Developing Guidance for the Application of Natural and Nature Based Features (NNBF) on Developed Shores: A Case Study from New Jersey, USA

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Abstract:

Developed shorelines represent a significant proportion (14%) of the world's shorelines. Historically these shores have been tamed or hardened using a variety of engineering interventions. Often these interventions have negative impacts on the local ecology. New Jersey (USA) is the most densely populated state in the United States, and not surprisingly has one of the highest percentages (34%) of hardened shorelines. In 2013, New Jersey created a set of engineering guidelines to promote the use of living shorelines or natural and nature-based features (NNBF) in the state. Like most similar documents, the guidance focused on more natural, estuarine, and bay shorelines. Recognizing that many of the traditional NNBF techniques described in the guidelines were less appropriate for developed shorelines, the state recently created a separate set of guidelines for developed shores. That document synthesizes information from peer-reviewed and gray literature, with lessons learned from six case studies to generate guidance for the application of NNBF along the developed shores of New Jersey. The resulting guidance is founded on three core Guiding Principles: 1) Maintain/Restore Natural areas, 2) Design for Resilience and Adaptability, 3) Monitor and Assess; and six recommended Design Elements: 1) Allow Light Penetration, 2) Use Alternative Materials, 3) Increase Surface Roughness, 4) Increase Water Retention, 5) Reduce Slope, and 6) Introduce Curvature. The guidance recommends that all developed

shoreline NNBF projects in the state adhere to the Guiding Principles and that they consider applying the Design Elements where appropriate.

Keywords: NNBF, living shorelines, urban, developed

1 Introduction

From the dawn of civilization, humans have been drawn to the shoreline as a place to live, work, and play. According to a report produced by the United Nations (2017) nearly 2.4 billion people or roughly 40% of the world's population live within 100 km of the coast. NOAA estimates that in the United States, 40% of the population lives along the coast, an area estimated to generate 53.8 million jobs and produce more than US$9.5 trillion in goods and services. While living in these areas brings a number of advantages, it also puts humans in direct conflict with natural processes such as flooding and erosion that endanger human activities and lives. The specter of sea level rise threatens to throw off the already delicate balance between natural and developed systems along the coast.

The traditional response to managing conflicts between inherently dynamic natural processes and the human preference/need for fixed systems, has been to tame nature by hardening or fixing the shoreline using engineering structures. The rate and extent of global shoreline hardening has dramatically increased since 1900. Traditional shoreline hardening involves the installation of engineered structures, such as seawalls, bulkheads, revetments, and breakwaters, along the shore to stabilize sediment, prevent erosion, and provide flood protection. Within the United States, 14% of all shorelines are hardened (Gittman *et al.*, 2015). This percentage dramatically increases in urbanized areas; almost 100% of the iconic island of Manhattan (NY, USA), is hardened and over 50% of New York City's (NY, USA) total shoreline is hardened (Gittman *et al.*, 2015). Even outside of urban centers, hardened shorelines are more common in developed areas, such as industrial centers, ports, marinas, and even residential areas such as canal communities.

While hardening shorelines has some advantages in terms of facilitating commerce, reducing minor to moderate flooding, and stabilizing shorelines, shoreline hardening has been shown to negatively impact habitat, cause scour that contributes to erosion, reduce sediment transport and supply to downstream areas, and limit biodiversity and species abundance as compared to natural shorelines (Morley, Toft and Hanson, 2012; Gittman *et al.*, 2016; Vona, Gray and Nardin, 2020). Shoreline hardening also contributes to coastal squeeze. Coastal squeeze is habitat loss in front of sea defenses; it is the result of sea level rise causing the low water mark to migrate landwards in areas where humans have created static artificial margins between land and sea (Doody, 2013; Pontee, 2013). Sea levels are rising; however, hardened shorelines do not allow for the same adaptability as natural shorelines for adjusting to these higher water levels. Over the past few decades, increasing awareness of the adverse impacts and drawbacks of traditional hardened shorelines have shifted the philosophy of shoreline management, and increased interest in living shorelines. Living shorelines, also known as Nature-Based Solutions (NBS) and Natural and Nature-Based Features (NNBF), achieve engineering shoreline protection objectives while also enhancing nearshore habitat through interdisciplinary collaboration of engineers, ecologists, and planners. However, this is only possible through the creation and adherence to robust guidance.

The state of New Jersey in the United States is on the front lines when it comes to dealing with the issues described above. Despite being the 4th smallest state by landmass, New Jersey is located in the New York metropolitan region and is the most densely populated state in the United States, with nearly 400 people per square kilometer. It is estimated that nearly 80% of the population live in a coastal area (NOAA, 2019). As a direct consequence, 36% of the state's shoreline is hardened, making it the state with the second most hardened shoreline in the United States (Correll-Brown *et al.*, 2022). These hardened shorelines vary from urban to industrial to suburban (Figure 1).

Consistent with worldwide initiatives that have attempted to balance the needs of human and natural systems in coastal environments, the state of New Jersey has re-envisioned its approach to coastal management over the past decade. Specifically, New Jersey has looked to encourage the use of "living shorelines" where appropriate. New Jersey defines a living shoreline as "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." In 2013, New Jersey adopted Coastal General Permit 24 (N.J.A.C. 7:7-6.24) which locally became known as the living shoreline general permit to facilitate the implementation of living shorelines projects. At the same time, the state released a set of engineering design guidance which was tailored towards low-moderate energy estuarine living shoreline approaches (Miller et al., 2015). Recently, this document was updated to reflect the current state of the science (Miller at al., 2022). As the science has advanced, New Jersey has begun to look towards the future and the application of living shorelines in more diverse environments, with an emphasis on developed shorelines. To assist in this effort New Jersey recently developed a document which outlines best practices and provides guidance for adapting living shoreline principles along developed shorelines (Miller et al., 2022). The document integrates lessons from existing peer-reviewed and gray literature and best practices from case studies, to derive three core guiding principles and six design elements.

2 Existing Developed Shoreline Design Guidance

Unlike NNBF projects on less developed coasts, for which a plethora of design guidance and research exists, design guidance on the application of NNBF along developed shorelines is relatively sparse (Miller *et al.*, 2015; Wiberg *et al.*, 2019; Meguro and Kim, 2021; Morris *et al.*, 2021; Polk *et al.*, 2022). As mentioned previously, 14% of the shoreline of the United States is hardened; the absence of guidance for "greening" these shorelines is extremely detrimental to developed areas and their coastal ecosystems, especially considering the challenges posed by sea level rise and climate change. Some literature exists providing review and research of NNBFs on developed coasts. Developed coastlines modified with living shoreline techniques have shown to be more resilient to climate change (Moosavi, 2017). Studies have identified the engineering, ecological, and design benefits and drawbacks for traditional hardened, natural, nature-based, and hybrid shorelines and found natural, nature-based, and hybrid structures are more resilient; however, little design guidance for planners and engineers is found and many of these studies call for more research (Moosavi, 2017; Strain *et al.*, 2018). Others advocate for best management practices for living shorelines such as science-based management and policy, streamlined regulation, innovative designs, improved public perception, increased design and maintenance guidance, and standardized monitoring and adaptive management (Bilkovic *et al.*, 2019; Palinkas *et al.*, 2022).

The newly developed New Jersey guidance leans heavily on two documents that provide specific guidance for developed shorelines. The Waterfront Edge Design Guidelines (WEDG) (Waterfront Alliance, 2018) were developed in 2018 by the Waterfront Alliance with the aim of encouraging science-based, sustainable waterfront design along New York City's heavily developed shorelines. The International Guidelines on Natural and Nature-Based Features for Flood Risk Management (IGNNBF) (Bridges, 2021) were released in 2022. Although the IGNNBF have a broad focus, there are several chapters devoted to fluvial and riverine environments with more of an emphasis on developed shorelines.

2.1 WEDG

The WEDG program was originally created by the Waterfront Alliance in New York City as a way of encouraging science-based sustainable waterfront design. The program began as a local certification-based program organized around three core principles: resilience, access, and ecology. In recent years, the program has expanded to take on a national focus and to include a wider array of waterbodies and shoreline types. The WEDG guidelines provide the backbone for the WEDG program. The guidelines outline the scoring system used in the WEDG certification process. Points can be earned in six categories (Site Assessment and Planning, Responsible Siting and Risk Reduction, Community Access and

Connection, Edge Resilience, and Natural Resources and Innovation). The recently adopted New Jersey guidance draws heavily on many of the concepts outlined in the WEDG guidelines, although the state did not adopt the certification process. WEDG concepts which appear in the New Jersey guidance include foundational principles such as maintaining existing natural shorelines, designing for resilience, and measuring success, as well as more practical design elements such as increasing shoreline curvature, reducing shoreline slope, increasing surface roughness, using alternative materials, and including water retaining features.

2.2 IGNNBF

The International Guidelines on Natural and Nature-Based Features (NNBF) for Flood Risk Management (IGNNBF) were released in 2022 by the US Army Corps of Engineers (USACE) Engineering with Nature (EWN) group. Although released by the USACE, the IGNNBF are the result of a multi-year effort that included many partners including the Rijkswaterstaat Ministry of Infrastructure and Water Management in the Netherlands and the Environment Agency in the United Kingdom. The IGNNBF were motivated by the need for a comprehensive guide to planning, designing, engineering, constructing, and operating NNBF. The document is divided into three sections, one covering topics applicable across a range of landscapes and NNBF types, one focused on coastal applications, and one focused on fluvial/riverine applications. The section focused on fluvial/riverine applications is of particular relevance to developed shorelines. Within that section, the lack of documentation of successful fluvial/riverine applications was identified as an impediment to the more widespread adoption of NNBF along developed shores. The IGNNBF also identify the need for cultivating and disseminating information on best practices when such information is available. This was one of the inspirations for adopting the case-study based approach used to develop the New Jersey guidelines. Some of the concepts promoted by the IGNNBF which appear in the New Jersey guidance include foundational principles such as preserving natural areas, designing for resilience and adaptability, and measuring success.

3 Case Studies

Inspired by the call within the IGNNBF for better documentation of successful projects and better communication of the results, six case studies representing successful applications of NNBF design principles along developed shorelines were identified. The selected case studies include projects from various regions of the United States: Harlem River Park, Sherman Creek, Brooklyn Bridge Park, and Lardner's Point Park in the northeastern United States, the Port of San Diego along the Southern California coastline, and the Seattle Seawall in the pacific northwest (Figure 2). These case studies were selected based on a number of factors including their location along a heavily developed shoreline and their incorporation of sustainable, resilient, ecologically focused, and potentially transferable design principles. The projects range in size, scope, cost, and setting from a relatively small US$100,000 project along the Harlem River (Sherman Creek) in New York City, to a much larger US$410 million seawall replacement in downtown Seattle (Seattle Seawall). Brief descriptions of the six case studies are included below.

3.1 Harlem River Park

Harlem River Park (Figure 2A) is located along the 15-kilometer tidal strait separating the Bronx and Manhattan known as the Harlem River. The park consists of 8-hectares of waterfront along the Harlem River. This river is highly modified through realignment, landfilling, dredging, and bulkheading and serves as a shipping channel. Seeking to "green" the shoreline, a task force was assembled in 2001 to reimagine how this area was currently developed (Johnson *et al.*, 2010). Through this effort, various greener options were identified and analyzed to re-design the shore edge. The final design was completed in 2009 with a budget of US$2.5 million and successfully balances the navigational needs of this heavily developed and active waterway with community needs while also providing ecosystem enhancements through the use of terraces, habitat pockets that act as water retaining tidal pools, and stone and oyster shell gabions that increase the porosity of the shoreline (Johnson *et al.*, 2010). These habitat pockets and pools help mitigate coastal squeeze impacts by providing different habitat zones that can adapt as sea level rises. The redesign of Harlem River Park created a more resilient and adaptable shoreline through the use of design features that introduced curvature and increased surface roughness and water retention while also focusing on the use of alternative materials.

3.2 Sherman Creek

Several kilometers north of Harlem River Park is the Sherman Creek living shoreline project (Figure 2B) which lies within Swindler Cove in Manhattan's Inwood neighborhood, a 2-hectare park also on the Harlem River in northern Manhattan. The park, located in a low-income neighborhood, sits on an illegal dumping ground that was transformed into a public park by New York Restoration Project (NYRP) in 2003 (NYRP, 2020). The focus of the Sherman Creek project was to construct an NNBF to protect the existing park edge from erosion from boat wakes and wind-wave energy while also improving habitat value and creating a more "natural" shoreline with habitat zones that are accessible to residents for educational and recreational purposes. Unlike many urban settings this stretch of urban shoreline was not already hardened and therefore incorporates many "traditional" NNBF design techniques such as planting native grasses and the use of alternative materials to encourage oyster colonization on sills called Oyster Castles (NYRP, 2020). The Sherman Creek project exemplifies the benefits of restoring natural areas while still providing for resilience and adaptability using alternative materials.

3.3 Brooklyn Bridge Park

Brooklyn Bridge Park (Figure 2C) is a 34-hectare park set along a 2.1-km reach of the tidal strait connecting Long Island Sound to New York Harbor (East River). The area was historically industrialized; however, over time it fell into disrepair and neglect. A redevelopment project was initiated in 2009 with the objective of turning this neglected area into a "world class" park. The park was designed with resilience in mind beginning with using the 2045 NOAA mean high water estimate and 100-yr storm surge elevations to regrade the park (AKRF Inc *et al.*, 2005). Upland areas were elevated to protect both the park and serve as a barrier to future sea level rise and storm events for the neighborhood behind. Shorelines that were previously bulkheaded were converted to riprap, which does not provide as much habitat as other solutions but is preferable to bulkheads or sheet pile walls (Pister, 2009). Overwater structures were removed, and new structures were oriented to allow for more light penetration into the water column when possible. Ecological concrete was also utilized in select areas to provide greater habitat while still meeting the engineering requirements 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 in an urban setting (Shibley, 2012). The project emphasizes resilience and adaptability while also restoring natural areas using techniques such as allowing for greater light penetration, reduction of slope, and increased surface roughness. The use of alternative materials further assists to this end and increases water retention. Continued monitoring and assessment of this site assures its success into the future and will inform future NNBF design.

3.4 Lardner's Point Park

Lardner's Point Park (Figure 2D) is a 1.8-hectare riverfront park in northeastern Philadelphia along the Delaware River that is a part of the North Delaware Riverfront Greenway. Once a neglected industrial shoreline, Lardner's Point was transformed into an ecologically rich, sustainable, and resilient public park that provides valuable water access. Completed in 2012 this project focused on restoring some of the natural shoreline to this area by creating 0.4 hectares of intertidal marsh and wet meadow. The original NNBF included a rubble/rock toe sill, marsh fill, marsh plantings, live branch layering, and plantings along the riverbank (Riverfront North Partnership, 2022). In 2017 a severe storm hit Lardner's Point Park with high winds causing significant damage and erosion to the living shoreline (Riverfront North Partnership, 2022). This led to new construction and reinforcement of the rock toe sill and other structures. This provides a valuable lesson in considering less frequent storm events when constructing an urban living shoreline. The Lardner's Point Park project demonstrates a focus on restoring natural areas through a reduction in slope and introduction of curvature to the site. Continued monitoring and assessment of this site assures its success into the future and will inform future NNBF design.

3.5 Port of San Diego

The Port of San Diego (Figure 2E) launched a pilot scale project in 2019 to understand the efficacy of using ecological concrete in port infrastructure, specifically coastal armor. Ecological concrete armor units were designed to capture water and act as tidal pools while also protecting the shoreline. These units increased surface roughness, water retention, and curvature to encourage species richness and abundance while also providing the engineering parameters required. The pilot project was largely seen as a success, with the shoreline effectively armored and habitat value significantly improved (Rella, 2022). As a continuation of the project the Port of San Diego plans to also study Reef Balls and artificial oyster reefs as innovative shoreline protection in 2022 (Page, 2021). The Port of San Diego achieved ecological uplift to the area by using alternative materials that assisted in reducing the slope of the area, and increased surface roughness, water retention and shoreline curvature. Continued monitoring and assessment of this site assures its success into the future and will inform future NNBF design.

3.6 Seattle Seawall

The Seattle Seawall Project (Figure 2F) was completed in 2017; the impetus for the project was to replace the damaged Alaskan Way Seawall running approximately 2.1 kilometers along the Elliot Bay waterfront southwest of downtown Seattle (City of Seattle, 2022). The project expanded to specifically target improving salmon habitat, although general ecosystem health was also considered (Sawyer, Toft and Cordell, 2020). While ecosystem goals were important to the project, recreational and tourism goals regarding the redevelopment of the waterfront and structural improvements after the seawall was damaged during an earthquake were the main focus. To accomplish these interdisciplinary goals, creativity and innovation were needed. Zee panels were installed to shift the seawall back 3 - 4.5 meters and support an overhanging pedestrian walkway above the water. This additional space was used for a variety of habitat enhancement along the wall. Light penetrating surfaces, textured face panels, habitat shelves, and a marine mattress were all included in the design to improve habitat value (Toft *et al.*, 2013). Public amenities were expanded with significant ecosystem improvements as well. This project is highly regarded among international engineering communities as it is highlights both resilience and adaptability through the use of techniques such as reducing slope, increasing surface roughness and water retention, and allowing for greater light penetration. Continued monitoring and assessment of this project assures its success into the future and will inform future NNBF design.

4 New Jersey Design Guidance

The existing design guidance and six case studies were integrated to develop guidance for the state of New Jersey (Table 1). The New Jersey guidance can be separated into three Guiding Principles and six Design Elements (Miller *et al.*, 2022) as shown in (Figure 3). The Guiding Principles and Design Elements differ in when and how they are applied during a project. Guiding Principles are applied during the planning and management phases of a project, whereas Design Elements represent key components that are incorporated during the engineering design phase. The Guiding Principles include restoring natural areas, creating resilient and adaptable designs, and monitoring and assessing the design over time to ensure it is meeting its goals and to inform future NNBF design. The Design Elements include allowing light penetration, using alternative materials, increasing surface roughness, increasing water retention, reducing slope, and introducing curvature. Some of the potential ecological, community and engineering benefits as well as some of the challenges of implementing the guiding principles and design elements within a project are highlighted in Table 2. Although the guidance was developed specifically for the state of New Jersey, most of the concepts are transferable to other regions.

4.1 Guiding Principles

The Guiding Principles (Figure 4) included in the recently adopted New Jersey guidance are considered core to the philosophy of developing sustainable, resilient shorelines along developed coasts. The principles are intended to help designers, engineers, planners, and regulators set high level goals for each project, and should ideally be incorporated into every project. The three principles are: 1) Maintain/Restore Natural Areas, 2) Design for Resilience and Adaptability, and 3) Monitor and Assess. Adhering to the core principles helps ensure that projects meet not only short-term goals but are also designed with long-term sustainability in mind. Monitoring and assessment ensure that project needs including maintenance and adaptive management are addressed in a timely manner and that successes and failures can be used to inform future projects.

4.1.1 Maintain/Restore Natural Areas

The most obvious, but often also the most difficult principle to apply along developed shorelines is to maintain or restore natural areas (Figure 4A) due to the inherent competition for space between natural and human interests. Along developed shorelines, restoring natural areas may require the reimagining of severely degraded areas that need to be restored to healthy natural habitat; successfully demonstrated in both the Lardner's Point Park and Sherman Creek case studies. When completed effectively, however, these restored areas can become critical assets, especially in overburdened communities where access to high-quality natural education and recreation is limited. Jabbar, Yusoff, and Shafie, 2022 have documented the clear psychological, economic, and physical benefits of green spaces and water access in developed areas (Jabbar, Yusoff and Shafie, 2022). Living shorelines that focus on preserving safe and natural shoreline access can become beloved spaces for the community as evidenced by the community feedback for both Lardner's Point Park and Sherman Creek.

When preserving and enhancing these limited natural areas in developed communities, various challenges can arise. Acquiring the rights to property is often a challenge and finding funding to acquire and redevelop this property is an even greater challenge. Organizations such as the New York Restoration Project (Sherman Creek) or collaborations between the community and local, state and federal government and non-governmental organizations (Lardner's Point Park) can facilitate the implementation of restoration projects. Both Sherman Creek and Lardner's Point Park were once neglected and redeveloped industrial sites that were naturally beginning to convert to habitat. These organizations collaborating with the purpose of enhancing and restoring natural areas with an eye on community need was a critical component of the holistic project success.

Designing restored natural areas along developed shorelines presents additional challenges compared to working in more natural settings. Along developed shorelines, space tends to be more constrained than a project in natural marsh or coastal setting. This can make the implementation of wave attenuating features, such as rock sills and breakwaters more important to ensure that the small amount of natural shoreline does not erode during large storms or from the constant boat wake experienced along many developed coasts.

Selecting sites that are most suitable for preserving natural areas is another barrier to this principle on the developed coast. While only a small extent of natural area was restored at Brooklyn Bridge Park, it was possible to restore water access and salt marshes in sections of the park, creating unique natural areas on a coastline where few remain. Appropriate locations for preserving natural areas tend to have lower offshore slope or are in areas where reducing the offshore slope and thereby slowing the currents immediately nearshore, such as in a cove or eddied area, does not impact the anthropogenic purposes of a waterway. In the Brooklyn Bridge Park case study, coves were recreated along the shoreline for this purpose. Creativity is important when preserving natural areas in a developed setting. While some projects, such as the redevelopment of a port or vertical shoreline may have more challenges in restoring natural areas, even converting a small section of shoreline to a natural area is beneficial. Suggested potential areas include an area of a terminal in a port that is no longer used, a small section of shoreline that is armored that may not need to be, such as in Brooklyn Bridge Park, or in the case of Sherman Creek and Lardner's Point Park, a brownfield that can be redeveloped. It is crucial to restore natural areas for ecosystem and habitat, and educational, community, and recreational value.

4.1.2 Design for Resilience and Adaptability

Developed coastlines are stressed systems that are the nexus of the natural and the built environment, yet they are extremely space limited and confined. Climate change will only increase this stress by further squeezing habitat along the shoreline. According to a panel of experts organized by the State of New Jersey, by 2050 local sea level is expected to have increased between 27 and 64 centimeters with respect to 2000 levels (Robinson *et al.*, 2019). Although this panel did not provide state specific guidance regarding future storms, it did conclude that there is evidence of an expected increase in tropical storm frequency and intensity. Other researchers also conclude that storms similar to Super Storm Sandy are going to become more frequent over the coming years in the New York metropolitan region (Lin *et al.*, 2016; Morris *et al.*, 2019). To be resilient to the impacts associated with built and climate driven stressors, the design phase of sustainable developed shorelines must take into account future climate change and sea level rise, environmental contamination, boat traffic, and future development, in spite of the challenges related to uncertain future conditions. One way that WEDG promotes resilience is by offering credits for designs that either move development out of the floodplain, or when necessary, elevate it above the floodplain (Waterfront Alliance, 2018). The IGNNBF offers a different perspective and encourages the use of adaptable designs (Figure 4B) that reduce the tendency to overbuild in the short-term as a way of accounting for long-term uncertainties in design parameters, such as sea level rise (Bridges *et al.*, 2021).

Resilience and adaptability have been incorporated into many of the case studies. At Brooklyn Bridge Park fill from other city projects was used to elevate the park above the projected 2045 mean high water level. The porous hills within the park are a feature that visitors currently recreationally enjoy; these hills were added with the additional intent of protecting upland development from future storms by absorbing runoff and storm surge and will also act as protection well into the future. Both the Seattle Seawall and Harlem River Park projects incorporated 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 which helps organisms migrate inland over time and encourages native species and biodiversity (Jackson and McIlvenny, 2011; Strayer *et al.*, 2012). Sherman Creek also includes raised walkways and boardwalks that make the space more resilient to sea level rise.

Future projects such as the Staten Island Living Breakwaters (Staten Island, NY), are designed to be extremely adaptable. Each breakwater has a submerged section, called "reef ridges", meant to attenuate some waves while primarily providing ecological enhancement through ecological concrete and oyster restoration (NYS, 2022). The breakwaters themselves will be tall emergent structures that attenuate waves traditionally. Water retaining features in the intertidal zone are also set to be included. Both existing projects and proposed future projects demonstrate the creativity that is needed to allow for adaptive management, and much more research needs to be done to explore additional methods for adaptively managing our shorelines.

4.1.3 Monitor and Assess

Innovation in any field rarely occurs spontaneously; rather, innovation is typically an iterative process that requires monitoring, assessment, and learning (Figure 4C). This is no different for projects involving infrastructure and habitat. Projects should be monitored to ensure both engineering (i.e., structural stability, limited scour, etc.) and ecological success (i.e., increased species richness, increased species abundance, reduction in invasive species, etc.). This data can be used to inform decisions to be made on site (i.e., maintenance and adaptive management decisions) and further used to inform future design of NNBF. The themes of monitoring and assessment are emphasized in both WEDG and IGNNBF. As IGNNBF highlights, the lack of high-quality data demonstrating the benefits of living shorelines is one of the roadblocks to widespread living shoreline application (Bridges *et al.*, 2021). While there is a lack of data and research for all NNBF, projects along developed shorelines have even more limited data available. The case study projects at Brooklyn Bridge Park, Seattle Seawall, and Port of San Diego have extensive datasets which are being collected. At Brooklyn Bridge Park monitoring data has shown the positive impact of several design elements including alternative material selection and increased water retention on habitat parameters such as biomass, biodiversity, and species abundance (Perkol-Finkel and Sella, 2015). Similarly, monitoring data from the Seattle Seawall project has shown positive impacts to native fish species including juvenile salmon (Sawyer, Toft and Cordell, 2020). At the Port of San Diego, baseline data was collected prior to the installation of ecological armor units which will subsequently be monitored for a minimum of two years. During the upcoming pilot projects, monitoring is scheduled for a minimum of five years. It is recommended that all living shoreline projects include monitoring and assessment in project budgets when funding is available. If funding is not available, partnerships through academia, NGOs, and other agencies might provide an alternative mechanism to uphold this principle.

4.2 Design Elements

Design Elements (Figure 5) are specific strategies that can be implemented at the engineering design phase that can provide ecological benefits without compromising engineering integrity. As opposed to the Guiding Principles, not all Design Elements are appropriate for all projects. Design Elements are tools in the engineering toolbox that require rigorous consideration and often creativity to fit into existing designs. The six Design Elements identified from the case studies are: 1) Allow Light Penetration, 2) Use Alternative Materials, 3) Increase Surface Roughness, 4) Increase Water Retention, 5) Reduce Slope, and 6) Introduce Curvature. The following sections describe each Design Element in more detail and provide examples of how they were used at the case study sites.

4.2.1 Allow Light Penetration

Light penetration into the water column is important for healthy marine habitats. In all developed living shoreline projects, light penetration should be considered, especially when overwater structures are being added or already exist. Photosynthesizing organisms require sunlight, other species require these organisms for sustenance, and many other nearshore species require light for behaviors such as hunting and breeding (Munsch, Cordell and Toft, 2017). The changes in sunlight over the course of the year are extremely important for fish behavior. Increased sunlight in spring and summer draws larval and juvenile fish to nearshore vegetation, increasing the abundance of nearshore predators (Schafer *et al.*, 2002). Reduced light levels and the alternation of ambient light patterns along developed shores also alters vegetation growth (Munsch, Cordell and Toft, 2017). Infrastructure can completely obstruct sunlight and dead zones are often created in the center of docks and piers where there is never any light (Duarte, 1991). Sharp changes in light penetration can also be problematic, especially when artificial lighting is present along developed shorelines; this can confuse juvenile fish and increase the risk of predation.

The Brooklyn Bridge Park and Seattle Seawall projects both included designs that increased light penetration. At Brooklyn Bridge Park, the approach was very simple. Five acres of unnecessary pier decks were removed, and all new over-water structures were kept as small as possible. This reduced the amount of dead zone caused by lack of light penetration. At the Seattle Sewall project, a more complex approach was taken. To increase light penetration, while also creating waterfront walkway, translucent panels were incorporated into the cantilevered walkway (Figure 5A). This provides ample light in an area that would otherwise form a dead zone. Other approaches for increasing light penetration that were shown to be successful in research include: utilizing open railings and reflective paint colors (i.e. painting the bottom of a dock structure white), providing at least three meters of clearance below all dock structures to reduce areas not reached by light, and orienting structures with the path of the sun to minimize shading (in the northern hemisphere this would mean orienting the longest side of a structure from north to south and the shortest side east and west) (Burdick and Short, 1999).

4.2.2 Use Alternative Materials

Historically, the materials used in waterfront construction were selected almost exclusively on the basis of their engineering properties (strength, durability, etc), ease of use, and cost, with minimal consideration given to environmental impact. Many of the materials commonly used in marine construction provide little to no habitat value or, even worse, release harmful contaminants into the environment. In some cases, harmful substances (creosote, for example) have even been added to relatively benign materials (wood) to improve their engineering performance and/or durability. There are, however, alternatives to these traditional materials that show evidence of not only increased habitat value, but also increased engineering value (Figure 5B).

One alternative that has traditionally been used along many developed shorelines is rock armoring. While not ideal from a habitat perspective, rock, including riprap, provides significantly more habitat value than sheet pile, concrete seawalls, or wooden bulkheads. Rock also provides more variable and textured shorelines than other traditional armoring, providing pits and spaces for organisms to hide and live (Pister, 2009). Joint planting, which is the process of adding vegetation within the interstitial spaces of rock structures, can be used to further increase the ecological value of rock structures.

More recently, innovation has led to the development of habitat-friendly concrete, also known as ecological concrete. All concrete is made of three main components: water, cement, and aggregate. Admixtures are often added to concrete mixes to achieve specific engineering objectives such as increasing strength, enhancing flexibility, or reducing cure time. Ecological concrete is typically formed by replacing the aggregate with biogenic materials, introducing special admixtures, or both. Shell fragments commonly replace sand as aggregate in ecological concrete designed to encourage reef building. Admixtures can also be incorporated to prevent toxic chemicals from leaching out of the concrete and potentially absorbed by sea life (Sella and Perkol-Finkel, 2015).

Many enhanced concrete mixtures have been shown to be as strong or stronger than traditional concrete (Risinger, 2012). This is largely due to the positive impact of hardened biologic growth on surfaces, also known as biogenic build-up. Concrete covered with marine growth shows a ten-fold increase in flexural strength (Risinger, 2012). This increase in strength was also noted at Brooklyn Bridge Park in the pilings created using ecological concrete (Sella and Perkol-Finkel, 2014). The enhanced biogenic build-up encouraged by these alternative material choices can increase the bond between infrastructural elements by acting as a “glue” that resists erosional forces on the structure. Chloride penetration is reduced by biogenic build-up as well. This is due to the protective layer that this biological layer forms between the concrete and water (Bone *et al.*, 2022). Ecologically enhanced concrete is also often combined with shellfish restoration as a substrate for reef building organisms, such as at Sherman Creek. The use of these materials when appropriate in concrete structures can greatly increase ecological value and improve the life and strength of the structure. In addition to current ecological concrete, new concrete mixtures, as well as new alternative materials, are constantly being innovated. As additional alternative materials are available, they should be considered for use in projects with both enthusiasm and caution.

4.2.3 Increase Surface Roughness

A common design element used in many of the case studies is increasing surface roughness (Figure 5C). Surface roughness has been shown to be important at both macro and micro scales (Morris *et al.*, 2019). Macro-scale roughness includes increasing surface area and creating pockets and nooks that retain water; this provides more opportunity for colonization and potentially more shelter for certain species. Macro-scale roughness can also create shade, thereby reducing surface temperatures and potentially creating more desirable habitat. Micro-scale roughness increases the texture of a surface which has been shown to encourage sessile organisms to colonize and grow on structures (MacArthur *et al.*, 2019). In the subtidal zone, increases in macro and micro-surface roughness have been shown to create important habitat for sessile organisms and increase diversity (Strain *et al.*, 2018).

From an engineering perspective, marine growth on certain structures has been shown to improve the engineering performance of the structures on which it grows. Biogenic build-up occurs when species such as oysters, worms, and barnacles deposit their skeletons onto hard surfaces and structures. This increases structure weight, potentially increasing the stability and strength of the structure (Risinger, 2012). Biogenic build-up can also form a barrier that will protect structures from chloride penetration, extending the life of concrete structures (Bone *et al.*, 2022). Riprap structures increase macro roughness, which can provide more habitat for motile organisms, but do not create as much of an ecological benefit as other shoreline protection (Tisserant *et al.*, 2021). When adding micro and/or macro roughness care needs to be taken to ensure that it does not compromise structural integrity. If roughened surfaces are designed incorrectly, it may increase the likelihood of degradation and erosion. Methods that do not jeopardize structural integrity and increase both micro and macro-surface roughness include adding pre-roughened armor units, increasing the roughness on superficial parts of structures, and adding textured panels on the surface of existing structures.

4.2.4 Increase Water Retention

Increasing water retention along developed shorelines has many positive impacts on habitat (Figure 5D). Nearly all natural shorelines have features that trap water, sediment, and nutrients creating important niches for organisms. Creating water retaining features on seawalls, breakwaters, and along the shoreline can create valuable microhabitat and increase species diversity (Chapman, Underwood and Browne, 2018; Strain *et al.*, 2018). At Brooklyn Bridge Park, ECOncrete™ tide pools were used to retained water on both micro and macro scales. At the micro scale, textured surfaces of precast units retain small amounts of water, ideal for algal growth. At the macro scale, the pools retain water during periods of low tide, providing habitat for crabs and other larger organisms. Armor units used at the Port of San Diego pilot study perform in a similar function, increasing the water retention along an otherwise riprap shoreline. Both of these case studies have monitoring data showing that increased water retention has led to more complex habitat and increased biodiversity. At Harlem River Park increased water retention along the wall created tide pools for habitat and a unique chance for locals to observe habitat that would otherwise be unavailable in such an urbanized landscape.

However, caution should be taken when incorporating water retaining features into infrastructure to ensure structural stability is not compromised. In areas with freeze-thaw cycles, water retaining feature incorporation requires additional scrutiny. Adding water retaining features using specially designed armor units or superficially on parts of structures are some of the more common methods to ensure structure integrity is maintained while providing unique ecological, recreational, and educational features in under-resourced urban communities.

4.2.5 Reduce Slope

Steep (vertical) shorelines are common in developed environments where space is at a premium. On land, real estate values often dictate building on as much of a site as possible. In water, navigation requirements influence the design depth and width of many waterways. These two constraints often lead to vertical or steep shorelines with little to no habitat value. In less space-constrained areas where it is possible to reduce slope, doing so provides both community benefits in terms of water access and ecological benefits through the expansion of intertidal habitat. Along more space-constrained shorelines, vertical barriers can often be modified with terraces, shelves, pockets, and other features to simulate multiple habitat zones in a steep space.

Vertical barriers were modified at several of the case study sites (Figure 5E). The Seattle Seawall project included a zee panel mounted on top of the wall; this panel extended perpendicular to shore from the top of the seawall. This created additional space for a pedestrian walkway and space below for habitat enhancement. Habitat benches were constructed below the zee panel along the wall creating a "simulated slope" to the shoreline. Habitat zones similar to that of a natural shoreline were able to be established with varied elevation benches. Harlem River Park used a similar concept, with terraced "greenwalls." These terraces established habitat zones similarly to the habitat benches at Seattle Seawall. This project included gabion baskets that artificially created tidal pools to create intertidal habitat where there would otherwise be none, increasing habitat and public access to nature and simulating the habitat zones of a sloped shoreline. In the Port of San Diego Project, the use of differently shaped armor units created new habitat in the intertidal and subtidal zones, where very little would otherwise exist. By creating ecologically-friendly shelves and semi-vertical surfaces through texture, porosity, or material choice, one can create a "simulated slope" on a vertical shoreline protection thereby creating valuable habitat and public space.

At Lardner's Point Park, Sherman Creek, and Brooklyn Bridge Park, portions of the restored natural shoreline required the restoration of slope to the beach or marsh. These projects all included areas that were replanted, regraded, and in some cases, reinforced to maintain slope. Reducing slope in these projects is a necessary part of restoring natural areas and creates unique natural shoreline access in developed areas.

From an engineering perspective, reducing shoreline slope has numerous benefits. Vertical surfaces reflect energy rather than dissipate it which can create navigational hazards and increase the likelihood of scour (Tsai, Chen and You, 2009). During the design of the Harlem River living shoreline, a variety of wall shapes were tested, and vertical sheet pile was found to do little in reducing water velocity or attenuating wave energy. However, the tidal pool design, terraced "greenwalls," porous walls, and slopes that tend to be more horizontal than vertical (20-45% grade) significantly reduced water velocity and effectively attenuated waves (Johnson *et al.*, 2010). By reducing slope in a design, habitat can be created, and structure life can be extended through the prevention of scour and attenuation of waves.

4.2.6 Introduce Curvature

Most natural shorelines are sinuous whereas most developed shorelines are straight. Straight shorelines provide convenience for ease of construction and urban purposes like shipping, transportation, and upland development. The curving of natural shorelines can provide refuge from strong currents for many species and creates numerous different microhabitats and niches; many species of fish and insects require slower currents to colonize and spawn. Curving shorelines can support this critical ecological function, even in developed areas. Curving shorelines that slow current can also reduce scour and erosion which can often damage bulkheads and seawalls (Johnson *et al.*, 2010).

(Re)introducing curvature to a shoreline also creates more appealing, unique spaces for public use by lengthening the shoreline. Research has shown that natural spaces have enormous benefit to urban residents (Jabbar, Yusoff and Shafie, 2022). The refuge from strong currents that attracts fish and other wildlife also attract recreational fisherman and wildlife enthusiasts. The slower currents provide safer opportunities for public water access. Examples of introducing curvature through design are found at both Brooklyn Bridge Park's piers, Harlem River Park, and Sherman Creek, where safe water access exists in protected coves (Figure 5F). Due to the complex nature of nearshore currents, physical and/or numerical models are often used to optimize designs and to ensure adjacent shorelines and existing structures are not impacted negatively.

5 Conclusion

In many ways, the challenges faced by New Jersey in adapting existing development and managing future development along its hardened shorelines are a microcosm of the challenges faced worldwide. Due to its population density and location between the urban centers of New York City and Philadelphia, a significant proportion of the state's shoreline has been hardened (36%). The challenges of climate change along with the region's growth suggest that number will only increase in the future. Recently, New Jersey took the proactive step of developing a set of guidelines for incorporating NNBF principles into shoreline projects in developed regions. These guidelines are intended to encourage sustainable, ecologically responsible shoreline designs that improve the resilience of both the built and natural environment. It is recognized that these projects often provide critical recreational and educational opportunities for the communities in which they are located which are often underserved.

The approach taken by New Jersey is considered adaptable to other regions. New Jersey's guidance is based on a synthesis of the peer-reviewed and gray literature, which is constantly evolving, and lessons learned from six well documented case study projects. The result is a document organized around three Guiding Principles and six Design Elements. The Guiding Principles are considered core to the philosophy of developing sustainable, resilient shorelines along developed coasts and include 1) Maintain/Restore Natural Areas, 2) Design for Resilience and Adaptability, and 3) Monitor and Assess. These principles are intended to help designers, engineers, planners, and regulators set high level goals for each project, and it is recommended that they be incorporated into every project. The Design Elements are techniques that can be used to help create developed shorelines that more effectively balance the needs of the natural and built environment. These Design Elements include: 1) Allow Light Penetration, 2) Use Alternative Materials, 3) Increase Surface Roughness, 4) Increase Water Retention, 5) Reduce Slope, and 6) Introduce Curvature. Design Elements should be applied only where appropriate. Table 2 summarizes some of the ecological, community, and engineering benefits and challenges associated with the Guiding Principles and Design Elements.

The guidance developed by New Jersey contributes to the continually growing body of knowledge on the design and function of NNBF on developed shorelines; however, more research and guidance is needed. Currently much of the existing research on the application of NNBF along developed shorelines is focused on ensuring biological needs are met; however additional research is needed on the engineering value, constructability, and cost of these designs if they are to be implemented more broadly. Additional research is also needed on the long-term performance of projects impacted by climate change (sea level rise, more intense storms). The formation of multi-disciplinary teams in research, design, construction, and monitoring is viewed as an important step that can help achieve the interdisciplinary goals associated with NNBF. Additional clear engineering guidance is required to make these projects standard as opposed to stand-out, and partnerships between engineers, planners and ecologists are necessary to ensure these projects achieve holistic goals. Focusing on improving the sustainability of developed shorelines will help to ensure that our cities and communities move towards healthier, greener, and more resilient versions of themselves.

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Figure captions

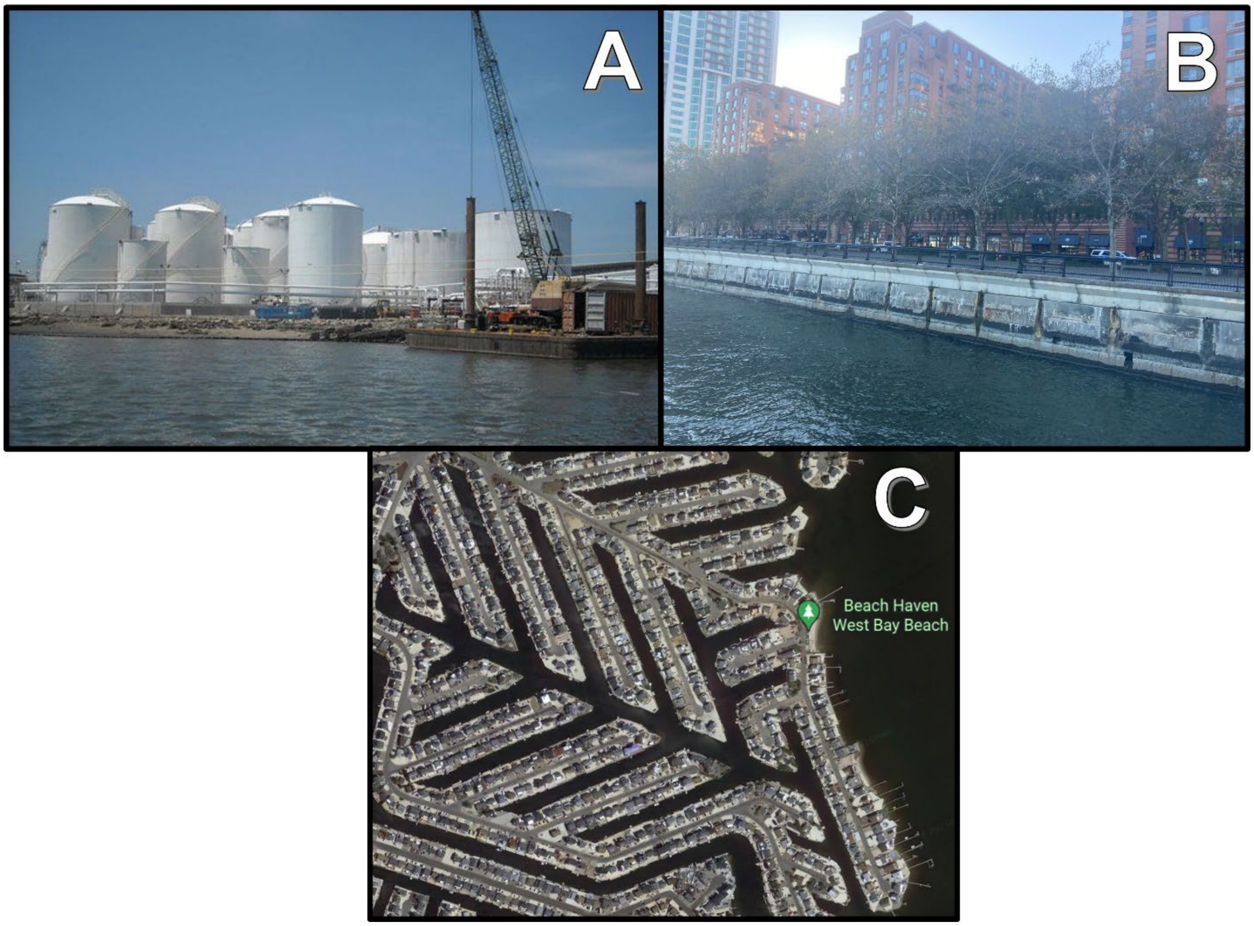

Figure 1. There are a wide variety of developed shorelines in New Jersey, including (A) industrial (Lower Hackensack River), (B) urban (Hoboken, NJ), and (C) suburban (Manahawkin Bay).

Figure 2: Developed natural and nature-based features (NNBF) case studies in the United States compiled for this study include (A) Harlem River Park (New York City, NY; *credit: NYC Parks Dept*), (B) Sherman Creek (New York City, NY; *credit: NYRP*), (C) Brooklyn Bridge Park (New York City, NY; *credit: Brooklyn Bridge Park*), (D) Lardner's Point Park (Philadelphia, PA), (E) Port of San Diego (San Diego, CA; *credit: ECOncrete*™), and (F) Seattle Seawall (Seattle, WA; *credit: City of Seattle*).

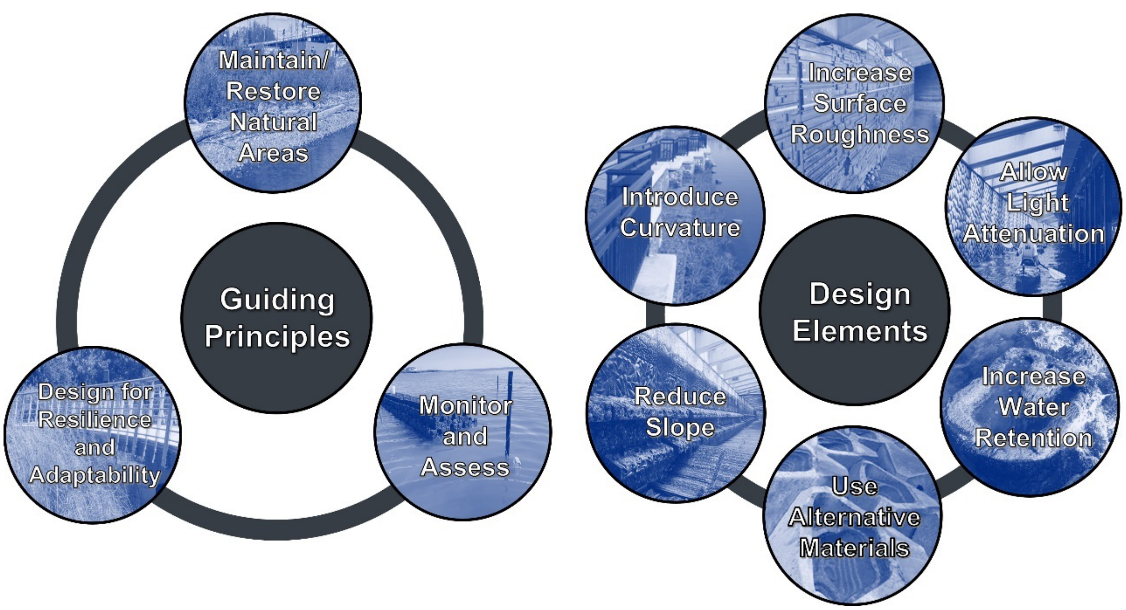

Figure 3. Design guidance for creating NNBFs on developed shorelines within New Jersey is separated into three Guiding Principles and six Design Elements. The Guiding Principles are considered core philosophies necessary for developing resilient, sustainable shorelines on developed coasts and include maintain/restore natural areas, monitor and assess, and design for resilience and adaptability. The Design Elements are specific strategies that can be implemented at the engineering design phase of a project that provide ecological benefits. These include increase surface roughness, allow light penetration, increase water retention, use alternative materials, reduce slope, and introduce curvature (*credits: NYRP, City of Seattle, NYC Parks Dept, ECOncrete^{TM}*).

Figure 4. Guiding Principles can be accomplished in a variety of ways; some examples are presented in this figure. (A) Maintain/Restore Natural Areas is accomplished through new plantings and marsh restoration at Lardner's Point Park. (B) Design for Resilience and Adaptability is accomplished through a raised walkway at Sherman Creek (*credit: NYRP*). (C) Monitor and Assess is accomplished through a pressure sensor deployment to assess wave attenuation by oyster castles at Gandys Beach, New Jersey.

Figure 5. The case studies analyzed for this study showcase the six Design Elements. (A) Allowing Light Penetration is accomplished through translucent panels incorporated into the cantilevered walkway at Seattle Seawall (*credit: City of Seattle*). (B) Using Alternative Materials is realized through the use of

ecological concrete to encourage organism growth at Port of San Diego (*credit: ECOncrete™*). (C) Increasing Surface Roughness is accomplished through textured panels on the seawall at Seattle Seawall (*credit: City of Seattle*). (D) Increasing Water Retention is accomplished through the use of artificial tidepool armor units at Brooklyn Bridge Park (*credit: Brooklyn Bridge Park*). (E) Reducing Slope is achieved artificially through habitat benches at various habitat zones at Seattle Seawall (*credit: City of Seattle*). (F) Introducing Curvature is accomplished by rebuilding a seawall at Harlem River Park (*credit: NYC Parks Dept*).

Tables

Table 1. Suggested Guiding Principles and Design Elements vary between the existing design guideline documents analyzed in this paper and the implemented Guiding Principles and Design Elements vary between the case studies; this table summarizes the results. The existing design guidance analyzed includes Waterfront Edge Design Guidelines (WEDG) and the International Guidelines on Natural and Nature-Based Features for Flood Risk Management (IGNNBF). The case studies included Harlem River Park (HRP), Sherman Creek (SC), Brooklyn Bridge Park (BBP), Lardner's Point Park (LPP), Port of Sand Diego (SD), and Seattle Seawall (SS).

		WEDG	IGNNBF	HRP	SC	BBP	LPP	SD	SS
Guiding Principles	Maintain/ Restore Natural Areas	✓	✓		✓	✓			✓
	Design for Resilience and Adaptability	✓	✓	✓	✓	✓		✓	
	Monitor and Assess	✓	✓			✓	✓	✓	✓

Design Elements	Allow Light Penetration	✓				✓		✓	
	Use Alternative Materials	✓	✓	✓	✓	✓	✓		
	Increase Surface Roughness	✓		✓		✓	✓	✓	
	Increase Water Retention	✓		✓		✓	✓	✓	
	Reduce Slope	✓				✓	✓	✓	✓
	Introduce Curvature	✓		✓				✓	✓

WEDG= Waterfront Edge Design Guidelines, IGNNBF= International Guidelines on Natural and Nature-Based Features for Flood Risk Management, HRP= Harlem River Park, SC= Sherman Creek, BBP= Brooklyn Bridge Park, LPP= Lardner's Point Park, SD= Port of San Diego, SS= Seattle Seawall

Table 2. Each piece of design guidance provides a variety of ecological, community, and engineering benefits. When planning and designing a project, the different potential benefits of each guiding principle and design element can be used to help engineers, ecologists, and planners select the best tools to reach the goals set for the site. While each design guidance provides benefits, there are also considerations that should be accounted for when applying it to a project.

	Design Guidance	Ecological Benefit	Community Benefit	Engineering Benefit	Challenges

Guiding Principles	Maintain/ Restore Natural Areas	-Promotes native habitat -Improves species richness and abundance	-Improves aesthetics -Proven psychological and economic benefits -Provides recreational and educational opportunities	-Natural resiliency -Lower cost of maintenance and repair	-Erosional/ flooding concerns -Navigational impacts -Energy reduction features may be necessary
	Design for Resilience and Adaptability	-Improves species richness and abundance -Reduces coastal squeeze -Allows for habitat transitions with SLR	-Protection from storms and flooding -Multiuse features provide recreational areas and protection	-Protection from storms and flooding -Reduces potential for over engineering -Allows for adaptative management under changing conditions	-Lack of robust research on best practices -Uncertainty in future SLR and storm conditions -Target design life must be considered
	Monitor and Assess	-Provides data to improve future projects -Provides data to prove benefits	-Opportunity for community involvement and educational outreach	-Provides data to improve future projects -Allows for maintenance and adaptive management -Evaluates engineering performance	-Cost must be accounted for in project budget
Design Elements	Allow Light Penetration	-Increases species richness and abundance -Improves juvenile fish survival -Improves SAV	-Improved recreational and educational opportunities	NA	-Requires removing or modifying overwater structures -May require innovative materials
	Use Alternative Materials	-Increases species richness and abundance	-Improves aesthetics	-Strengthens concrete structures	-Innovative materials need to

		-Can be used to increase shellfish populations	-Reduces environmental contamination and carbon footprint	-Biogenic build-up protects structures from chloride penetration - Biogenic build-up protects structures from erosion	be selected with caution -Limited options available on market
	Increase Surface Roughness	-Increases species richness and abundance -Encourages colonization by sessile organisms -Creates micro and macro habitat	-Improves aesthetics	-Strengthens concrete structures -Biogenic build-up protects structures from chloride penetration -Biogenic build-up protects structures from erosion	-Ensure structural integrity is not compromised
	Increase Water Retention	-Increases species richness and abundance -Provides intertidal habitat	-Creates opportunity for observation of intertidal zone	NA	-Ensure structural integrity is not compromised -Freeze thaw cycles should be considered
	Reduce Slope	-Increases species richness and abundance -Creates intertidal habitat -Allows for fauna shelter and access	-Increases public water access -Provides educational opportunities	-Attenuates wave energy -Reduces scour	-Not all sites are suitable -Land value may prevent regrading
	Introduce Curvature	-Increases species richness and abundance -Provides spawning habitat and shelter for fauna	-Improves aesthetics -Provides recreational opportunities -Provides safe public water access	-Reduces scour -Reduces nearshore currents	-Physical or numeric models may be required -Increases construction costs

		-Lengthens shoreline	-Lengthens shoreline		

SLR = Sea level rise, SAV = submerged aquatic vegetation, NA = not applicable

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