infrastructure that will not only provide shoreline stabilization but improve the ecology within the bay. This undertaking was performed under the Blue Incubator Program, a business incubator and investment program, established by the Port of San Diego (PoSD). The intent of the program is to assist in the creation, early development, and initial scaling of new business ventures targeted at key specific segments of the Blue Economy.

Figure 18: Pilot Project Installation on deployment day (A), eight months post construction (B), and three months post construction (C).

The primary objectives for the design of the ecological concrete armor units were to provide and mimic intertidal and subtidal habitats while providing the necessary coastal protection along a fully armored waterfront. The units were designed for use within breakwater systems and shoreline protection schemes as an alternative or complement to stone or traditional concrete armoring. As part of the site assessment, comprehensive analyses of all site-specific parameters were conducted. This included local and invasive species, nearshore and offshore bathymetry, hydraulic conditions including waves and currents, climate data, and water quality amongst others. This created a robust baseline data set against which future monitoring results can be compared. The data was also used to finalize the design of the 3.4 metric ton multidirectional, interlocking concrete armor units.

Traditional armor units are designed to withstand the intense hydrodynamic forces exerted upon coastal defense schemes (changing salinity and temperature, dry-wet and freeze-thaw cycles, ice loads and erosion by water currents), but due to a lack of surface roughness and curvature, these structures typically support lower species richness and diversity than naturally occurring substrates (Bulleri & Airoldi, 2005; Bulleri, et al. 2005; Moschella, et al. 2005; Chapman & Blockley, 2009; Martins, et al. 2010; Hawkins, 2012; Firth, et al. 2013a; Firth, et al. 2013b; Firth, et al. 2014a; Firth, et al. 2014b). However, with the use of ecological concrete materials as well as an increase in surface complexity, increased colonization, and enhanced biodiversity of marine species on artificial coastal armoring is possible (Evans, et al. 2016). As a means of mimicking these natural intertidal and subtidal habitats, the ecological armor unit was designed to accommodate numerous installation patterns, creating unique coastal habitats not typically found on armored waterfronts (Rella, et al. 2022). Some of the unique features include water retaining elements, overhangs and cave-like shelter depending upon the placement. Scientifically derived surface textures and bio-enhancing admixtures were added to improve the chemistry of the surface composition, and a low carbon concrete mix was implemented into the design of the units. A total of 74 armor units were placed across two locations within the existing riprap armored slope. Comprehensive structural and ecological monitoring is scheduled to take place for a two-year period to evaluate the success of the installation.

In November 2021, the first monitoring survey was conducted at 8 months post deployment. The communities on and within the ecological armor units were significantly different from those on the control rocks, with an increase of species richness on the ecological units. The ecological units were found to have more species diversity than the control rocks, with a total of 31 sessile species and 10 motile invertebrates compared to 22 sessile and 5 motile, respectively. In addition, bivalves, decapods, nudibranchs, and the gastropod Aplysia californica were noticed exclusively on the ecological units. Furthermore, when examining the algal community, the control rocks were highly dominated by a red invasive alga, while the armor units had 13 different algae species including green, red, brown, and coralline. Water quality was also improved as an increase in dissolved oxygen was found in the cavities of the ecological units.

Visual inspection of the units revealed no visible outer cracks, spalling or breaks on the surface. No notable movement or settlement of the units was observed. Surveys of the surrounding area did not identify scour or flanking. These observations indicate that from an engineering perspective, performance was not inhibited by the ecological design.

As a continuation of pilot studies, the Port of San Diego intends to test other technologies in 2022, including Reef Balls and artificial oyster reefs. These pilot studies will be completed using a partnership between the California State Coastal Conservancy and the Port. Each reef array will include

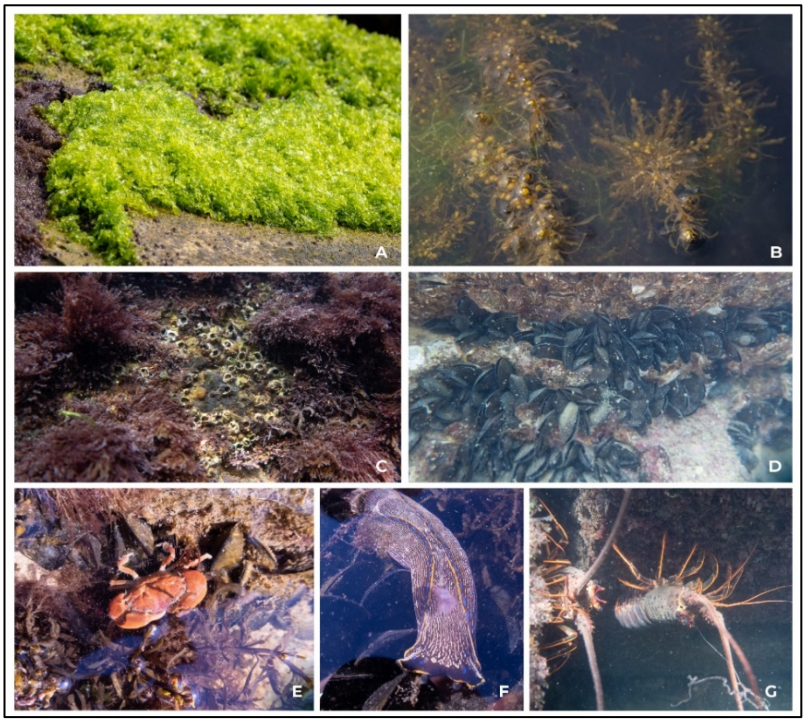


Figure 19: Examples of the biological development that covers the CL units; encrusting Ulva sp. (A), the brown algae Sargassum muticum (B), the red algae Asparagopsis armata and barnacles (C), clusters of Mytilus sp. bivalves (D), the crab Cancer productus (E), the nudibranch Navanax inermis (F) and the spiny lobsters Panulirus interruptus

15 reef groups composed of Reef Ball elements. The objective is to demonstrate the ability to attract native oysters and create structurally complex "reefs," providing habitat for fish, birds, invertebrates, and aquatic vegetation. This project, once constructed, will be monitored for 5 years to assess the success of the designs.

Key Takeaways

Although at a pilot scale, the Port of San Diego project is an excellent example of incorporating ecological enhancements along a heavily developed, active urban waterfront. In such environments, projects must meet both sustainability and development goals which are often at odds. Specifically designed **ecological enhanced concrete armor units** address not only the structural and coastal engineering requirements for shoreline stabilization but also provide habitat and increase species richness. The design of these armor units also includes **sloping** features, creating **intertidal and subtidal habitat** where none existed previously. A robust **monitoring plan** including a baseline dataset and control area, has been established to ensure that effectiveness of the project is accurately assessed. More broadly, the continuation of pilot studies at the Port of San Diego provides a great example of **adaptation** and **innovation**.

Synthesis

While existing guidance on the application of living shorelines along developed coasts is relatively sparse, WEDG and the IGNNBF provide a solid foundation on which to draw inspiration. In addition to specific design principles, the documents discuss related aspects such as education, diversity equity and inclusion and public access. The case studies on the other hand provide real world examples of many of the principles described in the guidance document. Although the presented case studies are all unique and represent the diversity of conditions that exist along developed shorelines, there are specific design principles that broadly can be applied to all developed shorelines. As a starting point, the following design principles are suggested for application along New Jersey's developed coastlines.

Preserve Natural Areas

One of the more obvious, but also potentially more difficult principles to apply along developed shorelines is preserving existing natural areas. That these natural areas exist at all along otherwise developed coastlines creates a clear conflict. Most often this conflict is resolved by choosing one alternative or the other – either allowing development and giving up on nature or prohibiting development all together. Both guidelines and several of the case studies provide examples where development and nature not only co-exist but also enrich the surrounding community. This can be especially important in overburdened communities where access to high-quality natural education opportunities is limited. Living shorelines that focus on preserving safe natural shoreline access in developed areas can become a valued space for the community by increasing recreational and educational opportunities, improving aesthetics, and even making a neighborhood more desirable.

Sherman Creek and Lardner's Point Park provide examples of maintaining and expanding natural ecosystems in highly developed areas. Both Sherman Creek and Lardner's Point Park are redeveloped industrial sites that create valuable spaces for their respective communities through focusing on expanding the natural aspects of the location. Selecting sites that are most suitable for preserving natural areas can be difficult and can involve regrading of the site, demolition, and cleanup. Appropriate sites for preserving nature tend to be in less industrialized waterways, or sections of the waterway, with lower offshore slope and slower currents immediately on the shoreline (such as in a cove).

When taking a more “traditional” approach to living shoreline design (space is more constrained than a project in a “natural” setting), care needs to be taken to select the correct plants, structures, and grading. In these environments, rock sills, breakwaters, and other energy attenuating features may be necessary to ensure that erosive forces and storms do not destroy the restored habitat and public water access.

Increase Surface Roughness

Figure 20: Example of surface roughness used in the Seattle Seawall project. Source: https://waterfrontseattle.org/waterfront-projects/seawall

One of the common elements described in the design guidelines and addressed in the case studies is the importance of surface roughness. Surface roughness has been shown to be important at both the macro and micro scales (Morris, et al. 2019). At the macro-scale, increasing surface roughness increases surface area, which provides more opportunity for colonization. Roughened surfaces can also create more favorable habitat conditions by creating water retention features, as further described below, and by provisioning shade which reduces the surface temperature. At the micro-scale, textured surfaces are easier for colonizing species to attach to and grow on and has been shown to increase biodiversity (MacArthur, et al. 2019). From an engineering perspective, certain types of marine growth have been shown to improve the engineering performance of the structures on which it grows. The process of biogenic build up (when engineering species like oysters, worms, and barnacles deposit their skeletons onto hard surfaces) increases a structure’s weight which contributes to its stability and strength. This biogenic build up can also increase the bond between structures and reduce chloride penetration, extending the life of a structure.

Figure 21: Example of marine growth on an ECOncrete armor unit in Haifa Israel. Source: https://econcretetech.com/econcrete-solution/

Increasing surface roughness must be done carefully however to ensure that the roughness features do not jeopardize the structural integrity of the built structure. For example, if cutouts are integrated into a keystone wall, the removed elements must be selected carefully so as not to compromise the integrity of the wall. Another concern may be chloride penetration. If the roughened surfaces are designed incorrectly, they may create weak areas that can crack and erode. Methods that can be used to add surface roughness without jeopardizing structural integrity or introducing weakness in a structure include adding pre-roughened armor units, increasing the roughness on "superficial" parts of structures, or adding textured panels.

Alternative Materials

Figure 22: Effect of using enhanced concrete and surface texture to enhance habitat. Source: https://econcretetech.com/blogcat/ecological-concrete-block-mattresses-acbm-scientific-study/

Materials such as steel sheet pile, concrete, and even wood have been used for decades in waterfront construction due to their structural properties and ease of construction, with little thought of their impact on the environment. Most of these common materials provide little to no habitat value and in some cases harm the environment (chemicals leaching from timber piles for example). Recent advances in material design and selection however have shown that it is possible to build waterfront edges using, safe, sustainable materials that enhance the local ecology, while maintaining or even improving structural performance.

Although, not ideal from an ecological perspective, rip-rap and rock armored shorelines have several advantages compared to bulkheaded shorelines. Rock provides a more variable and textural shoreline than traditional armoring that creates pockets of space for flaura and fauna. Vegetation will often colonize open space between rocks and be added to rock armoring projects at the design phase using a technique called joint planting.

Innovation has led to the introduction of habitat friendly concrete, or ecological concrete. Concrete contains three main ingredients: water, cement, and aggregate. Admixtures are often a component of concrete as well to assist with certain design purposes of the concrete. Most ecological concrete works by replacing either the aggregate or the cement, preventing toxic chemicals from leaching out of the concrete to sea life. Shell fragments and other specific aggregates can be added to encourage the growth of certain species like oysters and mussels. Many of the enhanced concrete mixtures have been shown to be as strong or stronger than traditional concrete. This is largely due to the positive impact of biological growth, as mentioned above. While there are known cases where the growth of marine organisms can deteriorate traditional concrete surfaces, this is not the case in ecological concrete. In fact, according to a study by Rissinger (2012), concrete covered with marine growth showed a ten-fold increase in flexural strength. This enhanced biological growth encouraged by correct material choice can increase the bond between adjacent infrastructural elements and act as a "glue" that resists erosional forces on the structure. Chloride penetration can be reduced by biogenic build up by creating a protective layer between the concrete and water. Ecologically enhanced concrete is often combined with shellfish restoration as these materials can serve as the basis for reef building organisms. The use of these materials in traditional concrete infrastructure can greatly increase the ecological value of a bulkhead or seawall.

Several of the case studies incorporated the use of alternative materials. At Harlem River Park, a portion of the seawall was replaced with oyster shell filled gabions. At Brooklyn Bridge Park, precast ECOncrete tide pools were integrated into the rock revetment. The Seattle Seawall project used innovative translucent panels to increase light penetration. In San Diego, an entirely new type of ecological armore unit was developed and deployed.

Reduce Slope

Figure 23: Terracing used to reduce slope in a space constrained environment. Figure 21: Terracing used to reduce slope in a space constrained environment. Source: https://harlemriverpark.weebly.com/gallery.html Photo by: Thomas Lunke

Vertical barriers between land and water are common in urban environments where space is often at a premium. Not only is space at a premium on land but also in water. Urban waterways typically need to accommodate vessels of a certain size which requires a design width and depth of a channel. This creates steep banks that have limited habitat value. There are several methods to increase habitat value in such space-limited situations. Vertical barriers can be modified with terraces, shelves, tidal pools, and other features to create multiple habitat zones in a steep space. Additionally, areas may be identified where steep slopes are not necessary for the use of the waterway, and they can be restored to provide both an ecological and a community benefit of access to water and natural habitat rarely available to city residents.

Vertical barriers were modified in the Seattle Seawall, Harlem River, and Port of San Diego projects. In the Seattle Seawall project, a zee panel was mounted on top of the wall, extending perpendicular to shore, creating a pedestrian walkway and space for habitat. Habitat benches were mounted at different elevations along the wall below the zee panels. This forms habitat zones similar to those in a naturally-sloped shoreline, while maintaining the engineering design requirements of a seawall. In the Harlem River project, terraced “greenwalls” were installed, creating habitat zones similar to the Seattle Seawall. The Harlem River project also included gabion baskets that artificially created a tidal pool to create habitat and an opportunity for public engagement, another example of effectively reducing slope. In the Port of San Diego project, the use of differently shaped features as armor units created new habitat in intertidal and subtidal zones, where very little would otherwise exist. By creating ecologically friendly shelves and semi-vertical surfaces, either through material choice, texture, or porosity, traditional vertical shoreline protection can become valuable habitat and public space.

In the Lardner’s Point Park, Sherman Creek, and Brooklyn Bridge Park projects, portions of the shoreline with available space for sloped beaches and marshes were regraded and replanted to create habitat and enjoyable public spaces, maintaining natural areas. In the case of these projects, some areas either reduced or maintained a shallow slope on the shoreline. Reducing slope in the case of these projects, creates unique natural shoreline access where it did not exist previously, while also enhancing the ecological value or the area.

From an engineering perspective, reducing shoreline slope has several benefits. Vertical surfaces tend to reflect energy, rather than dissipate it. Waves and/or currents reflecting off vertical surfaces can create a navigational hazard as well as increase the tendency for scour. During the design of the Harlem River living shoreline, several wall shapes were tested, and vertical sheet pile walls were found to do little to reduce water velocity or to attenuate wave energy. However, it was found that the tidal pool design, terraced “greenwall,” porous walls, and slopes trending to be more horizontal than vertical (20-45% grade) significantly reduced water velocity and effectively attenuated waves. By reducing slope in a project, habitat can be created, the public can have increased access to the water’s edge, and waves can be attenuated while decreasing the likelihood of scour.

Increase Sinuosity

Most natural shorelines are curved or sinuous, while most artificial shorelines are straight. Straight shorelines provide convenience for urban uses such as shipping, transportation, upland development, and recreation. The curving nature of natural shorelines on the other hand, provides a number of ecosystem benefits including the creation of micro-habitats sheltered from the stronger currents often present in the main body of artificially straightened channels. Many species of fish and insects require slower currents to colonize and spawn. Creative ecoshoreline design can restore sinuosity and helps support these critical ecological functions.

Introducing curvature in an ecoshoreline design also creates beautiful and unique public spaces. Fish and other wildlife are often attracted to these low-energy areas, creating opportunities for recreational fishing and wildlife observation. These areas often also function as safe places for the public to access the water due to their more tranquil nature. Figure 24 shows an example of how innovative design was used to restore sinuosity along a heavily developed, otherwise straight portion of the Harlem River.

Figure 24: Reintroducing curvature along the Harlem River. Source: https://harlemriverpark.weebly.com/gallery.html Photo by: Thomas Lunke

Allow Light Penetration

Light penetration is important for healthy marine habitats. Not only do photosynthesizing organisms require sunlight, but many nearshore species require light for specific behaviors. For example, changes in sunlight over the course of the year influence the breeding and feeding of fish. Increased sunlight in the spring and summer draws larval and juvenile fish to seek refuge in nearshore vegetation which increases the abundance of nearshore predators. Reduced light levels and alterations of ambient light patterns along developed shores can alter vegetation growth and animal behavior. On average, submerged aquatic vegetation requires light 10.8% of the time. Some over water structures can completely block sunlight creating dead zones with the center of docks and piers being particularly dark (Duarte, 1991). Sharp changes in light penetration can also be problematic. Artificial light along developed shorelines can confuse juvenile fish, increasing the threat of predation.

Figure 25: Translucent panels for light penetration. Source: https://www.youtube.com/watch?v=4MhEPHP6rWs&ab_channel=EarthFixMedia

Several of the projects described above included techniques for increasing light penetration. At Brooklyn Bridge Park, five acres of unnecessary pier decks were removed, and all over-water structures were kept as narrow as possible. A more sophisticated approach was used in the Seattle Seawall project. To increase light penetration, translucent panels were incorporated into the cantilevered walkway, providing light in an area that otherwise would be completely dark. Munsch, et al. (2017a) documented the positive impact these changes have had on the local salmon population. Other approaches for increasing light penetration include utilizing open railings and reflective paint colors, providing at least three meters of clearance for all dock structures, and orienting structures to minimize shading (Burdick & Short 1995).

Increase Water Retention

Increasing water retention along developed shorelines has many positive impacts. Nearly all natural shorelines contain features that trap water, sediment, and nutrients which are critical to the development of life. Several of the selected case studies include features that retain water on a variety of scales. The precast ECOncrete tide pools used at Brooklyn Bridge Park are an example of water retention at both a micro and macro scale. At the micro scale, the textured surfaces of the precast units retain small amounts of water which provide ideal growing conditions for algae and other simple organisms. At the macro scale, the main pool itself retains water during periods of low tide, providing habitat for crabs and other more complex organisms. The armor units used at the Port of San Diego perform a similar function, increasing water retention along a section of rip-rap shoreline. In both cases, monitoring data has shown that increased water retention has led to more complex habitats that encourage and increase biodiversity along the shoreline (Rella, et al. 2022).

Figure 26: ECOncrete tide pool with both micro and macro scale water retention features. Source: https://soa.utexas.edu/file/tide-pool-armor

Resilience and Adaptability

Developed coastlines by their nature are stressed systems. They exist at the nexus between the natural and built environment and must endure a variety of stressors. Climate change will only enhance these stressors. According to a panel of experts convened by the State of New Jersey, local sea level in 2050 is expected to be between 0.9 and 2.1 feet higher than in 2000 (Kopp, et al. 2019). Although the panel did not provide any state-specific guidance related to future storms, it did conclude that there was evidence for a global increase in the frequency of tropical cyclones and an increase in precipitation associated with them. In order to be resilient to the potential impacts associated with these stressors, NNBF on developed coastlines must take these factors into account at the design phase. WEDG awards credits for siting development out of or above the floodplain. The IGNNBF take a slightly different approach. Since it is assumed that nearly all NNBF projects will be built along the shoreline, the IGNNBF promotes the use of adaptable approaches which can be modified as conditions change. Adaptive management is promoted as a way of avoiding overbuilding today, for the conditions of an uncertain tomorrow.

Resilience and adaptability have been incorporated into the case study projects in different ways. At Brooklyn Bridge Park, fill from other city projects was used to elevate the park above the projected 2045 sea level. This was achieved by creating porous hills to protect upland development that are capable of absorbing urban runoff and storm surge. Additional features were constructed in water to act as a sponge for increased water volumes. Both the Seattle Seawall and Harlem River Park projects incorporate habitat benches that are designed to support different habitats as sea level rises. The Sherman Creek and Lardner's Point Park project designs maintain a natural sloping shoreline capable of migrating inland over time. The Sherman Creek project also includes raised walkways and boardwalks to make the space more resilient to sea level rise.

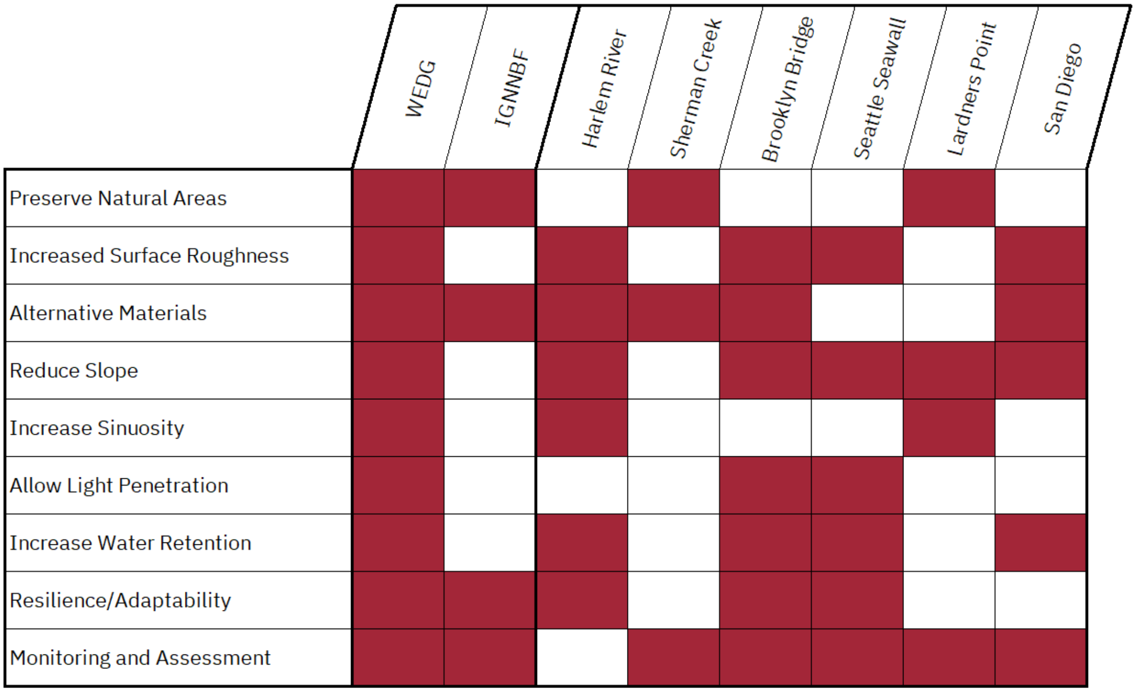
Monitoring and Assessment

Monitoring and assessment are themes that are stressed in both WEDG and the IGNNBF. Monitoring plays a critical role in understanding how a project is performing and provides the data required to assess and adaptively manage projects. As highlighted in the IGNNBF, the lack of high-quality data demonstrating the benefits of NNBF is one of the factors that prevents more widespread application of NNBF techniques. Although this plagues NNBF along both natural and developed coasts, the lack of information along developed coasts is even more critical. Three recently implemented projects actively seeking to change this narrative are the Brooklyn Bridge Park, Seattle Seawall, and Port of San Diego projects. Extensive amounts of data are being collected at each project site, with the aim of documenting project success. At Brooklyn Bridge Park, monitoring data has documented the positive impact of material selection and water retention on parameters such as biomass, biodiversity, and species abundance (Perkol-Finkl & Sella, 2015). Similarly, monitoring data from the Seattle Seawall project highlights the net positive impact of the ecological enhancements on native fish species including juvenile salmon (Sawyer, et al. 2020). At the Port of San Diego baseline data was collected prior to the installation of ecological armor units which will be monitored for a minimum of two years. During upcoming project phases two other types of ecological enhancements will be constructed and monitored for five years. To ensure that future projects benefit from the lessons of newly constructed projects in New Jersey, it is recommended that project budgets include long-term monitoring, or that alternate monitoring plans be made (potentially through partnering with academic institutions or NGO's).

Summary

Recently there has been an explosion in the number of developed shorelines designed or retrofitted using ecological principles. While the body of knowledge is continually growing, guidance documents specific to developed shorelines remain limited. Two of the more relevant documents - the *Waterfront Edge Design Guidelines (WEDG)* and the *International Guidelines on Natural and Nature-Based Features for Flood Risk Management (IGNNBF)* – were reviewed. Each contains a wealth of information on design principles and specific techniques that can be used in New Jersey. To supplement this information, six specific case studies were reviewed. The case studies vary in size, scope and setting, and are reflective of the diverse conditions likely to be encountered along developed shorelines. Each case study contains one or more project element that relates to one of nine recommended guiding principles for ecoshoreline design.

Figure 27 below maps the design principles to the guidance documents/case studies. Consistent with traditional living shoreline design, the chances of project success increases exponentially when multi-disciplinary teams are formed early and communication with stakeholders is honest and open.



	WEDG	IGNNBF	Harlem River	Sherman Creek	Brooklyn Bridge	Seattle Seawall	Lardners Point	San Diego
Preserve Natural Areas	■	■		■			■	
Increased Surface Roughness	■		■		■	■		■
Alternative Materials	■	■	■	■	■			■
Reduce Slope	■		■		■	■	■	■
Increase Sinuosity	■		■				■	
Allow Light Penetration	■				■	■		
Increase Water Retention	■		■		■	■		■
Resilience/Adaptability	■	■	■		■	■		
Monitoring and Assessment	■	■		■	■	■	■	■

Figure 27: Mapping of principles to guidelines and case studies

Glossary

Armor Stone (or Rock armor) – stone placed in the outer layer of a revetment or breakwater that is sized to be stable for the given wave conditions

Armor Unit – manufactured units, typically concrete, that are designed to be placed together and layered to form a protective coastal structure, such as a revetment or breakwater

Beneficial Reuse – use of dredged material for habitat restoration or creation

Breakwater - offshore structure typically aligned parallel to the shore intended to break/reduce incoming waves before they reach the shoreline

Bulkhead - vertical wall constructed along an existing shoreline intended to prevent the loss of soil; common construction materials include rock, steel, concrete, and wood

Coastal Squeeze – loss of intertidal habitat which arises due to the high-water mark being fixed by upland development as the low water mark migrates landwards in response to sea level rise

Coir Log – dense biodegradable log made from fibers obtained from the husks of coconuts that can be placed along low-energy shoreline to provide temporary erosion protection

Dredging - the removal of sediment and debris from the bottom of lakes, rivers, harbors, and other water bodies

Eddies – fast moving circular water currents often induced by coastal structures

Esplanade - long, open, level area, usually next to a river or large body of water, where people may walk

Gabion – a metal-wired cage, often filled with rock or shell that can be layered and stacked to form retaining walls or breakwaters

Geogrid – a synthetic material, usually fabricated into woven grids with large voids, used to provide reinforcement behind a retaining wall

Green Wall – term used to refer to a bulkhead which has been modified to include some sort of ecological enhancement

Habitat Shelf or Bench – horizontal or angled protrusion added to a bulkhead or seawall to artificially create or extend intertidal habitat

Intertidal Zone – the area between high and low tide

Littoral Zone – area near the shoreline where significant sediment transport occurs

Marine Borer - invertebrates that burrow into and damage wood exposed to water

Marine Mattress – flexible mat typically consisting of stone encased in a geotextile grid commonly used to provide erosion or scour protection, or to disperse the weight of a heavy structure (such as a breakwater)

Oyster Castle – proprietary artificial reef substrate made of ecologically enhanced concrete used to accelerate the development of an oyster reef breakwater

Overtopping – passage of water over the top of a structure such as a breakwater, sill, bulkhead or revetment

Pier-head/Bulkhead line - a legal boundary beyond which artificial structures (such as piers) may not be built into navigable waters

Pile/piling - post used to support an over water structure

Rectilinear - in a straight line

Revetments – engineered shore parallel sloped structure consisting of multiple layers of uniformly sized stone typically placed along an eroding shoreline

Rip-rap – shore parallel structure consisting of mixed sized stone typically placed along eroding shorelines

Seawall - shore parallel structure constructed along an open coast designed to resist and dissipate the energy of large waves and hold back floodwaters

Sheet Pile Wall – bulkhead composed of steel or vinyl sheets driven into the seabed

Sill - low-profile nearshore structure intended to dissipate wave energy and provide erosion protection to the shoreline behind it

Silt – fine-grained material that is readily carried and transported by moving water

Subtidal Zone - area of the shoreline that is always underwater

Terrace – broad flat section of land that can either be under water or exposed

Tidal Flat - area of lower elevation within the intertidal zone that is inundated daily

Wave Attenuation – loss in intensity of waves, or wave energy.

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