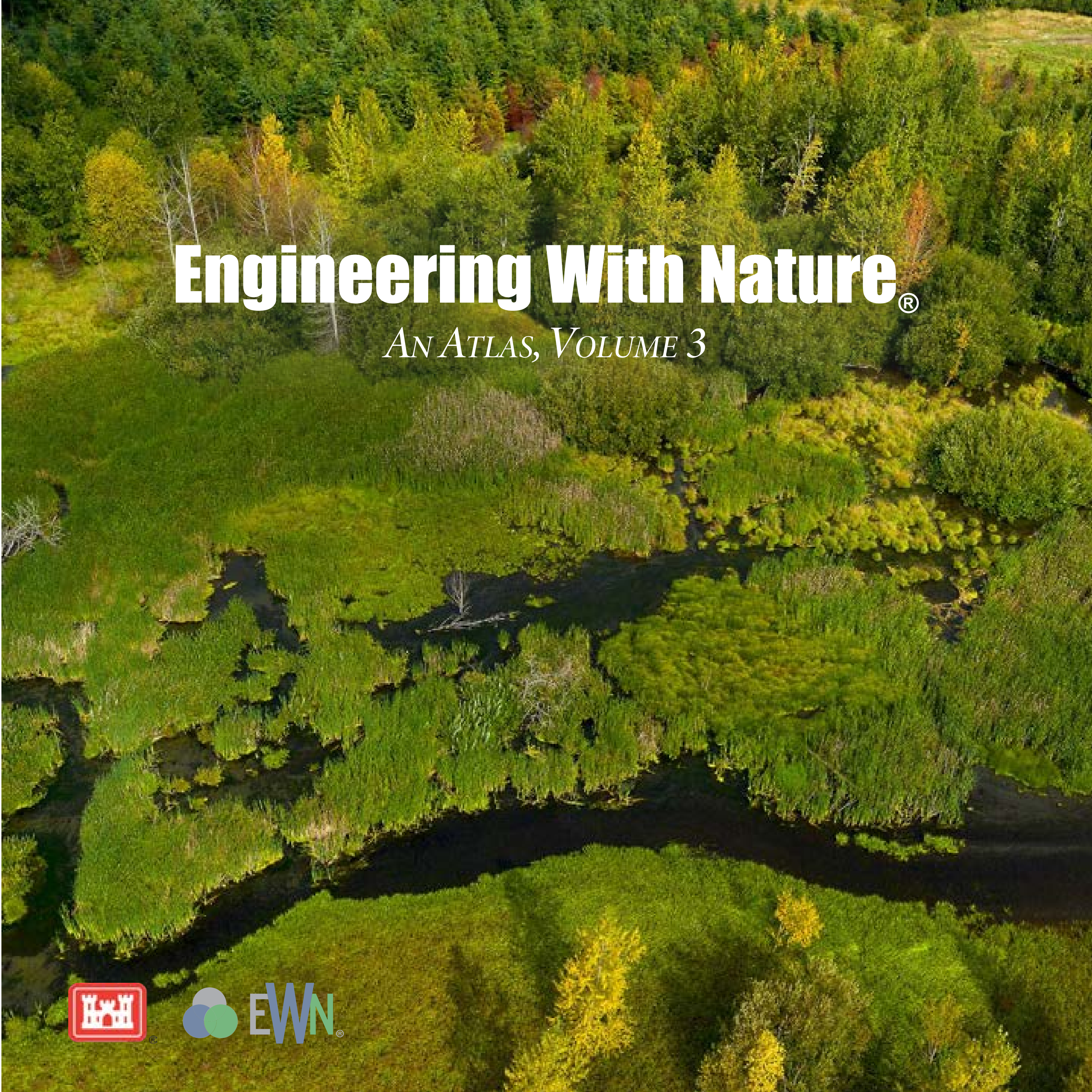
Engineering With Nature®

An Atlas, Volume 3



Engineering With Nature®

An Atlas, Volume 3

Published 2024. Printed in the United States of America.

Engineering With Nature® is the intentional alignment of natural and engineering processes to efficiently and sustainably deliver economic, environmental, and social benefits through collaboration.

www.engineeringwithnature.org

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

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

Project Team **ERDC**
Project Lead: Jeffrey King
Project Manager: Burton Suedel
Designer and Editor: Emily Moynihan
Technical Advisors: Amanda Tritinger, Courtney Chambers, and Michelle Bourne

Anchor QEA
Project Director: Ram Mohan
Project Manager: Zelini Hubbard
Technical Support: Lydia Pudzianowski, Ken Mayo, and Zheng Fang

ISBN Ebook: 978-1-7378868-5-3
Paperback: 978-1-7378868-7-7
Hardback: 978-1-7378868-6-0

DOI http://dx.doi.org/10.21079/11681/48453

Report Number ERDC SR-24-2

Citation A. Tritinger, Z. Hubbard, C. E. Chambers, B. C. Suedel, E. M. Bourne, E. B. Moynihan, R. K. Mohan, and J. K. King. 2024. *Engineering With Nature: An Atlas, Volume 3*. ERDC SR-24-2. Vicksburg, MS: U.S. Army Engineer Research and Development Center. http://dx.doi.org/10.21079/11681/48453.

Cover Photo Panorama showing the habitat in a portion of the Lower Dungeness River project wetted floodplain, bookended by the flood return channel on the upper right and the lower oxbow outlet on the upper left (project details on page 188). (Photo by John Gussman)

Foreword

Building on a Strong Foundation

Engineering With Nature® (EWN®) represents a transformative approach that aligns natural and engineering processes to deliver broader, sustainable benefits to our communities. As we embark on our third volume of the *EWN Atlas*, it is an ideal opportunity to reflect on our journey and lessons learned in anticipation of the future of EWN.

In 2010, the U.S. Army Corps of Engineers (USACE) began EWN as an initiative to promote the use of science and engineering to produce operational efficiencies; incorporate social, economic, and environmental benefits into projects; and leverage natural processes to maximize those benefits while working collaboratively. Since then, EWN has expanded exponentially to encompass partnerships with public, private, academic, and nonprofit sectors both domestically and internationally. The USACE EWN Proving Grounds and the Network for Engineering With Nature (https://n-ewn.org) exemplify USACE's dedication to collaborating and advancing the use of nature-based solutions (NBS). Driven by a shared resolve to address complex challenges and create sustainable infrastructure, the pursuit of NBS continues to gain momentum.

With that growing trajectory in mind, I am delighted to introduce the next installment of our *EWN Atlas* series. Building on the success of previous volumes, *Volume 3* showcases a diverse array of domestic and international projects that embody the principles of EWN and demonstrate the myriad of benefits NBS offer. Through stunning visuals and compelling narratives, this volume aims to inspire and inform practitioners, policymakers, and stakeholders worldwide. It is the high caliber of nature-based projects being built globally—often in multiparty collaborations—that inspires our dedication to publish these engaging project collections. They serve as a platform for the international community to exchange knowledge, foster collaboration, and continuously improve our infrastructure for the benefit of society and the ecosystems that support us. I greatly appreciate the contributions of the organizations who nominated projects to include in this book.

As we navigate the challenges and opportunities ahead, let us remain steadfast in our commitment to EWN, exercising foresight for the years ahead. I invite you to travel through the pages of *Engineering With Nature: An Atlas, Volume 3*, take time to admire the beauty of these projects, and join us in shaping a more resilient future!

Jeffrey King, PhD, PE
National Lead and Program Manager
Engineering With Nature®

Charting a Sustainable Course

As we navigate the challenges and opportunities of the twenty-first century, the U.S. Army Corps of Engineers (USACE) remains resolute in our mission to deliver essential engineering services that fortify our nation's security, stimulate economic growth, and mitigate risks posed by disasters.

Embracing this mission, Engineering With Nature® stands as a cornerstone initiative for USACE, aligning with our commitment to innovate sustainable infrastructure development.

Today's challenges demand a collective and visionary response from the entire engineering enterprise. Readiness means envisioning and actualizing the practices and capabilities that will propel us forward. To achieve this, we must continue fostering relationships across organizational boundaries and missions. Integrating engineering with natural systems unlocks enduring value for our nation and allows us all to deliver projects that are timely and cost-effective and that yield economic, social, and environmental benefits.

This volume of *Engineering With Nature: An Atlas* presents projects highlighting fully implemented, nature-based solutions. Collaborative multiorganizational teams, both within and beyond USACE, showcase solutions that transcend traditional infrastructure. These projects spotlight practices from around the globe, inspiring a collective vision for the Engineering With Nature community.

As you delve into the narratives of these projects, I hope you find inspiration, fresh perspectives, and new avenues for collaboration. Working together, we will shape a future where sustainability and partnerships define our engineering legacy.

Essayons! Building Strong! Be All You Can Be!

LTG Scott A. Spellmon
55th Chief of Engineers
Commanding General
U.S. Army Corps of Engineers

Making Natural Flood Management an Everyday Choice for All

Millions of people are at risk of flooding from rivers and the sea in the United Kingdom, and a growing number are at risk from surface-water flooding. We therefore cannot afford to take our eye off the ball when it comes to tackling the climate emergency.

Harnessing the power of nature helps to drive greater flood and coastal resilience and enables us to keep communities safe. It also creates better places for people and wildlife through enhancing habitats and biodiversity, improving water quality, and storing carbon. That is why natural flood management and working with natural processes is a central pillar of our National Flood and Coastal Risk Management Strategy.

The seven case studies from the United Kingdom in *Engineering With Nature: An Atlas, Volume 3* show the many ways in which natural flood management can help to protect, restore, and mimic the natural functions of catchments, floodplains, and the coast to slow and store water. The case studies all included partnerships with landowners, farmers, local authorities, and local environmental groups as key ingredients to their success and to embedding the benefits over time.

In the United Kingdom, we are mainstreaming nature-based solutions to reduce flood and coastal erosion risk. At the end of 2023, the Environment Agency and the government launched a new £25 million programme—our biggest-ever single investment in natural flood management. The new programme will enable us to accelerate new opportunities for delivering nature-based solutions while also further improving our knowledge.

We hope you are inspired by the case studies in this volume and that they embolden you to be part of making natural flood management an everyday choice for all rather than a special case for some.

J. K. Foley

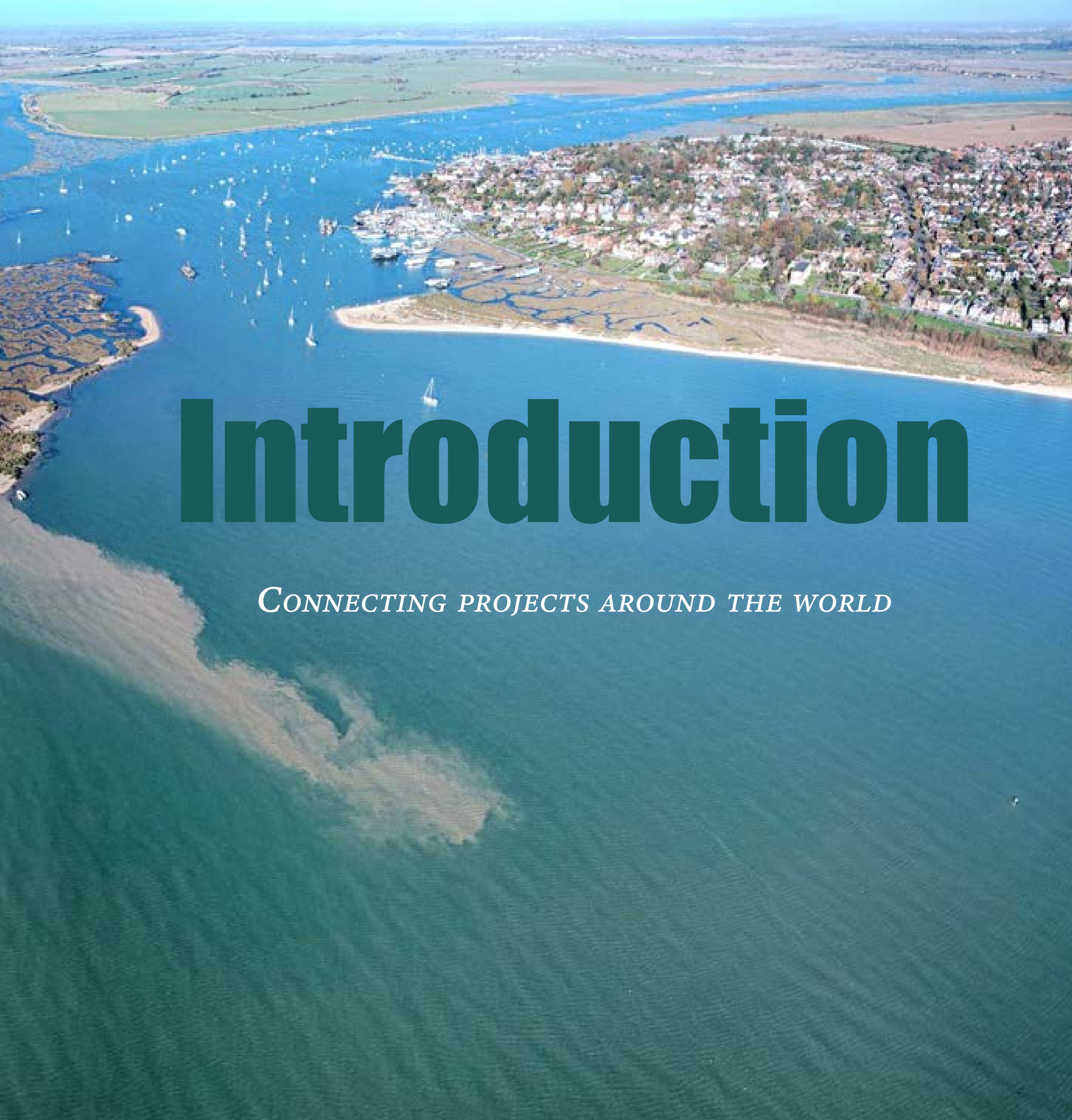
Julie Foley OBE
Director of Flood Risk Strategy and Natural Adaptation
Environment Agency

A damselfly (Coenagrionidae) *enjoying new vegetation in Toronto's Port Lands (project details on page 252). (Photo by Waterfront Toronto / Vid Ingelevics / Ryan Walker)*

*The vegetation of Sand Dollar Island park's dunes, including sea oats (*Uniola paniculata*), an important grass species in dune ecosystems that accumulate sand and prevent erosion while providing habitat and food for wildlife (project details on page 96). (Photo by Jack Hartfelder, Turrell Hall & Associates)*

Contents

Material being hydraulically pumped ashore via pipeline onto Cobmarsh Island, with Packing Marsh and Old Hall Point in the background, by using dredged material to enhance the area's sustainability (project details on page 212). (Photo by Jim Pullen Surveys on behalf of Royal Society for the Protection of Birds and Harwich Haven Authority)



Introduction

Connecting projects around the world

Background

In every walk with nature one receives far more than he seeks.
—John Muir

There is profound value inherent in natural systems. Recognizing, utilizing, and sharing this value is the ethos of Engineering With Nature® (EWN®). As humanity grapples with the challenges of a rapidly changing world, with the compounding risks posed by natural hazards, climate change, and aging infrastructure, there is a growing imperative to innovate and take decisive action to design and build resilient and sustainable infrastructure. As we navigate the complexities of the twenty-first century, the need to harness nature's wisdom in our engineering endeavors has never been more urgent. This *Atlas*, the third in a series, serves as a beacon of inspiration and insight, drawing upon the work of many within the EWN community to pursue.

For over a decade, the EWN Initiative, spearheaded by the U.S. Army Corps of Engineers (USACE), has been at the forefront of advancing nature-based solutions (NBS) to address critical engineering challenges while bolstering resilience and pursuing the *intentional alignment of natural and engineering processes to efficiently and sustainably deliver economic, environmental, and social benefits through collaboration* (www.engineeringwithnature.org).

These solutions not only offer robust responses to pressing issues but also yield multifaceted economic, environmental, and community benefits. The progress made during this period is a testament to the collaborative efforts of numerous projects, partnerships, technological advancements, and communication initiatives.

The *EWN Atlas* series highlights projects and partnerships that meet these challenges, showcasing the multifaceted benefits of integrating natural processes into engineering solutions. Just as trees offer more than mere timber or shade, so too do natural systems offer a wealth of services, processes, and materials that can enhance infrastructure, safeguard communities, and nurture biodiversity. From the filtration prowess of wetlands to the protective embrace of coastal mangroves, nature's contributions are vast and invaluable.

Bypass channel diverting water through the historic Espada Remnant of the San Antonio River. The bypass channel provides fish passage around a large flood control impoundment (project details on page 148). (Photo by San Antonio River Authority)

Though we currently strive for innovation, Theodore Roosevelt's words from 1908 remind us that our pursuit of sustainable practices, including NBS, is not merely a modern endeavor but a timeless obligation rooted in the foresight of truly civilized societies.

> We have become great in a material sense because of the lavish use of our resources, and we have just reason to be proud of our growth. But the time has come to inquire seriously what will happen when our forests are gone, when the coal, the iron, the oil, and the gas are exhausted, when the soils shall have been still further impoverished and washed into the streams, polluting the rivers, denuding the fields, and obstructing navigation. These questions do not relate only to the next century or to the next generation. One distinguishing characteristic of really civilized men is foresight; we have to, as a nation, exercise foresight for this nation in the future; and if we do not exercise that foresight, dark will be the future![1]

The imperative to collaborate with nature becomes increasingly clear.

Within these pages, readers will discover a tapestry of case studies, methodologies, and success stories, each illustrating the transformative power of EWN. From restoring degraded landscapes to enhancing urban resilience, the applications of EWN principles are as diverse as the environments they inhabit. As we share the story of this journey, let us heed the wisdom of those who have come before us, from the visionary ecologists of the past to the trailblazing practitioners of today. Together, let us forge a path toward a more harmonious relationship between humanity and the natural world, where engineering serves as a conduit for collaboration rather than domination.

In the spirit of John Muir's timeless maxim, may each step we take in partnership with nature yield untold treasures, enriching not only our infrastructure but also our collective well-being and stewardship of the planet.

[1] Theodore Roosevelt, "Conservation as a National Duty," opening address, Governors' Conference on the Conservation of Natural Resources, May 13, 1908, Washington, DC.

A monarch butterfly (Danaus plexippus) *exploring new green spaces in Toronto's Port Lands (project details on page 252). (Photo by Waterfront Toronto / Vid Ingelevics / Ryan Walker)*

The EWN Initiative

The journey of the EWN Initiative began in 2010 within USACE, marking a pivotal moment in our collective recognition of the intrinsic value of nature within engineering endeavors. Over the past decade, this initiative has evolved from its nascent origins to become a beacon of collaboration, drawing together a diverse array of partner organizations and collaborators. Serving as an enabler for exploration and innovation, the initiative stands as a testament to our ongoing commitment to harmonizing natural and engineering processes to achieve sustainable water resources and infrastructure practices.

As we navigate the intricate pathways of our future, let us look to the EWN Initiative as a guide, shepherding our steps as we embark on our walk through nature and toward a more resilient tomorrow.

Four critical elements define the EWN approach:

Using science and engineering to produce operational efficiencies

Using natural processes to maximize benefit

Increasing the value provided by projects to include social, environmental, and economic benefits

Using collaborative processes to organize, engage, and focus interests, stakeholders, and partners

Just as in the previous volumes of the *EWN Atlas*, *Volume 3* employs these four essential elements to delineate advancements and achievements of projects. This framework facilitates the illumination of project outcomes, effectively showcasing the multibenefits attained, use of natural processes, and collaborative partnerships inherent to EWN.

Eco-armor units hosting algae growth and bivalves (project details on page 244). (Photo by Environment Agency)

Expanding the Community of Practice on Nature-Based Solutions

The *EWN Atlas* series shares examples of EWN practice, allowing readers to learn from project examples around the world in a visually compelling way. As with earlier volumes of the *Atlas*, the current collection of projects illustrates a diverse portfolio of circumstances, inspirations, obstacles, and achievements. All projects presented in this *Atlas* highlight the importance of collaboration to diversify project value (i.e., multipurpose projects). They showcase the benefits that can be produced when engineering and natural processes are successfully integrated to support navigation, flood risk management, ecosystem restoration, and other infrastructure purposes. Each project example introduces unique facets of developing sustainable projects while also revealing the four common elements of EWN.

Collaboration and partnerships are key to learning from and with others; building capacity to bridge perspectives, mandates, and objectives; and providing the means and reach for landscape-scale implementation. By working together, we benefit from a wealth of knowledge and expertise, enabling us to address complex challenges more effectively. Within USACE, the EWN Practice Leads, who are seasoned practitioners with specialized expertise and a passion for EWN, support implementation in districts across the nation. They also lead the EWN Implementation Cadre, a group of 500 USACE practitioners representing a variety of disciplines across the enterprise, applying EWN elements to deliver NBS. Beyond USACE, the Network for Engineering with Nature (N-EWN), comprising 26 organizations as of January 2024, are collectively working to create a resilient future by integrating conventional and natural infrastructure to improve societal well-being by sustainably delivering more value and benefits to people and the environment. EWN similarly extends beyond national borders, as evidenced by the inclusion of project examples from countries outside the United States.

This global perspective underscores the collective effort toward advancing sustainable practices on a global scale. Additionally, the establishment of an international NBS working group further underscores the commitment to cross-border collaboration and knowledge exchange, driving the continual evolution and application of EWN principles worldwide. Despite variations in context and particulars across communities and countries, shared principles serve as pivotal catalysts for advancement on a global scale.

To highlight the expansive strides being taken to incorporate nature into the spectrum of engineering endeavors, we use the globe symbol (below) to signify projects beyond the borders of the United States.

Hydraulic structure on the salt marshes of the Leyre Delta, France (project details on page 76). (Photo by Conservatoire du littoral)

Connectivity to Natural Hazards and Flood Risk Management

Natural disasters claim thousands of lives and result in billions of dollars in damages annually worldwide. Over the past 7 years (2017–2023), there have been 137 separate billion-dollar disasters, resulting in the loss of at least 5,500 lives and exceeding $1 trillion in damages.[2] Flooding accounts for a significant portion of both the annual loss of life and economic devastation caused by natural hazards, not only in the U.S. but also globally.

While conventional engineering solutions for flooding show promise in mitigating damages, the broader application of NBS presents an even greater potential for long-term risk reduction. With an estimated $100 trillion slated for global infrastructure investment between 2020 and midcentury, crucial questions arise regarding the nature of this infrastructure, its integration with natural elements, its functionality, and the diverse range of benefits it can offer.

[2] Adam B. Smith, "2023: A Historic Year of U.S. Billion-Dollar Weather and Climate Disasters," Climate.gov, January 8, 2024, https://www.climate.gov/node/838923.

The concept of advancing NBS encompasses the utilization of landscape features to fulfill engineering functions pertinent to flood risk management, while concurrently providing a multitude of economic, environmental, and social advantages. These features, which include beaches, dunes, islands, forests, wetlands, and reefs, can occur naturally or be constructed as natural and nature-based features (NNBF) through human intervention. In that vein, we have designated projects in the *EWN Atlas, Volume 3* that were developed as NNBF projects with the following symbol:

NNBF

Advancing NBS offers a pathway to simultaneously address flood risk management and sustainability objectives. In realizing this potential, a diverse array of interested parties, including engineers, environmental scientists, conservationists, social scientists, government officials, and the public, must actively participate in the process, shaping the development of new, resilient infrastructure solutions. The *EWN Atlas* series aims to achieve this by showcasing the tangible outcomes of EWN using vivid imagery and concise descriptions. This approach makes the concepts easily accessible to a broad audience while also offering a compelling vision for the achievable.

Black ducks (Anas rubripes) *using one of the 20 constructed pools at Teaneck Creek Park. The project restored eight hectares of diverse wetland habitat and protected adjacent lands from stormwater erosion, localized flooding, and ongoing degradation (project details on page 52). (Photo by David Ike Photography)*

With a View Toward the Future

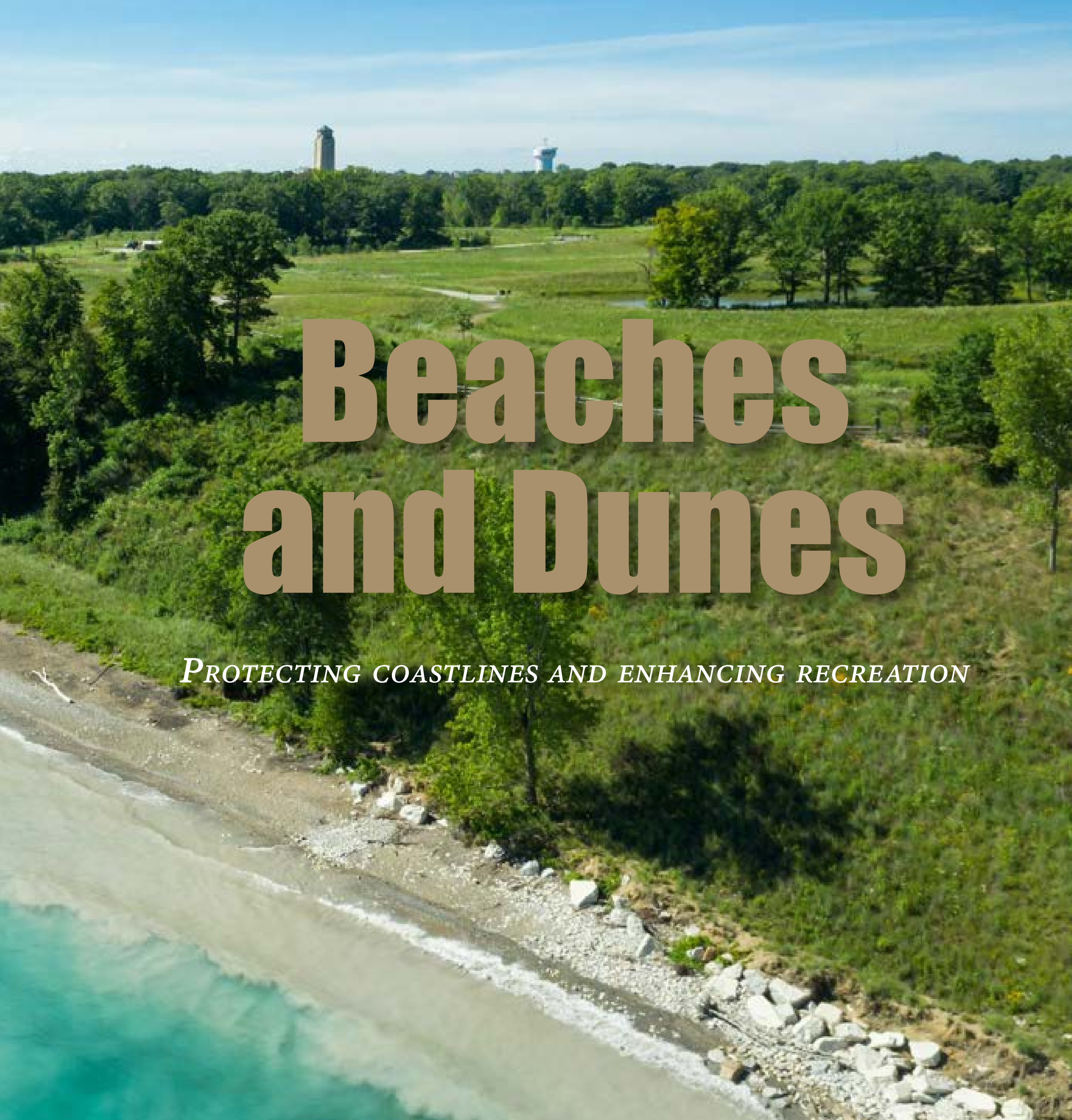
Nature is pleased with simplicity.
—Sir Isaac Newton

As you journey through the examples presented within this *Atlas*, it is valuable to cultivate a mindset aligned with the purpose at hand. The 58 projects showcased in the following pages offer a glimpse into a growing array of interventions and collaborations between engineering and nature. As you delve into these examples, we encourage contemplation of the following inquiries:

- What insights do these projects impart, drawing from nature's own designs?
- In what ways could the elements of EWN be harnessed to benefit my community?
- Where do opportunities lie for cultivating new value through EWN within my sphere of influence?
- What challenges hinder the widespread adoption of NBS, and how might they be overcome?
- How can individual contributions foster the innovation necessary to propel EWN forward, enriching infrastructure in the twenty-first century?

The trajectory of the future is shaped by understanding the achievements of others and envisioning possibilities for even greater advancements. Just as nature seamlessly integrates across landscapes, so too can our infrastructure, forging a path toward a more sustainable future.

Restored bluffs and foredune at the Lake County Forest Preserve, Lake Forest, Illinois (project details on page 16). (Photo by FadeOut Media)



Beaches and Dunes

Protecting coastlines and enhancing recreation

Beaches and Dunes

Introduction

Beaches and dunes continue to play a major role as features that help reduce flood risk in marine and freshwater coastal areas around the world. Dunes are being designed as natural infrastructure and shaped to improve resiliency, especially when opportunities arise to beneficially use material dredged from local navigation channels. Dune designs to reduce coastal storm risk include planting native grasses and placing other features to support the dunes as natural infrastructure well into the future. Coastal features like groins are being designed and built more sustainably to harness nature's energy and to enhance the economic, environmental, and social benefits of beaches and dunes. For example, nature's energy is being used to nourish an offshore ebb-tidal delta that provides greater economic benefits than conventional beach nourishment techniques. Other projects are engineering with nature more holistically, developing solutions that integrate adjacent features, including ravine, woodland, bluff, and lacustrine habitats, to enhance the resiliency of the dune system.

Fort Sheridan

Lake Forest, Highland Park, and Fort Sheridan, Illinois, United States

Using historical native plant ecotypes and natural processes to restore a coastal ecosystem. Although northeastern Illinois lies largely within the Chicago metropolitan area, the Fort Sheridan Restoration Project rests within the suburb of the Town of Fort Sheridan, surrounded by neighborhoods, parks, and forests along four kilometers of Lake Michigan shoreline. Completed in fall 2020, the project aimed to bring ecological benefits to the coastal environment, from the ravines down into the nearshore underwater habitats, and social and economic benefits to the community. The effort restored 84 hectares of ravines, riparian woodlands, coastal bluff, beach, dunes, and lacustrine habitat to connect coastal natural habitats, restore historical native plant communities, and increase resilience along the coast. The U.S. Army Corps of Engineers (USACE)–Chicago District was joined by the Lake County Forest Preserve District, Openlands, the City of Lake Forest, and the Lake Forest Open Lands Association in the project, which benefited rare and endangered ravine and coastal plants and animals while taking care not to disrupt patches of high-quality habitat. The project provided habitat structure; used natural processes to ensure sustainability; and, where natural processes were no longer functional, mimicked natural habitat using native materials.

Producing Efficiencies

The project was able to meet societal needs while preserving and enhancing environmental quality by using natural materials. Reefs were constructed with native limestone and trees, which are discharged from ravines, to provide foraging opportunities for fish. The limestone retaining walls provide structural stability in the ravine and maximize habitat heterogeneity for terrestrial animals in this comprehensive coastal system. The reefs and ravine's natural retaining walls will interact with natural processes as the structures move toward dynamic equilibrium within the ecosystem. This holistic approach reduced the need for artificial structures, enhanced the habitat, and will minimize long-term maintenance costs.

Using Natural Processes

Removing the dam and reestablishing the ravine stream's riffles and pools promoted the natural sediment transport and substrate sorting a healthy ecosystem requires. A wide streambed with a base of large natural cobblestone was installed to prevent stream incision in the active ravine and to provide structural stability while natural sediment transport and dynamic equilibrium occurred. Underwater reefs mimicked Lake Michigan's rocky reefs, providing structural and hydrodynamic habitats for fish, and engaged the natural littoral drift process to induce sandbar and lake-bed nonconformities that diversify littoral-zone habitats and enable sand to accumulate between the reefs and the shore.

Previous page: Aerial view of restored woodland, ravine, and ravine stream. (Photo by FadeOut Media)

Top: Broken ceramic storm sewer pipe in the ravine stream prior to restoration. (Photo by USACE Chicago District)

Bottom: Restored ravine stream with rounded cobble for erosion protection. (Photo by USACE Chicago District)

Broadening Benefits

Restoration not only enhanced the natural habitats and plant communities in the ravine, woodlands, bluff, dunes, and lacustrine nearshore but also increased ecological benefits such as biodiversity, connectivity throughout the coastal area, native species richness and abundance, and habitat opportunities. The natural materials used along with the natural processes were cost-effective, sustainable, and reduced long-term maintenance costs. The high-quality and diverse habitats also created recreational and educational opportunities for the local community. Using natural materials and processes in the actively eroding ravine also provides economic benefits to nearby properties in the form of aesthetics and slope stabilization.

Promoting Collaboration

The Chicago District collaborated with local partners, interested parties, and experts throughout the project's duration. The team preserved the genetic diversity of the ravine's unique ecosystem and native plant ecotypes by gathering seeds and propagating plants; local partners continue the plant management effort to ensure the local ecosystem thrives. The Chicago District erected a bridge over the ravine stream as part of the restoration, and the Lake Forest Open Lands Association installed educational signage, connected trails along the ravine, and provided stairs down to the ravine stream bridge and out to the stream mouth at Lake Michigan.

*Top: Longnose Dace (*Rhinichthys cataractae*) collected in the restored ravine stream. (Photo by FadeOut Media)*

Middle: Completed habitat reefs in the Lake Michigan nearshore highlight the limestone blocks. (Photo by USACE Chicago District)

Bottom: Step pool cascade with restored sediment transport under the bridge connecting foot trails to the natural stone retaining wall within the ravine. (Photo by FadeOut Media)

North Sandy Pond

Sandy Creek, New York, United States

Placing dredged sand to repair barrier bar breaches. The northern barrier bar in North Sandy Pond was severely eroded by very high lake levels and storms in spring 2017. Washovers were common, and the barrier was in danger of being breached. A breach would have exposed wetlands and properties to strong waves and increased the risk of floods and erosion. Additional breaches would have threatened to dissolve the barrier bar itself, endangering public and private lands on shore and in the pond. A similar process occurred throughout the 1970s and was expected to recur without intervention. Changes in the shape and nearshore dynamics of the barrier bar had caused sand from the eroded beach to accumulate in a 611,644-cubic-meter shoal adjacent to the channel connecting North Sandy Pond to Lake Ontario. Further expansion of the shoal threatened to close the channel, blocking the exchange of water between the pond and the lake and degrading water quality in the pond. This project used local natural materials to replenish a barrier bar sheltering businesses, homes, and wetlands from the full force of Lake Ontario. It is a partnership involving the Town of Sandy Creek, local businesses, Oswego County, a state park, and a conservation organization.

Producing Efficiencies

Previous research and analysis of the evolution of the shore and channel, based on detailed geospatial analysis of historical maps and aerial images, was presented in *The North Pond Resiliency Project*, a 2017 report by Thomas Hart and Geoffrey Steadman. In addition to a series of management recommendations, the report recommended a planning approach to address the issues posed by the erosion of the protective barrier bar and the possible loss of the channel. Hart and Steadman's recommended approach was adopted for this project, which was funded by the State of New York's Water Quality Improvement Project (WQIP) program.

Using Natural Processes

The project used longshore currents to move sand placed at the northern and southern ends of the barrier bar and to replenish eroded sections of the beach that shelter the wetlands of North Sandy Pond from Lake Ontario. The longshore currents on the eastern coast of Lake Ontario are complex and switch directions seasonally, so sand positioned at either end of the barrier bar can benefit the entire barrier system. This "sand engine" method has worked very well in placing 60,340 cubic meters of sand to repair breaches in the north barrier bar, and this process is continuing on the southern barrier bar to shelter infrastructure in Sandy Island Beach State Park.

Previous page: Aerial image of the North Sandy Pond Resiliency Project. Sand dredged from the shoal and channel was used to replenish the eroded north barrier bar sheltering North Sandy Pond. (Photo by Thomas Hart, Hart Environmental Science & Planning)

Right: Previously overwashed area in a low-lying part of the north barrier during the "Halloween storm" of November 2019, when levels of Lake Ontario were very high. (Photo by David Klein)

Broadening Benefits

Community engagement was critical in strengthening the barrier system, benefiting businesses and the pond's recreational economy. After 915 meters of sand fencing was installed, 126 volunteers contributed more than 544 hours to dig and transplant existing beach grass and plant 35,000 native beach grass shoots along 488 meters of shoreline in 2020 and 2021. Additional project benefits realized for the community's quality of life included access to a beautiful walkable beach; a crucial shelter to marinas, restaurants, and shoreline property from the full force of Lake Ontario; and a restored barrier beach, which stabilizes the channel flanked by state park lands, providing a recreational destination that serves over 3,000 boats.

Promoting Collaboration

A walkable beach emerged as a top priority at a public meeting held to discuss conservation priorities. An advisory committee, the North Pond Resiliency Committee (NPRC), was formed to guide project planning and help secure WQIP funding. With matching support from The Nature Conservancy (TNC), planning consultant Thomas Hart was engaged to design the dredging and placement of sand, and coastal engineering firm Anchor QEA was engaged to provide feedback on restoration methods and processes. TNC also assembled and convened the stakeholder committee that provided community guidance for the project. Their professional guidance and the feedback from the NPRC provided the basis for the successful funding proposals submitted by the town and partners.

Top: The newly constructed dune with dredged sand and rows of transplanted beach grass. This dune has continued to accrete with sand from aeolian drift captured by the beach grass. (Photo by David Klein)

Bottom: Beach grass planted on the newly restored dune. About 60,400 cubic meters of sand have been dredged from the shoal and moved to this beach in heavy trucks and shaped with a bulldozer. (Photo by David Klein)

Oranjestad Shoreline

Oranjestad, Aruba

Using an adaptive shoreline management technique to nourish a sand-scarce beach. Approximately 40 kilometers of Aruba's roughly 80-kilometer-long coast are undeveloped, and sand is scarce. Covering 402 meters of this coastline on a recreational beach that is traversed daily by thousands and resting three kilometers north of a cruise ship terminal, the project site suffered from chronic sand loss and erosion. The sand had eroded to the point where only rock was present. During weather cycles, the sand would naturally accrete. However, this did not happen for about a year where it had in the past naturally occurred. Buildings were on the verge of being threatened, and the beach was unusable. To address conditions and add resiliency to this coastline, geosynthetic containers, manufactured by Solmax, were deployed in various groin layouts. Sand had to be carefully sourced from proximate areas where it accumulated naturally in shoals or localized areas because barging is the only other source of sand. The sand deposited between the control groins, along with the groins themselves, provided protection during larger wave events that previously washed the sand away. After deployment, and with some nourishment, sand remained in place and resilient through large storms.

Producing Efficiencies

The layout and sizing of the geosynthetic composite containers were based on weather and wave patterns. The site is on the leeward side of the island 99% of the time, and waves there are the result of larger waves that come from the east and wrap around the island. Slight changes in wind direction, from east to east-northeast, can cause drastically different wave and coastal dynamics. Preliminary groin layouts were installed, and orientations that naturally promoted sand accretion were extended farther while groins that did not perform as well were not extended.

Using Natural Processes

Instead of using dredging and heavy machinery, the use of control points with the innovative composite harnessed the natural forces of the local coastal dynamics to deposit sand using the force of the waves themselves during calm conditions when the water washed up and retracted. The geosynthetic composite containers held the sand at these point control locations. They offset and pushed seaward the shearing force of the water in the littoral current and wave approach so that sand between these controlled point locations remained. The more the project progressed with installation, the more sand accumulated.

Previous page: Aerial view of the Oranjestad Shoreline project. Ongoing monitoring and intermittent GPS monitoring are currently being carried out. (Photo by Little Environments)

Top: Previously eroded conditions. (Photo by Joseph Little, Little Environments)

Bottom: Sand being sourced using the pump attached to the installation rig. (Photo by Joseph Little, Little Environments)

Broadening Benefits

Besides a sandy beach where before there was none, the project has yielded numerous environmental and recreational benefits. Hard and soft sea creatures accumulate below the wash line on the geosynthetic containers, and fish congregate there to feed on them. Puffer fish (*Tetraodontidae*) and snapper (*Lutjanidae*) are common. Pelicans (*Pelecanus*) and other seabirds rest on the containers. And fishermen walk atop the containers to reach areas once inaccessible because of hazardous rocks. At the project's far northwest end is a bunker used in World War II to watch for incoming ships. A bar built over the bunker prevents it from being eroded and undermined.

Promoting Collaboration

Working across borders and across languages is sometimes difficult, especially on a small island with limited access to machinery and other supplies readily available on the mainland. The Dutch-Aruban owners of the project worked with the engineers and environmental consultants at Little Environments, PLLC, in Raleigh, North Carolina, to develop a process for installing the geosynthetic composite containers using their own maintenance and landscaping teams. Minimal heavy machinery was used on the project. The primary machinery used for the installation was a small sand pump installed atop the hull of a salvaged Hobie Cat sailboat.

Top: The installation rig sits adjacent to a groin. (Photo by Joseph Little, Little Environments)

Middle: Natural beach crest forming between the groins, demonstrating the health of the growing sand system. (Photo by Joseph Little, Little Environments)

Bottom: Marine growth in the submerged and wet splash and intertidal zones on the geosynthetic containers. Puffer fish along with snapper are common in and around the containers. (Photo by Joseph Little, Little Environments)

Sodus Point Beach

Sodus Point, New York, United States

Using a sand-capturing dune feature to restore a flood-damaged beach. Constructed dunes and beach along 610 meters of shoreline fronting a developed village were significantly damaged by floods during high-water events in 2017 and 2019 due to a flat beach profile. Flood damage in this small community of modest beach houses exceeded $3 million, and another $500,000 was spent on mobilization and flood-mitigation efforts by emergency responders for each event. The beach restoration and dune construction were funded by New York State through a Regional Economic Development Initiative created in response to the adverse impacts of record-setting high water in Lake Ontario. Restorative methods included creating a sand-collection feature using a dune, sand fencing, and 30,000 native dune-grass plants to capture wind-borne sands and confine the sand additions to the beach. Effective use of natural methods resulted in the restoration of the entire beach, with fronting dunes complemented by concentrated public use and access at Sodus Point Beach County Park and enhanced public access at the ends of eight streets. The Village of Sodus Point, Wayne County, and New York State joined forces to provide enhanced social, environmental, and economic benefits in this project, which received a 2022 Best Restored Beaches in America award from the American Shore and Beach Preservation Association.

Producing Efficiencies

The village, county, and state worked together to construct the dunes so they would capture wind-borne sand and build flood protection. Early analysis determined wind-borne sand lost from the system could be recaptured by properly designed dunes. The scientific premise of the project was to create a natural upland barrier to prevent sand loss and to capture the available sand between the created dunes and the lake shore. The capture method has been effective as measured by beach height and width and by the reduced accumulation of sand that had been filling the neighborhood and county parking.

Using Natural Processes

The overall project concept was to create a sand trap that would naturally build dunes. Upland sand of appropriate grain size was available to construct a small-profile core dune tall enough to initially provide flood protection. The dune incorporated beach grass and sand fencing to trap sand and develop the full design dune profile and to increase the beach volume. The cost to restore 610 meters of shoreline and provide enhanced county park and street-end public access was only $280,000, largely because much of the restoration harnessed natural processes to complete the project design by capturing wind-borne sand.

Previous page: Aerial view of Sodus Point Beach. In 2017 and 2019, the beach was inundated by floodwaters from record high Lake Ontario water levels. Aquadams and extensive sandbag barriers were used to mitigate flooding, which continued for over a month. (Photo by Hart Environmental Science & Planning)

Right: The dune flanks either side of the board walkway and crosses over the lower berm to the beach. Enough sand was placed at the end of each roadway to enable the Village Highway Department to form a continuous dune if high lake levels threaten to flood the Village again. (Photo by Thomas Hart)

Broadening Benefits

The project provided social benefits by creating a relationship between the community and its public and private beaches. The community features an area of eight numbered streets. Each block accesses the beach through an inviting, low maintenance street end designed to integrate public use with the protective dune. Environmental benefits come from the new natural-shore landscape that includes extensive natural plantings to replace the sandbags and hydro barriers previously used during high water. Economic benefits include greater public use and more visitors to the keystone county park at one end of the project, which features a broad beach with enhanced access.

Promoting Collaboration

Prior to the second round of high-water flooding, the project was initiated by trustees whose search for information on natural shoreline restoration led them to other shared-experience Lake Ontario projects and to funding from the Regional Economic Development Initiative. The village established an advisory committee comprising members of the neighborhood association to help design the project and develop the phased approach to test and ensure community acceptance before full implementation. A project website and community outreach collected public input. Property owners were contacted directly, and any owner whose property included construction activity cosigned the required permits. Community partners helped implement the project.

Top: Even after floodwaters receded, the community remained barricaded from its beach, which was degraded from loss of beach sand and placement of sandbag walls. (Photo by Thomas Hart)

Middle: The full dune construction involved filling the individual dune bays with an additional 4,717 tonnes of sand. (Photo by Thomas Hart)

Bottom: Community engagement included planting Great Lakes stock dune grasses on several volunteer day events. (Photo by Thomas Hart)

Ameland Inlet

Ameland, Friesland, the Netherlands

Implementing the world's first-ever ebb-tidal delta nourishment. Ebb-tidal deltas are large volumes of sand on the seaward side of tidal inlets. They are an important and integral part of barrier coasts because they provide sand for barrier islands and shelter back-barrier basins from high-energy swells. Many of the world's ebb-tidal deltas are at risk because of structural erosion, dredging, and sand mining. This risk will increase with climate change and the associated increase in coastal erosion. In 2019, Rijkswaterstaat—the operational agency of the Dutch Ministry of Infrastructure and Water Management—undertook a five million cubic meter sand nourishment at the ebb-tidal delta of Ameland Inlet, in the north of the Netherlands. This first-ever nourishment scheme at an ebb-tidal delta was implemented within the framework of the Coastal Genesis 2.0 research program. The goal of the scheme was threefold: to enhance understanding of the ecological and morphological dynamics of tidal inlet systems and ebb-tidal deltas, to gain operational insights into the possibilities of nourishing ebb-tidal deltas and the technical design of this type of nourishment scheme, and to feed the coastal system with sediments in line with Dutch coastal policy.

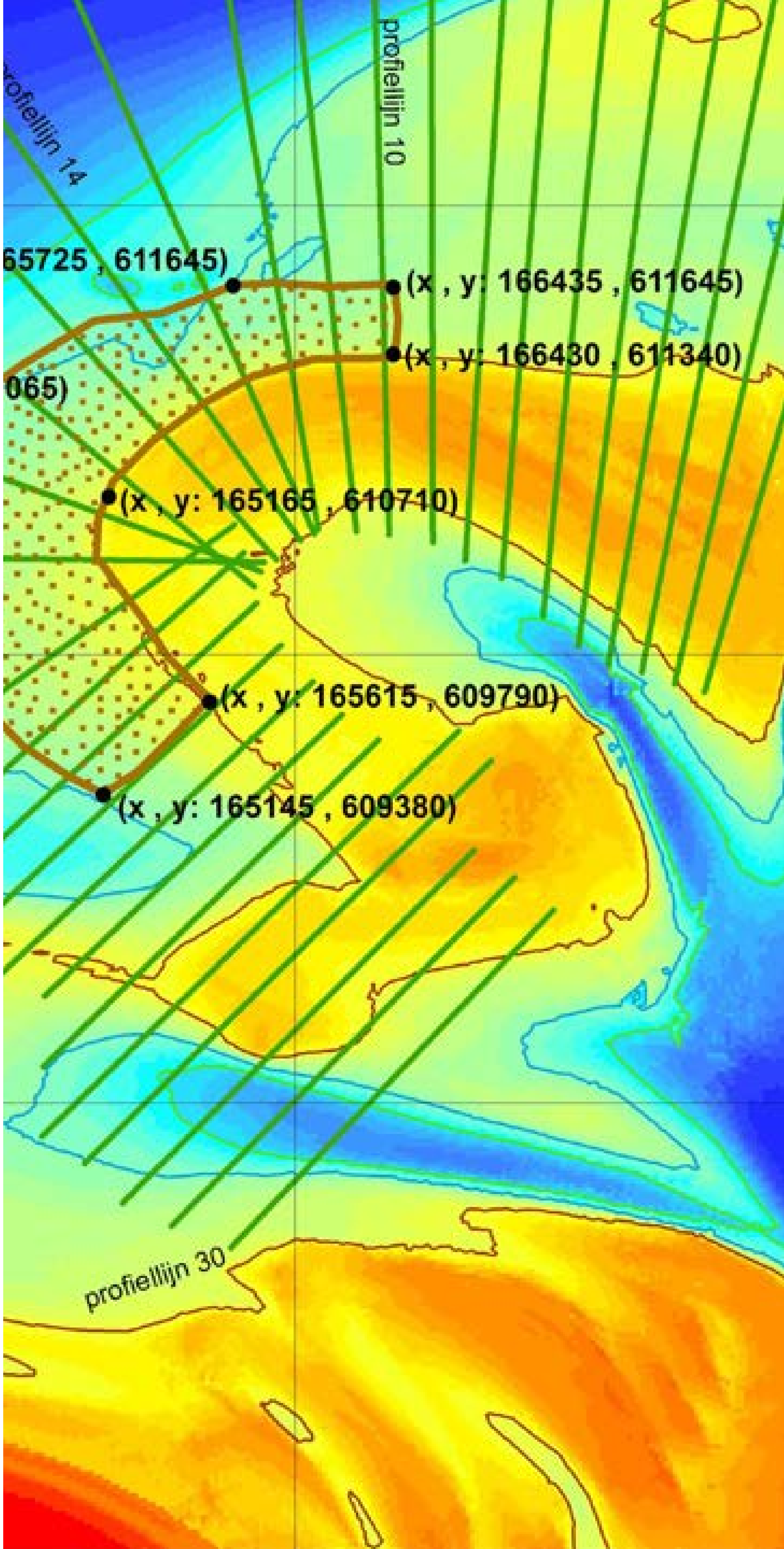
Producing Efficiencies

The dredging contractor collaborated closely on the technical design to ensure the safe construction of the nourishment scheme was feasible in this highly dynamic environment. Rijkswaterstaat partnered with research institutes Deltares and Wageningen Marine Research to track and evaluate the development of ebb-tidal delta nourishment during and after construction. Dutch universities like Delft University of Technology and Utrecht University collaborated closely with Rijkswaterstaat to establish the academic research program SEAWAD (SEdiment supply At the WAdden sea ebb-tidal Delta) to investigate hydrodynamics, sediment transport, and benthic species at Ameland Inlet by collecting data through a field campaign, regular surveys, and numerical modeling.

Using Natural Processes

Technical design included placing five million cubic meters of sand against an outer ebb-shield along the rim of the ebb-tidal delta, where natural currents and waves redistributed the sand throughout the delta. The sand assimilated in the surrounding area as typical morphological features like underwater ridges formed, and the sand largely dissipated into the adjacent ebb shoal. Benthic communities were hardly affected because the nourishment site is subject to strong tidal currents and large waves. This showed that carefully selecting nourishment locations will not alter autonomous coastal morphodynamics or ecological processes and can restore the natural functions of ebb-tidal deltas.

Previous page: Aerial photo of the Wadden Sea (back-barrier basin) in the direction of the North Sea open coast, where the ebb-tidal delta is located. (Photo by Rijkswaterstaat)



Right: The ebb-tidal delta nourishment plan with delineated nourishment area. Natural features, such as ebb-tidal deltas, require sediment import to sustain over time. When no natural source of sediment is available, periodic maintenance by means of sand nourishments may be a solution. (Image by Rijkswaterstaat)

Broadening Benefits

Off-shore nourishment at ebb-tidal deltas provided economic benefits over traditional beach nourishment due to possible cost reductions. It can also reduce greenhouse gas emissions by requiring less material and fewer barge and boat trips to the placement site. In the Netherlands, sand is extracted offshore, seaward of the long-term depth of closure. Dynamic environments subject to high waves and strong tidal currents, ebb-tidal deltas are resilient and able to recover from disturbances, such as nourishment. Moreover, to sustain ebb-tidal deltas over time, sediment import is required. When no natural sediment source is available, dredged sediments or beneficial use of dredged material can feed ebb-tidal deltas.

Promoting Collaboration

In parallel with the Coastal Genesis 2.0 research program investigating sand nourishment, the universities of Delft, Utrecht, and Twente, along with other partners, established SEAWAD in close collaboration with Rijkswaterstaat. SEAWAD was a five-year scientific program (2016–2021) to investigate hydrodynamics, sediment transport processes, and benthic species in Ameland Inlet by collecting data through a field campaign, regular surveys, and numerical modeling. SEAWAD and Coastal Genesis 2.0 reinforced each other and resulted in the wide dissemination of new scientific and applied knowledge about the dynamics of tidal inlet systems and ebb-tidal deltas.

Top and middle: Satellite image and satellite-derived bathymetry, respectively, of the ebb-tidal delta with the encircled nourishment site. (Images by Sentinel Hub and Rijkswaterstaat)

Bottom: Bird's eye view of the measured bathymetry of the nourishment site. (Image by Thijs van Rhijn)

Hancock County Marsh Coastal Preserve wetlands. The marsh restoration component of the project used dredged material from an adjacent port project as fill (project details on page 44). (Photo by Anchor QEA)

Wetlands

Creating natural defenses and aquatic habitats

Wetlands

Introduction

Wetlands in freshwater and marine coastal environments worldwide are playing a growing role in reducing flood and other risks from natural hazards. As evidence, living shorelines continue to play a role in applying EWN in wetlands. The first living shoreline in New Hampshire was designed and built to restore low and high marsh and a tidal buffer to reverse decades of impacts from foot traffic, ice needles, wind-driven ice, tides, boat waves, and shade from adjacent trees. Along the Mississippi Gulf Coast, the largest coastal restoration project in Mississippi's history used living shoreline and associated structural features to protect thousands of hectares of marsh habitat, provide multiple lines of defense to reduce storm risk, and create and restore degraded marsh habitats. Completed EWN wetland projects showcase how such work can serve as a hub for recreation, education, and ecotourism. This work can also be engineered to reduce nutrient loadings via natural processes, limiting the adverse impacts of biological stressors like harmful algal blooms. Natural materials, such as root wads and other large woody debris, are serving engineering functions as well as enhancing habitat value. Notable is the upscaling of several projects, demonstrating how EWN can be successful at field scale. And finally, constructed project features have withstood multiple natural hazards since completion, showing the resilience of EWN principles applied in practice.

Lower Brule

Lower Brule, South Dakota, United States

Collaborating with a tribal nation to restore an ecosystem. The Missouri River has historically played a central role in many aspects of life and culture to the Lower Brule Sioux Tribe; however, shoreline erosion and habitat loss have inhibited tribal use and access. To counter these effects, this nation's first Tribal Partnership Program project restored degraded wetland and riparian habitats along almost two kilometers of Lake Sharpe (Big Bend Dam) shoreline and combined ecosystem restoration with natural and nature-based techniques to provide bank stabilization and resiliency. The project included a new boat ramp and recreation site to replace a previous recreation site lost to shoreline erosion and provided members of the tribe with safe access to the Missouri River. In addition, the project protected wastewater lagoons from erosion due to ice shove and wave action that had eroded the shoreline to within 12 meters of the lagoon embankments. The project was approved in December 2019 and promptly proceeded to design and construction. Construction was completed in May 2023, and the five-year plant-establishment, adaptive-management, and monitoring phase is underway. The project was awarded the 2019 Outstanding Planning Achievement Award by the U.S. Army Corps of Engineers (USACE)–Omaha District and Northwestern Division and the 2023 Project Delivery Team of the Year by USACE Omaha District.

Producing Efficiencies

Climate and ice-force data informed the project alternatives' development and evaluation. Data on the forces ice sheets can exert on shorelines and how ice performs when it meets a barrier were used to design the slope and height of breakwaters and address the preservation of natural resources and the resiliency of restored habitats. A climate assessment helped to evaluate risks to project performance from future ice and wave conditions and the climate's effects on the habitat-restoration plantings. Shorter, warmer winters expected in the project area could lead to thinner ice sheets and longer periods of open water and waves.

Using Natural Processes

The offshore breakwater creates a 1.5 kilometer-long wetland sheltered from waves and driven ice, which will permit the reestablishment of wetland plant species that are scarce along the otherwise turbulent and turbid shoreline. The wetland is up to one meter deep, and the transitional shoreline zones are being planted in native wetland seeds. Four large box culverts connect the wetlands and Lake Sharpe and allow water to flow freely between them. The resulting exchange of nutrients and aquatic species also helps preserve the wetlands' water quality.

Previous page: Aerial view of the completed breakwater. (Photo by the Lower Brule Sioux Tribe)

Top: Aerial view of the preproject Lower Brule shoreline and sewage lagoons. (Photo by the Lower Brule Sioux Tribe)

Middle: Preproject erosion impacting a Lower Brule town playground. (Photo by the Lower Brule Sioux Tribe)

Bottom: Aerial view of construction of the wetlands area. The ability to safely access and interact with the restored plants and the Missouri River will provide unique opportunities for the Lower Brule Sioux Tribe to pass on indigenous knowledge and traditions to future generations. (Photo by the Lower Brule Sioux Tribe)

Broadening Benefits

The offshore breakwater helps preserve the shoreline and restored habitats. Its integrated riparian planting bench will hold a strip of native cottonwoods planted to address the loss of thousands of hectares of cottonwood forests. Cottonwoods (*Populus deltoides*) and native plants are used for fuel, medicine, and ceremonial purposes. Reestablishing them will restore some of those activities. The breakwater's three-kilometer maintenance trail along the shoreline loops around the wetland and is already a popular hiking path. The project's swim area, boat launch, and picnic area will become a focal point for many tribal and family gatherings for many years.

Promoting Collaboration

This project required the efforts of many leaders over several years. Workshops involving several federal agencies explored authorities that could help achieve the tribe's vision. The Tribal Council and Elders identified the most historically important aspects of the Missouri River ecosystem. Coordination with the Tribal Fish and Wildlife Office and the Tribal Historic Preservation Office was continuous. Tribal, agency, and public meetings gathered insights, and meetings held during review of the draft report gathered feedback on the analysis and recommended plan. Once the project moved into design and construction, the Tribal Wildlife Office's role grew, and their participation was instrumental in its success.

Top: Construction of the boat ramp and swim beach. (Photo by the Lower Brule Sioux Tribe)

Middle and bottom: Aerial view of the constructed recreation area and swim beach, respectively. These integrated features will be an essential part of the Tribal community. (Photo by the Lower Brule Sioux Tribe)

Hancock County Marsh

Hancock County, Mississippi, United States

Constructing the longest continuous living shoreline in Mississippi. Located in the Gulf Coast, the 8,462-hectare, state-owned Hancock County Marsh Coastal Preserve was the fastest eroding marsh in Mississippi, experiencing a loss of one to five meters, or roughly three hectares, of intertidal marsh each year. Funded under the Resources and Ecosystems Sustainability, Tourist, Opportunities, and Revived Economies of the Gulf Coast States Act and settlement funds from the *Deepwater Horizon* oil spill, the first major coastal ecosystem restoration in Mississippi was initiated in 2015 to stem this loss. Early restoration goals included reducing marsh erosion along the coastal preserve, protecting existing habitat, and enhancing secondary benthic productivity. The Mississippi Department of Environmental Quality (MDEQ), partnering with the National Oceanic and Atmospheric Administration (NOAA), worked with Anchor QEA to design, permit, and construct three habitat-restoration components in five phases: an almost 10-kilometer segmented living shoreline breakwater built on the coastal preserve, 19 hectares of restored intertidal marsh, and a 19-hectare subtidal reef constructed in Heron Bay. Since construction, the project has weathered with minimal damage multiple impacts from more than 17 hurricanes and tropical storms. Because of the success of the breakwater construction, an additional phase is underway to connect the living shoreline system to a U.S. Army Corps of Engineers (USACE)–Mobile District project at Bayou Caddy, protecting 12 kilometers of the coastal preserve shoreline.

Producing Efficiencies

The project design team used studies conducted by the University of South Alabama, Mississippi State University, and the University of New Orleans to evaluate the marsh shoreline failure mechanism coupled with 2D and 3D hydrodynamic and wave models to analyze wave energy and currents acting on the area and the proposed project additions. These model analyses were used to design natural features as well as a low-relief artificial breakwater (to reduce shoreline erosion by dampening wave and current energy), a subtidal reef (for cover and forage habitat for benthic and finfish species), and dredging templates (for the marsh fill).

Using Natural Processes

While the project aimed to provide coastal storm damage reduction and habitat protection, the project was also designed to encourage sediment trapping from this sediment-starved shoreline segment. Ongoing beach nourishment for maintenance of the coastal beaches will eventually provide a source to recover lost coastal preserve hectares leeward of the living shoreline breakwater. In the future, additional dredged materials can be placed along this shoreline segment to augment recovery of the lost coastal preserve, renourish the restored marsh, and enhance the marshes in the coastal preserve. The project's series of natural and nature-based features (especially the segmented breakwater) serve as multiple lines of defense to reduce flood risk and enhance habitat value in the area.

Previous page: Aerial view from Mississippi Sound, looking north and west into Heron Bay during a low-tide event in February 2023. (Photo by Anchor QEA)

Right: A blue crab hiding among the breakwater rocks, waiting for its next meal. (Photo by Sarah Ballard, Anchor QEA)

Broadening Benefits

Ongoing annual monitoring of the project has shown new marsh growth and increased shellfish and biomass accumulation on the sill, marsh, and reefs. Leeward marshes are now stable and have started to recover behind the living shoreline. Additionally, monitoring has demonstrated the project's ecosystem value, attaining more than 100% of the seven-year ecological goals in some segments over the first year. Enhanced commercial and recreational fishing opportunities are also now available in this area of Mississippi that is underserved by coastal infrastructure.

Promoting Collaboration

Successful collaboration between NOAA and MDEQ allowed the efficient planning, design, construction, and monitoring of this large-scale restoration project, achieving the goals of federal, state, and local stakeholders. Components of the design were realigned to optimize positive impacts to the project area based on concurrent reviews and coordination with USACE Mobile District, state resource agencies, and the stakeholders. Several public awareness meetings were held with local and regional stakeholders. Furthermore, the design team leveraged their relationships with USACE Mobile District and the Mississippi Department of Marine Resources to secure difficult-to-obtain permit approvals.

Top: Birds loafing on the breakwaters. (Photo by Anchor QEA)

Middle: Colonization of mussels on the rocks collected from the subtidal reef. (Photo by Sarah Ballard, Anchor QEA)

Bottom: Measuring bivalve abundance and size for biological monitoring on the subtidal reef. (Photo by Sarah Ballard, Anchor QEA)

Lightning Point

Bayou La Batre, Alabama, United States

Using green and gray infrastructure to revitalize a culturally important shoreline. Bayou La Batre is the Seafood Capital of Alabama and the heart of the Gulf of Mexico seafood and fisheries industry. Lightning Point is where the Bayou La Batre navigation channel and the Mississippi Sound meet. The adjacent public lands and boat basin are used frequently by locals and tourists for recreational boating and fishing from shore. The response and cleanup after the *Deepwater Horizon* (DWH) oil spill in 2010 was staged from there and directly affected this important coastal habitat due to primary water access being available at Lightning Point. The shore on either side at the mouth of the channel has retreated approximately 229 to 305 meters since 1916, the result of daily wave action from boats and severe coastal storms, like one in 2017 when over nine meters were lost. The Nature Conservancy contracted with Moffatt & Nichol to design an innovative project to restore habitats and resources lost to the DWH oil spill in a variety of subtidal, intertidal, and higher elevation scrub-shrub environments. The final plans incorporated elements to promote resiliency and adaptation to the uncertainties of sea level rise and storm-induced erosion along the roughly two-kilometer shoreline. The project included offshore curvilinear segmented breakwaters, tidal creeks, intertidal marsh habitat construction, and the beneficial use of dredged material.

Producing Efficiencies

Curvilinear breakwaters, the project's first line of defense, feature overlapping gaps to allow fish to pass and to avoid erosional hot spots. Wave transmission and breakwater crests were calculated under operational and extreme environmental scenarios to assign probability of exceedance percentages to the breakwater design and to ensure waves remained under 15 centimeters to protect the marsh edge. The project's new tidal creek network is flushing properly, and vegetation and fish are abundant throughout. A long-term maintenance plan and strategies to reuse sediment dredged from the navigation channel were developed to promote resilience and to abate the impacts of sea level rise.

Using Natural Processes

Gray infrastructure and green features reduce coastal hazard risks and sustain coastal protection measures. Over 80,000 plugs of five native plant species have been installed. A vegetated shoreline stabilization feature along the edge of the East Marsh Creation Area has protected an eroding bluff from tropical storm surges exceeding one meter. Reconnecting an old tidal creek through that area brought tidal exchange to intertidal marshes for the first time in 75 years and enhanced 12 hectares of marsh formerly cut off from Mississippi Sound. Overall, almost three kilometers of new creeks ensure sufficient tidal exchange throughout the network.

Previous page: Scrub-shrub habitat, tidal marsh, and tidal creeks, looking west across the East Marsh Creation Area of Lightning Point and overlooking the heterogeneous connection among the breakwaters. (Photo by Moffatt & Nichol)

Top: A marsh buggy excavator being used to restore tidal flow to the adjacent 12-hectare north marsh and wetland area, which had been deprived of daily tidal influence over several decades. (Photo by Gulf Equipment Corporation)

Bottom: Hydraulic dredging and material placement to restore the West Marsh Creation Area out to the newly constructed shoreline protection. (Photo by Moffatt & Nichol)

Broadening Benefits

Bayou La Batre is home to fishing, seafood processing, and shipbuilding. This project's environmental enhancements have attracted wildlife and boosted demand for recreational access. Many businesses and individuals were harmed by Hurricane Katrina in 2005; this project has helped reconnect them with nature while increasing the resilience of this vibrant, culturally rich community. A fishing platform, viewing pavilion, and walking trail were added to the site in 2021 and 2022. The upcoming City Docks project will include boat slips, updated parking for recreational boaters and anglers, and a market where the public can buy Gulf seafood directly from local fishermen.

Promoting Collaboration

A charette with the city, Mobile County, State of Alabama, Mobile Bay National Estuary Program, and nongovernmental stakeholders collected ideas and lessons from earlier shoreline restoration projects in the region. Consequently, the project team developed this multifaceted and innovative shoreline restoration design, attended city council meetings, produced project signs and fact sheets, met with local stakeholders and residents during design and construction, and updated the estuary program's Project Implementation Committee at least twice a year. High school students grew and planted supplemental vegetation. Federal and state agencies have toured the completed site and its nature-based features.

Top: Constructing the last remaining breakwaters on the east side of Lightning Point to protect the culturally important oyster cannery in Bayou La Batre. (Photo by Moffatt & Nichol)

*Middle: Nesting terns (*Sternidae*) and gulls at the project site immediately after construction. More than 50 bird and wildlife species have been seen at the project site since the completion of construction. (Photo by Moffatt & Nichol)*

Bottom: Spartina *marsh growing successfully after two years of initial planting along the created tidal creeks and after two seasons of hurricanes and coastal storms. (Photo by The Nature Conservancy)*

Teaneck Creek Park

Teaneck, New Jersey, United States

Using natural systems to restore freshwater wetlands. Low-lying Teaneck Creek Park in highly urbanized northern New Jersey is surrounded by residential and commercial development. Planned as a landfill in the 1950s, the site collected stormwater runoff from the surrounding development and was used as a rubble fill. A group of community partners, led by the Bergen County Department of Parks, undertook this project to restore eight hectares of diverse wetland habitat lost with the installation of a downstream tide gate and to protect adjacent land from stormwater erosion, localized flooding, and the ongoing degradation of Teaneck Creek. The project design, led by Biohabitats, called for excavating the rubble mounds and 30 centimeters of the surface soil dominated by *Phragmites*. A stormwater best management practice called regenerative stormwater conveyance (RSC) was used to repair the eroded stormwater flow paths and attenuate the runoff. Readily available sand and wood chips were used to construct an approximately eight-hectare wetland that stores runoff in more than 20 shallow pools. Water in the pools drains through vegetated, carbon-rich sand seepage berms, transforming nutrients into microbial biomass. The RSCs, pools, and berms reduce peak discharge and improve water quality via physical, chemical, and biological treatment of the runoff. This process delivers cleaner, cooler water to Teaneck Creek. Construction was substantially completed in fall 2022.

Producing Efficiencies

This project transformed a waste (i.e., stormwater) that was adversely affecting green space into a resource, restoring eight hectares of wetland; adding high-diversity habitat in an urban park; and reducing erosion, sediment, and nutrient pollution due to runoff. Dramatically increasing the surface area of the green space that comes into contact with the stormwater runoff reduced peak discharges, the flow path erosion associated with those peak discharges, and their associated shear stresses. It also increased the area of the natural resource in contact with the stormwater runoff, improving water quality and wetland habitat in the process.

Using Natural Processes

This project directs stormwater flows to a repeating series of 20 pools and carbon-rich sand berms with riffles to convey the runoff without causing erosion. The pools increase the surface area that the stormwater contacts; increase stormwater storage and infiltration in the landscape; and support physical, chemical, and biological treatment of pollutants in the stormwater. The carbon-rich sand berms serve as barriers to rapid drainage and support the development of hyporheic flows through the berms, further improving water quality. This process restored wetland form and function to eight hectares of degraded urban land, dramatically improving habitat for a variety of species.

Previous page: The interspersion of the plant communities at Teaneck Creek Park. Today, the site is a hot spot for family recreation and environmental education for school children. Additionally, it is a local source of pride for what is possible when diverse organizations collaborate. (Photo by David Ike Photography)

*Right: Whitetail doe and buck (*Odocoileus virginianus*) using the wet meadow area interspersed between and around the sand seepage pools at Teaneck Creek Park. (Photo by David Ike Photography)*

Broadening Benefits

This project aimed to improve conditions at a county park and resulted in a significant increase in the open space available to visitors. Before the project, most of the park was a difficult-to-access mosaic of rubble fill and *Phragmites*. Now, after the restoration project, large open areas are readily accessible from a series of earthen trails and elevated boardwalks. Environmental education and stewardship opportunities, as well as commitments to the park from Bergen County, have increased as a result of the project.

Promoting Collaboration

This project was a collaboration of various groups, including Bergen County Public Works, Bergen County Parks, Rutgers University, Bergen County Audubon Society, and the Teaneck Creek Conservancy. The project emphasized enhancing county parkland, repairing erosion problems due to stormwater runoff into the park, controlling invasive species, improving wildlife habitat to support the primary park uses of bird and wildlife viewing, and cleaning up past problems like rubble placement.

Top: Aerial view of part of the Teaneck Creek Park sand seepage network, which includes a series of pools, sand seepage berms, and riffle grade controls. Old sand stockpiles were repurposed to build the sand berms, and grounded street trees were used as the carbon source for the berms. (Photo by David Ike Photography)

Middle: Regenerative stormwater conveyance (RSC) discharge under a boardwalk to the sand seepage network. A similar sand seepage wetland design approach was undertaken in an agricultural watershed at Bishopville, Maryland, in 2011. (Photo by David Ike Photography)

Bottom: One of the riffle grade controls at the project site. (Photo by David Ike Photography)

Amoco

Muskegon, Michigan, United States

Placing a shoal system to create a vegetated, yet resilient, shoreline. State and federal agencies declared the 1,679-hectare Muskegon Lake, a drowned river mouth connected to Lake Michigan by a navigation channel, a Great Lakes Area of Concern in 1985. Years of industrial waste disposal, shoreline land use, and stormwater management had filled the lake's shallow shoreline waters and wetlands. The Amoco Fish and Wildlife Habitat Restoration Project used Engineering With Nature (EWN) techniques to restore wetlands and improve fish and wildlife habitat at a nine-hectare site on Muskegon Lake where a lumber mill and, later, a petroleum tank farm once stood. A nature-based segmented shoal system in the nearshore provides spawning habitat and protects restored wetlands from wave damage. The top of the shoal is designed to remain above water when Lake Michigan levels are low and below water when lake levels are high. A 427-meter segment of a 701-meter concrete wall separating former wetlands from the lake was removed to promote the creation of new wetlands, and a sloped embankment planted with native vegetation on its lake-facing side now separates contaminated uplands from clean nearshore environments. A riprap toe protects the embankment from wave energy and ice scour. A recreational path damaged by high water was relocated atop the embankment, above the 100-year-flood elevation.

Producing Efficiencies

The project team used multibeam bathymetry and side-scan sonar, confirmed by underwater cameras and probing, to locate debris for removal on the nearshore lake bottom. To keep contaminants in the site's upland area from migrating to the lake, Ramboll designed and Job Site Services, Inc. constructed a berm at the transition area between the upland contamination and the clean nearshore that blocks the intermittent petroleum sheens. The berm also protects the upland contaminants from waves and ice scour and serves as the foundation for a relocated bike path.

Using Natural Processes

This project fostered the restoration of a coastal wetland complex by removing concrete walls and eroding paths and connected isolated wetlands with the lake. The EWN techniques used at this City of Muskegon Lake property created a soft wetland edge along the shoreline that provides protection from wave forces in quiescent conditions whether lake water levels are low or high. The segmented, nearshore shoal system provides cover and habitat for spawning and foraging fish while attenuating wave energy to protect the restored wetland complex. The vegetated embankment and riprap toe promote coastal resiliency when lake water is high.

Previous page: Aerial view of the restoration site showing multiple benefits, including the trail system compliant with the Americans with Disabilities Act. (Photo by Ramboll)

Top: Installation of habitat logs and anchors for the segmented shoal system, which provides resiliency and habitat. Portions of the former shoreline were left in place to help protect the restored wetland area, allowing the project team to address the stakeholder goals of resiliency and vegetated shorelines. (Photo by Great Lakes Dock and Materials, LLC)

Bottom: Shoal construction with an excavator on a floating pontoon. (Photo by Great Lakes Dock and Materials, LLC)

Broadening Benefits

The project improved fishing opportunities in Muskegon Lake by creating cover, spawning, and foraging habitats. The new Americans with Disabilities Act–compliant bike path has better sight lines and makes recreation safer. Enhancements to over one hectare of wet meadow and shallow emergent marsh improved shoreline appearance and habitat functionality. The enhancements are expected to boost the local economy by supporting jobs (e.g., in construction, environmental consulting, and engineering), increasing property values, generating new tax revenues, reducing flood damage, and drawing more tourists to Muskegon Lake. For its positive effects, the project received the American Society of Civil Engineers Michigan Section's 2022 Quality-of-Life Certificate of Merit.

Promoting Collaboration

Stakeholders wanted a vegetated yet resilient shoreline. Monthly public meetings held by the Muskegon Lake Watershed Partnership (MLWP) kept the Muskegon community actively engaged during all phases of the Amoco Fish and Wildlife Habitat Restoration Project. The MLWP keeps the community involved through the Annual Muskegon Lake Spring Cleanup—where volunteers clear debris from around the lake—and the Shoreline Stewards Program. The Stewards Program encourages volunteer citizen scientists to support the collection of data used in long-term monitoring of the project site.

Top: The wetland with compost and plantings over Envirolok with a riprap toe. (Photo by Ramboll)

Middle: The restored wetland, depicting native seeding and plant proliferation. Located in a historically industrialized area with legacy contamination, the restoration design was adapted to allow for wetland creation and restoration in areas absent of contamination while constructing a barrier to restrict contaminant exposure and migration. (Photo by Ramboll)

*Bottom: A mallard duck (*Anas platyrhynchos*) roosting on a placed habitat stump in the restored wetland landward of a softened shoreline. (Photo by Ramboll)*

Belcher Street Marsh

Kentville, Nova Scotia, Canada

Implementing Nova Scotia's first hybrid foreshore marsh. Acadian settlers introduced agricultural diking in the upper Bay of Fundy of Nova Scotia and New Brunswick in the seventeenth century; since then, the region has lost 80% of its nutrient-rich tidal marsh. Now protected by about 241 kilometers of vulnerable dike infrastructure, the towns, farmlands, and wildlife habitat of the Bay of Fundy dikelands are susceptible to flooding and other climate change effects. The Belcher Street Marsh, part of the Making Room for Wetlands Project, is the site of a dike realignment and tidal wetland restoration to increase the resiliency of the macrotidal Jijuktu'kwejk (Cornwallis River), reduce neighboring towns' flood risk, and restore almost 10 hectares of tidal wetland on former farmland. In June 2018, a tract of dike over one kilometer closely following the river was reduced, straightened, and realigned and a tidal channel excavated to open a section of fallow and underused agricultural land. A living shoreline on a section of riverbank particularly vulnerable to erosion is now in place and augmented with root wads, wattle fencing, vegetation mats, and live silt fences. Postrestoration revegetation of the site has grown from 30% bare ground in the first year to less than 6% by the third year.

Producing Efficiencies

The Belcher Street Marsh project reduced (by 500 meters), straightened, and upgraded the original over one-kilometer dike along the sinuous Jijuktu'kwejk (Cornwallis River), lessening the infrastructure that required labor-intensive, costly maintenance and upgrades and restoring tidal wetlands that protect surrounding areas from flood and erosion. Extensive baseline monitoring identified areas with issues like riverbank scouring and erosion. Future adaptive management techniques identified included a hybrid living shoreline to slow water flow, prevent scour, and increase sediment deposition at selected locations. The excavated tidal channel improved pond connectivity with the larger drainage network and promoted rapid revegetation and soil stability at the site.

Using Natural Processes

Restoring almost 10 hectares of tidal wetlands made Kentville more resilient to floods and protects the realigned dike and the land beyond from storm surge, waves, and erosion. A living shoreline planted with native salt marsh species stabilized the bank at certain at-risk areas and provides additional wildlife and plant habitat. Adaptive management techniques, including wattle fencing and brush mats at scour locations and small conifers to fill gaps in the root-wad revetment, helped slow scour and enabled the marsh platform behind to increase and revegetate rapidly so that only 6% of the ground remained bare three years after restoration.

Previous page: Aerial view of Belcher Street Marsh Managed Dike Realignment and Tidal Wetland Restoration site in 2021, four years after restoration. (Photo by CB Wetlands and Environmental Specialists Inc. [CBWES Inc.])

Top to bottom: The inverted root-wad living shoreline with wattle fencing at the Belcher Street Marsh site in 2018, five months postrestoration; in 2020, two years postrestoration; and in 2021, three years postrestoration, respectively. (Photos by CBWES Inc.)

Broadening Benefits

As a Making Room for Wetlands educational site, the Belcher Street Marsh is an excellent introduction to the concept of nature-based solutions. The relatively accessible site has been used for undergraduate and graduate student research projects on a variety of topics and as a hands-on field-trip destination for an experiential-learning secondary school. The site imparts lessons on community vulnerabilities to the hazards posed by climate change; local land use patterns and planning; and the barriers to the project, the drivers that pushed it forward, and the lessons learned along the way.

Promoting Collaboration

The project was a collaborative effort involving the Nova Scotia Department of Agriculture, CBWES Inc., and Saint Mary's University, in addition to Dalhousie University, and Department of Fisheries and Oceans Canada. Making Room for Wetlands projects like this one follow a nonlinear framework for managed dike realignment and tidal wetland restoration that comprises these general stages: monitor, engage, gather baseline, design, and implement. This project provided valuable insights for future tidal wetland and managed dike realignment projects, fostered continued collaboration with the Province of Nova Scotia on future Making Room for Wetlands projects, and opened the door to new partnerships.

Top: Project team is improving drainage as an adaptive management measure to address ponding water. (Photo by CBWES Inc.)

Middle: Participants, ranging from students to government officials, of the Coastal Nature-Based Infrastructure Workshop Series visited the marsh in 2022. (Photo by Eric Thurston, TransCoastal Adaptations)

Bottom: View from the mouth of the constructed tidal channel looking over the river to the project reference site, three years postrestoration, showing rapid revegetation. (Photo by Megan Elliott, TransCoastal Adaptations)

Spicer Creek

Grand Island, New York, United States

Creating a multifaceted wave-attenuation system to restore coastal wetlands. A segmented stone breakwater and large engineered wood structure are reversing the loss of wetlands and the fish and wildlife habitat they provide in the Spice Creek Wildlife Management Area (WMA) along the Upper Niagara River. The new structures combine natural materials and processes in a resilient, minimalist system to mitigate wave action and the erosion and scour it causes and to promote nearshore sediment deposition and wetland creation in this part of the Niagara River Area of Concern (AOC). Biological surveys from the early 1900s describe the Upper Niagara River near the mouth of Spicer Creek as a wetland biodiversity hot spot. But from 1967 to 2021, almost two hectares of wetlands were lost along 1,097 meters of shoreline fringe wetlands, approximately 5% of Grand Island's eastern shore. The wetland restoration project aims to address beneficial use impairments (BUIs), including degraded fish and wildlife populations. Key design considerations for the project included safety, riverbed geotechnical conditions, aligning design features along the Niagara River shoreline, and minimizing downstream impacts to the Niagara River. An ongoing adaptive management program monitors wetland recovery and will be used in considering additional design features or modifications if needed to continue supporting wetland habitat uplift.

Producing Efficiencies

The project works with natural hydrodynamic conditions by subtly modifying physical conditions in its area, minimizing the materials introduced to the river, and using natural sedimentation and other processes to restore wetlands while limiting riverbed and downstream impacts. Exposure ratios in the USACE's *Engineering Design Guidance for Detached Breakwaters as Shoreline Stabilization Structures* helped shape design parameters so the segmented breakwater would attenuate waves but not significantly inhibit sediment flux downstream, which would have exacerbated erosion. Hydrodynamic and sediment flux were modeled to refine the design parameters and evaluate design impacts on river processes.

Using Natural Processes

By using natural processes such as natural sediment accretion, organic matter deposition, and vegetation establishment to reduce physical stresses to the shoreline, the project design facilitates the natural recovery of wetlands along the Spicer Creek WMA shoreline. Plantings in a portion of the project area near the remnant wetland at the mouth of Spicer Creek helped initiate these processes. The wave-attenuating structures and ballasted woody debris were designed by fisheries biologists to attenuate physical stresses while providing habitat for fish.

Previous page: Aerial view of the multifaceted wave attenuation system. The Spicer Creek WMA is in a largely suburban area, approximately 16 kilometers from the northern limit of the City of Buffalo. (Photo by BIDCO Marine Co.)

Right: Ballasted woody debris placed in the gaps of the segmented breakwater to attenuate waves and provide habitat for fish. Following construction in 2021, monitoring observations indicate that the system is working as intended. (Photo by BIDCO Marine Co.)

Broadening Benefits

Lake Erie and the Upper Niagara River are a recognized world-class fishery, so it is not surprising there was interest in improving fish habitat in the river in addition to obtaining the natural wetland benefits this design would provide. The ballasted woody debris placed in the gaps of the segmented breakwater not only help attenuate wave action but also provide habitat for fish. A local charter captain sums up the springtime smallmouth bass (*Micropterus dolomieu*) fishing at the project area in one word: "Prolific!" The site also includes an accessible walkway to the shoreline and two multiuse structures that serve as rest stops for people interested in spending time by the water.

Promoting Collaboration

This project in the Niagara River AOC arose from the collaborative process in the binational Great Lakes Water Quality Agreement, first signed in 1972. This agreement calls for AOCs to be established where significant local BUIs are the legacy of human actions. Such areas require the development of a collaborative Remedial Action Plan that identifies the BUIs and the restorative projects like the one at the Spicer Creek WMA. Multiple stakeholders collaborated to align remedial strategies that could achieve multiple desired outcomes. Among the stakeholders were representatives from federal, state, and local agencies; local businesses; universities; and nonprofit environmental organizations.

Top: Varying sizes of rocks and large woody debris with intact root wads help create diverse habitat. (Photo by Ramboll)

Middle: The ballasted woody debris provides wave attenuation and fish habitat. Construction of the wave-attenuating structures was completed using an excavator on a floating pontoon. (Photo by Ramboll)

Bottom: Anchors securing the woody debris to the river bottom. (Photo by Ramboll)

Baptiste Collette Bayou

Venice, Louisiana, United States

Applying an innovative adaptive management approach. Dating to the late 1860s, Baptiste Collette Bayou was a small canal between the Mississippi River and Breton Island Sound. The bayou's natural subdelta, once covering up to 52 square kilometers, began to deteriorate in the 1950s due to subsidence and ponding. Federal interest in Baptiste Collette as a navigation route grew during this period and led Congress to authorize channel improvements that began in the early 1970s, when dredging enabled the channel to be used as an alternate route for the Gulf Intracoastal Waterway (GIWW). Material dredged from the channel was used to restore degraded wetlands. By 1977, this practice was expanded to include construction of bird nesting islands. Today, sediment from maintenance of the Baptiste Collette Bayou channel is placed in shallow, open water suitable for nesting seabird colonies on either side of the channel. This unconfined placement creates a wetland habitat adjacent to the waterway's jettied entrance and the islands seaward of the jetties. Created habitats include marsh, scrub-shrub, bare land, and beach. Using dredged sediment to create or restore coastal habitat has become the current state of the practice in the U.S. Army Corps of Engineers, Mississippi Valley Division, New Orleans District (CEMVN) Navigation Program.

Producing Efficiencies

The bird islands were constructed with dredged sediment with a minimum 366-meter offset from neighboring lands to reduce predator access, size restrictions to limit resources available to predators, and elevation limitations to promote tidal exchange and natural wetland development. Wetland and bird island placement areas used during routine maintenance dredging are environmentally preferred and are cost effective. Using existing landforms as containment and allowing free-flowing dredged slurry to create broad tidal flats eliminate the need for dikes. A navigation channel in the bayou supports over 4,000 vessel trips annually and is the only alternative to the GIWW when the Inner Harbor Navigation Canal Lock is out of service.

Using Natural Processes

The National Audubon Society has identified the bird nesting islands as an Important Bird Area because of the essential habitat they provide to significant numbers of breeding Caspian (*Hydroprogne caspia*) and gull-billed terns (*Gelochelidon nilotica*), brown pelicans (*Pelecanus occidentalis*), black skimmers (*Rynchops niger*), and other colonial nesting seabirds. The islands' success as nesting habitat is due to a combination of factors: their remote location discourages terrestrial predators, their small size limits the spread of avian diseases, the presence of bare sand promotes nesting by certain bird species, and the islands' elevation is sufficient to prevent tidal and storm-driven inundation.

Previous page: Gunn Island in late July 2021 showing dominant growth of Phragmites *during that year's breeding season. (Photo by Jake Jung)*

Right: Gunn Island in May 2021 soon after sediment placement and before breeding by coastal birds had begun. (Photo by Michael Guilfoyle)

Broadening Benefits

In 2020, Gunn Island, one of the Baptiste Collette Bayou bird islands, hosted Louisiana's most significant nesting tern colony, which was believed to have been displaced from the low-lying Breton Island by tropical storm overwash. Gunn Island was specifically designed for use by nesting seabirds; surveys of the Gunn Island seabird colony in 2021 observed over 77,000 nesting seabirds from 68 species. Almost half (45%) were royal terns (*Thalasseus maximus*). The remaining included 21% black skimmers, 14% sandwich terns (*Thalasseus sandvicensis*), 8% gull-billed terns, 5% Caspian terns, 5% laughing gulls (*Leucophaeus atricilla*), and 2% of 19 other species.

Promoting Collaboration

Summer 2020 brought Louisiana's largest colony of some 50,000 nesting royal terns to Gunn Island just as dredged material placement began for the year's Baptiste Collette Bayou maintenance. The state and federal fish and wildlife departments helped the CEMVN survey the island's nesting birds and establish equipment corridors to reduce disturbance from ongoing dredging activities. After completion of the 2020 maintenance cycle, U.S. Geological Survey ornithologists were contracted to regularly survey Baptiste Collette Bayou's island and wetland habitats and develop design goals for future beneficial use activities that could make them more productive nesting, foraging, and overwintering grounds.

Top: Coastal birds on Gunn Island in 2020. That summer, the island's royal tern nesting colony—the largest in Louisiana—was estimated at 50,000. (Photo by P.J. Hahn)

Middle: The black skimmer is one of the native seabird species that uses Baptiste Collette Bayou islands for nesting and other activities. (Photo by P.J. Hahn)

Bottom: Tern nestlings hatched on Gunn Island. Sediment dredged from the adjacent federal navigation channel provides the habitats needed to sustain native seabird populations. (Photo by P.J. Hahn)

Wagon Hill Farm

Durham, New Hampshire, United States

Constructing New Hampshire's first living shoreline. The Wagon Hill living shoreline project addressed the loss of almost 30 centimeters per year of fringing salt marsh due to foot traffic from people and dogs, soil ice needles, wind-driven ice, tides, boat waves, and shade from nearby trees that prevented the growth of marsh vegetation. Decades of erosion had created a shoreline scarp approximately one meter high. Rather than fill in the mudflats with a long, gentle slope leading up to the remaining marsh, project designers opted to build out the marsh approximately nine meters into the mudflats and grow new salt marsh to replace what had been there 25 years earlier. The project has three planting zones: low marsh (mean tide to mean high water), high marsh (mean high tide to mean higher high water [MHHW]), and a tidal buffer zone above MHHW. Trees were removed so sunlight could reach the new marsh plants. A nearly vertical rock sill incorporating root wads in places was constructed as the new shoreline. Fencing above the tidal buffer and extending into the water protects the site, and a viewing deck and walkway connect the public to Great Bay and the marsh. The project took almost three years of monthly meetings to plan and was completed in 2019.

Producing Efficiencies

The retreat of the Wagon Hill shoreline and loss of salt marsh plants was remarkable. One fence was moved back at least eight meters in 25 years, and pins along the shoreline measured an annual average erosion rate of almost 30 centimeters. Game cameras recorded people and dogs walking on the marsh daily and small waves removing sediment from the shoreline. Light at the tree line was insufficient for marsh vegetation. Winter ice broke apart shoreline soil, promoting erosion when the banks thawed. Ice also shoved against the banks and undercut marsh blocks. Sea level rise outpacing marsh accretion exacerbated shoreline erosion.

Using Natural Processes

A perimeter fence protects the restored salt marsh from people and dogs. Gentle marsh slopes limit outgoing tide velocities. Rocks provide perches for birds, break up blankets of ice, and prevent ice rafting of surface sediments and vegetation. Coir logs parallel to the shoreline permit marsh inspections without trampling plants and interrupt erosion rill formation until full salt marsh vegetation coverage occurs. The plants also dramatically reduce boat and wind waves. Root wads and the rock sill arrest marsh edge erosion; the sill withstands ice shoving and waves. A shoreward tidal buffer accommodates marsh migration as sea level rises. Tree removal improved light on the marsh.

Previous page: Restored marsh. (Photo by Michael Lynch, Durham Public Works Department)

Top: Aerial view of the prerestoration shoreline and fence. (Photo by Michael Lynch, Durham Public Works Department)

Middle: Prerestoration marsh erosion. (Photo by Tom Ballestero, University of New Hampshire Coastal Habitat Research Team, [UNH CHaRT])

Bottom: Sill and marsh construction. (Photo by Tom Ballestero, UNH CHaRT)

Broadening Benefits

A focal point of a very public setting, the restored salt marsh is often the site for weddings, graduations, announcements, and other photo opportunities. A boardwalk and viewing platform were also constructed to maintain the public's connection to the bay and the marsh environment. The marsh is again functioning as a fringing salt marsh with attendant flora and fauna. It has galvanized the community's dedication to restoring impaired aquatic systems in general—more specifically, restoring the additional 426 meters of shoreline at this property—erecting additional fencing, and relocating trails to protect them.

Promoting Collaboration

Three years of monthly meetings were held with the Durham Planning Department, Durham Conservation Commission, Durham Public Works Department, University of New Hampshire Coastal Habitat Research Team, Strafford Regional Planning Commission, New Hampshire Coastal Program, New Hampshire Department of Environmental Services, U.S. Army Corps of Engineers, and U.S. Environmental Protection Agency. The New Hampshire Port Authority, New Hampshire Fish and Game Department, and U.S. Coast Guard also provided input. These meetings dissected the field data and discussed the universe of available solutions to develop a final system that met all stakeholder and environmental needs.

Top: Sill and marsh construction with habitat boulders that provide perches for birds but, more important, break up large ice sheets and prevent ice rafting of marsh plants and sediments. (Photo by Tom Ballestero, UNH CHaRT)

Middle: Sill and root wads incorporated into the rock sill to provide microtopography that leads to local hydraulic and habitat diversity. (Photo by Tom Ballestero, UNH CHaRT)

Bottom: Colonization of the rock sill by algae. (Photo by Tom Ballestero, UNH CHaRT)

LIFE Adapto

Authie Bay, Orne Estuary, Lancieux Bay, Moëze Marsh, Gironde Estuary, Leyre Delta, Petit et Grand Travers, Vieux-Salins d'Hyères, and Golo Delta, France

Mana, French Guiana

Addressing climate change through flexible coastal management. The LIFE adapto project takes place against the backdrop of climate change's threats to coastlines around the world, including rises in average sea level and increases in the intensity of extreme weather. These threats increase the risks of erosion and submersion, while natural areas are under constant pressure from urbanization and human use. As a result, transitional spaces between marine environments and coastal defenses are gradually disappearing. The Conservatoire du littoral, France's coastal protection agency, initiated the adapto project to advocate flexible shoreline management when exploring solutions to target the effects of climate change on coastal areas. The project was rolled out at ten pilot project sites, nine in mainland France and one in French Guiana, from 2017 to 2022. The implementation of each pilot project drew on the experience gained at the sites that preceded it to showcase a variety of situations while adding to an overall strategic perspective. The project's multidisciplinary approach combined ecology, economics, social science, politics, communication, and public education to break down preconceptions about coastal risk and climate change.

Producing Efficiencies

The adapto project combined scientific studies, engineering, and fieldwork, including creating (or combating the clogging of) breaches in front-line dikes; removing or retreating first-line defenses and restoring coastal interface habitats; and regulating tidal flow. Fifty-five hectares of coastal marsh were restored by marine reconnection, and 900 meters of dune strips were restored. Scientific studies focused on risk management by modeling sea level rise at pilot sites, gauged the effects of flooding on the biodiversity and functionality of natural habitats using an ecological quality indicator, and measured the local populations' perceptions of adaptation methods.

Using Natural Processes

A wide coastal strip with a healthy ecology unencumbered by anthropogenic structures increases habitats' ability to adapt or respond to climate extremes in the medium term by migrating under natural processes. Salt marshes confronting sea level rise can retreat landward and upward by gradually adding sediment and vegetation; sediment transport can maintain dunes during periods of erosion and accretion. By providing a gradual transition between freshwater and brackish or saltwater environments, these areas promoted habitat and species migration. Understanding these benefits and the mobile nature of coastlines, local stakeholders, inhabitants, and managers chose to work with, rather than indefinitely fight, the sea.

Previous page: The Beaussais Marsh in Côtes-d'Armor, which was reconnected to the Lancieux Bay in 2020 following a breach in the dike. (Photo by Nancy Lamontagne and Antoine Collin, Centre de Géoécologie Littorale, École Pratique des Hautes Études–Université Paris Sciences et Lettres)

Right: Aerial view of the Moëze Marsh breach. (Photo by Géos-AEL)

Broadening Benefits

Adapto funded the acquisition of 172 hectares of private land in a wide coastal strip. Protecting and restoring this land—or even letting it take its natural course—provides many direct environmental benefits, including restored coastal biodiversity; related ecosystem services like carbon sequestration; and greater resilience to floods, erosion, and submersion. Flexible management solutions are often cheaper than maintaining protective structures on static and rigid coastlines. Adaptation scenarios based on a flexible management policy will provide local economic and social benefits that guarantee the good ecological condition of these environments, enable sustainable activities like walking and cycling, and ensure user satisfaction with specific renaturalization works.

Promoting Collaboration

The adapto project brought several benefits to stakeholders by proposing engineering strategies using a logical national approach. By integrating local priorities in projects and coastal management scenarios, the project suggested solutions for adapting the coast to climate change. Its dedicated teams presented relevant studies, organized consultative events, and promoted compromises on management scenarios. Building on projects at various adapto sites, the project became part of and contributed to local policies regarding regional and urban planning, environmental quality and protection, and climate change adaptation and mitigation. The project also contributed to national efforts and shared feedback in regional, national, and European events.

Top: Petit Travers (Hérault) renaturation of the dune by removing a road. (Photo by Frédéric Larrey, Conservatoire du littoral)

Middle: Meeting with farmers on the Moëze Marsh. (Photo by Conservatoire du littoral)

Bottom: Site visit to Lancieux Bay by elected officials and interested parties. (Photo by Conservatoire du littoral)

Great Lakes Wetland

Defiance, Ohio, United States

Developing nutrient retention wetlands to improve water quality. Harmful algal blooms in Lake Erie and across the Great Lakes region have been linked to excessive phosphorus loading from numerous sources, including agricultural, urban, and suburban runoff. The Phosphorus Optimal Wetland Demonstration Project built a wetland system along a tributary of the Maumee River in Defiance, Ohio, to investigate techniques to maximize phosphorus uptake from a waterway draining large areas of row crops. Water is diverted from the waterway to the wetland when phosphorous concentrations are typically greatest and passed through a series of treatment cells. Measurements taken throughout the process show typical dissolved phosphorus reductions between 50% and 80%. Researchers also use benchtop laboratory models and a mesocosm of the wetland to test strategies to increase the system's nutrient-reduction efficiency and recommend improvements in the design and management of similar wetlands to optimize their capture and retention of phosphorous. The U.S. Army Corps of Engineers (USACE)–Buffalo District and the U.S. Army Engineer Research and Development Center (ERDC) are collaborating on the project, with support from the City of Defiance, the U.S. Geological Survey, and LimnoTech, a private environmental and water resources engineering firm. Funding comes from the Great Lakes Restoration Initiative administered by the U.S. Environmental Protection Agency.

Producing Efficiencies

The wetland site was selected for its favorable characteristics (high concentration of nonpoint nutrient sources and location within a nutrient-reduction priority watershed) and its soil's substantial phosphorus-storage capacity. The site was engineered to provide various elevations, including a simulated stream channel and floodplain features. A series of pumps facilitate experiments regarding hydropattern and hydroperiod, retention times, and associated implications for nutrient reduction. The wetland's operational features promote investigations of engineering approaches to optimize phosphorus removal in a way that can be scaled up to improve regional water quality and help address the challenges of harmful algal blooms.

Using Natural Processes

The project restored a former forested wetland that had been ditched, drained, and planted with row crops. The reestablishment of the wetland hydrology and the reconnection of the wetland with its historical water source are significant. Phosphorous is removed through the natural processes of particulate nutrient sedimentation, sorption of dissolved nutrients to soil particles, and uptake of nutrients by the plants that thrive in the wetland. This project not only uses natural processes but also seeks to optimize those processes to maximize positive outcomes for the environment and provides a valuable template to develop additional nutrient-reduction wetlands.

Previous page: Aerial view one year after completion, showing the inundated channel and partially inundated floodplain features. (Photo by LimnoTech)

Top: Aerial view of the project site during construction with the four wetland treatment cells designed to optimize nutrient retention under a variety of scenarios. (Photo by LimnoTech)

*Bottom: Wild turkey (*Meleagris gallopavo*) and other wildlife frequently use the site, demonstrating the cobenefits associated with nutrient-reduction wetland establishment. (Photo by LimnoTech)*

Broadening Benefits

The Phosphorus Optimal Wetland Demonstration Project provided opportunities for public outreach and education. Multiple stakeholder and community engagement events have been conducted at the site, bringing together dozens of interested individuals from local municipalities; federal, state, and local agencies; nongovernmental organizations; and the public. Future activities will communicate to local school groups the environmental benefits of wetlands. Although the project is designed to reduce excess nutrients and improve water quality, many cobenefits have resulted, including a proliferation of wildlife and fish that frequently use the area (e.g., migratory birds and waterfowl, wild turkey, and deer).

Promoting Collaboration

The project resulted from a collaborative partnership among multiple federal and state agencies, the municipality that owns the property, private sector partners, and the leadership of the binational Great Lakes Restoration Initiative. Ongoing research and monitoring activities are being led by multiple entities, including the private-sector practitioner LimnoTech (site operations and wetland internal nutrient cycling), the U.S. Geological Survey (nutrient mass balance and hydrology), USACE Buffalo District (project management), and ERDC (soils nutrient analysis and laboratory and mesocosm studies).

Top: A wide variety of wildflowers and other vegetation species proliferate throughout the year. Continuous water quality, hydrology, and meteorological monitoring data are collected at the site to inform operations and management. (Photo by LimnoTech)

Middle: A soil scientist collects samples and completes a soil description in Cell 4. Measurements were used to monitor hydric soil conditions and nutrient retention through time. (Photo by ERDC)

Bottom: Project stakeholders attend a collaborative project-outreach event. (Photo by USACE Buffalo District)

Crumpmeadow

CINDERFORD, ENGLAND, UNITED KINGDOM

Constructing wetlands to improve local biodiversity. Five interconnected ponds between 2.6 and 5 meters deep promote biodiversity and reduce surface water runoff into Cinderford Brook at Crumpmeadow wetland near Gloucester in southwest England. The ponds' variously angled slopes and internal shelves promote a more natural, diverse habitat for insects, amphibians, and reptiles that are of conservation concern. Initiated in 2019, the project began when regional water company Severn Trent Water contracted Mott MacDonald to develop feasibility and concept designs, and pond construction began in 2021. Challenges faced included the presence of protected great crested newts (*Triturus cristatus*), eels in Cinderford Brook, the lingering environmental impacts from the operation of old coal mines in the area, and the potential for high groundwater levels. Ground investigations, including trial pitting, boreholes, soil sampling, and a geophysical survey, were completed to understand the risks from historical mining. Newt fencing was installed, and resident amphibians and reptiles were relocated to a nearby woods. Afterward, the area was seeded with native wildflowers and planted with trees. Mott MacDonald Bentley and Severn Trent Water were awarded the Institute of Civil Engineers West Midlands' 2022 Team Achievement Award for their collaboration with project stakeholders comprising the Gloucestershire Wildlife Trust, local landowners, Forestry England, and the Forest of Dean District Council.

Producing Efficiencies

Silt fencing along the site perimeter and silt socks used where groundwater was pumped from excavations protected water quality in Cinderford Brook. Solar pods, not diesel generators, powered the worksite, saving about 1,400 liters of fuel and avoiding noise pollution and nine tonnes of CO^2 emissions. Hybrid excavators were used, and excavated soil was kept on site as much as possible to create bunds with south-facing slopes, designed to provide suitable habitat for reptiles, invertebrates, birds, and small mammals and areas for planting of local species. The project used only recycled stone, and at the end of construction, to reduce single-use plastics, fencing to protect the great crested newt was removed for use on another project.

Using Natural Processes

Vegetation strips along the edge of the worksite protected the surrounding area from on-site activities. Plant species well established in the area—including march violet (*Viola palustris*), cowslip primrose (*Primula veris*), and water mint (*Mentha aquatica*)—were sown to encourage habitation by various invertebrates and birds. The ponds were lined with clay excavated on site, not geotextile, and excavated wood and stone were used to make hibernacula (refuge spaces for hibernation). The wetlands attenuate runoff into Cinderford Brook and function without pumps, so their operation is low carbon. By avoiding existing high-priority grassland , the project raised the biodiversity value of the rest of Crumpmeadow.

Previous page: One of the five new wetland ponds and connecting channel. (Photo by Helen Leyshon, Mott MacDonald Bentley)

Right: Closeup of one of the freshwater wetland ponds. To attract newts, low shelves and topographical diversity were incorporated into the design. (Photo by Mott MacDonald Bentley)

Broadening Benefits

This project spawned numerous community and educational events, including information sessions, community drop-ins, and a poster competition, to promote local ownership and support for this and other environmental efforts. Brownies and Girl Guides planted trees and other vegetation and built "bug hotels" at an educational planting and engagement event commemorated by a special Brownie badge and a plaque. Cinderford's mayor planted an oak tree to celebrate the queen's platinum jubilee. The water cycle, the importance of biodiversity, and environmental careers were discussed at the local school. Further, posters displayed at a drop-in event explained the project's purpose and progress.

Promoting Collaboration

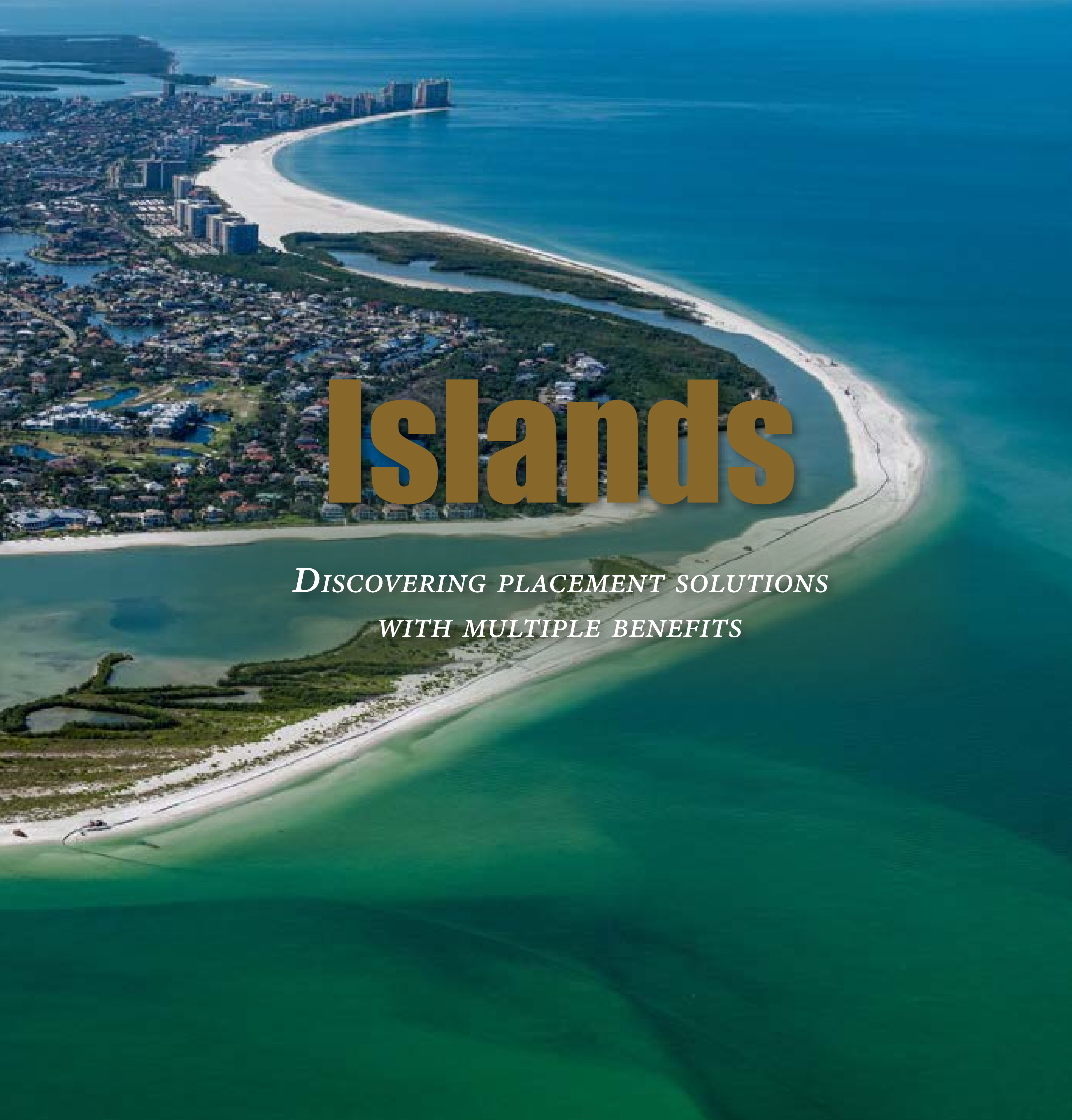
Extensive collaboration by the Mott MacDonald designers, the Mott MacDonald Bentley technical experts, the client (Severn Trent Water), and key stakeholders from the Environment Agency (EA) and Gloucester Wildlife Trust meant no project decision was made in isolation. The feasibility team originated the ground investigation plan, which was refined by the contractor, site manager, and ecologists, to gather the required data without ecological or environmental harm. The EA and its consultant helped to address risks to eels. Regular design packs kept the EA abreast of project progress and gave opportunities for regulator input into the design.

Top: Four of the five wetland ponds and their connecting channels shortly after excavation. (Photo by Paul Smith, Mott MacDonald Bentley)

Middle: A hybrid excavator digs a wetland pond and shelf created for habitat diversity. (Photo by Mott MacDonald Bentley)

*Bottom: Over 100 reptiles and amphibians, including this common toad (*Bufo bufo*), were moved from Crumpmeadow to a neighboring woodland prior to wetland excavation. (Photo by Mott MacDonald Bentley)*

*Aerial view of Tigertail Lagoon. Restoration enabled habitat for piping plovers (*Charadrius melodus*), reddish egret (*Egretta rufescens*), least terns (*Sternula antillarum*), black skimmer (*Rynchops niger*), and red knot (*Calidris canutus*) (project details on page 96). (Photo by Andres Ramirez, Aerial Innovations)*



Islands

Discovering placement solutions with multiple benefits

Islands

Introduction

From the Great Lakes to the Atlantic and Gulf coasts of the United States to the Middle East, islands provide substantial engineering, economic, environmental, and social benefits. For this reason, as natural infrastructure, islands are being used to restore engineering and other functions using EWN principles. In the United Arab Emirates, mangroves are being planted at a substantial field scale to restore coastal habitat and to protect the coast from further erosion. Along the Gulf Coast of the U.S., a system of barrier islands and associated habitats was restored to enhance coastal resiliency. Dredged material was used to expand the area and restore the unique coastal features of an island where a threated bird species nests. Another Gulf Coast project created ephemeral islands in an ebb-tidal delta where placed sediments are being transported by natural processes in a tidal delta shield while providing a natural wave break and habitat features for birds and other marine wildlife. A system of living breakwaters was developed as a series of nature-based features to protect a city waterfront along the U.S. East Coast and to enhance habitat value in the area. A key to the success of each project presented in this chapter was the beneficial use of dredged material.

Mubarraz Island

Mubarraz Island, Abu Dhabi, United Arab Emirates

Planting mangrove habitat for shoreline protection. Offshore of Abu Dhabi in the Arabian Gulf, Mubarraz Island has faced increasing shoreline erosion. In the 1980s, an international oil company initiated the beneficial use of 12 million cubic meters of dredged seabed material from a channel-dredging operation for the construction of a causeway on the island to protect oil pipelines and serve as a road connection. For environmental enhancement and protection from erosion, mangrove habitats were created along the shorelines of the causeway. Over a 35-year period, more than half a million nursery-raised mangrove seedlings were planted annually. Initial plantings focused on environmental enhancement and were successful in only sheltered corners of the causeway. Since 2009, a new Engineering With Nature (EWN) approach has been adopted by creating artificial tidal channels that are excavated parallel to the causeway and planted annually with tens of thousands of seedlings. Because of the innovative approach and persistent planting over many years, mangrove vegetation has been successfully established along nearly seven kilometers, or approximately 20%, of the causeway's shorelines, with new plantings along an additional nine kilometers underway. For this use of EWN approaches, the project was awarded a PIANC Supporter of Working with Nature certificate in July 2021.

Producing Efficiencies

A nature-based solution using planted mangroves was adopted to protect shoreline erosion along the causeway. Artificial tidal channels, running parallel to the causeway, were created for the specific purpose of providing suitable habitat for the mangroves while leaving a protective barrier of dredged material between the channels and the sea. Ultimately, once the sea has eroded the barrier of dredged material, the mangroves behind it will have established successfully and grown into mature stands capable of resisting the hydrodynamic forces of tides and waves to effectively protect the causeway from further erosion.

Using Natural Processes

The entire causeway was built from beneficially used dredged material. The tidal channels were subsequently excavated within this dredged material to a depth known to result in tidal inundation characteristics conducive to the growth of *Avicennia marina* (gray mangrove). Because of their dense and extensive network of stems, pneumatophores, and cable root systems, the mangroves are able to protect the shorelines from erosion through attenuating wave energy and binding and trapping sediments, thereby contributing to the protection of critical oil pipeline infrastructure. Mangrove planting activities at Mubarraz Island have been highly successful and continue to this day.

Previous page: The Mubarraz Island mangrove plantation along the excavated causeway, which was created from beneficially used dredged material. (Photo by Abu Dhabi Oil Co. Ltd [Japan] [ADOC Japan])

Top to bottom: Progression of the mangrove plantation growth at 3, 7, and 15 years old, respectively. (Photos by ADOC Japan)

Broadening Benefits

The mangroves have attracted significant biodiversity over the years, including more than 60 bird species and an assortment of gastropods, crabs, and fishes. With the ability to self-repair and maintain, mangrove plantings have proven to be a significantly cheaper and more sustainable solution to shoreline protection than conventional engineering approaches. Costs of mangrove planting were five- to tenfold lower than the costs of sheet piling or other hard engineering solutions. This project demonstrated that planting mangroves on dredged material was feasible, even under extreme climatic conditions, offering a cost-effective, low-maintenance, and sustainable solution for shoreline protection, with added benefits for biodiversity conservation.

Promoting Collaboration

This project demonstrated that it is feasible for an oil company to operate responsibly within a wider marine protected area by working closely together with environmental authorities and international experts over a multidecadal time scale to preserve and significantly enhance environmental values in a climatologically extreme region. Internal mangrove planting work procedures were drafted, and staff that were trained in nursery and planting techniques persisted year after year to plant hundreds of thousands of mangrove seedlings, learning along the way from successes and failures, resulting in more than 17.5 hectares of healthy mangrove stands in various stages of maturity.

Top: Annual monitoring of the performance of the planted mangroves. (Photo by ADOC Japan)

Bottom: The mangrove tree nursery on Mubarraz Island has a capacity of up to 80,000 seedlings per year. (Photo by ADOC Japan)

Tigertail Lagoon / Sand Dollar Island

Marco Island, Florida, United States

Increasing coastal resiliency through a multitiered coastal barrier system. Shaped by the natural sand bypassing processes at the Big Marco River, landward migration of emergent shoals since the 1990s has formed a lagoon sheltered by an attached sand spit known as Sand Dollar Island. Natural processes led to continued landward migration of the spit, pinching the tidal channel and reducing coastal protection. The mangrove-lined back bay was next to be eroded. The Tigertail Lagoon and Sand Dollar Island Ecosystem Restoration project area lies on the northwest part of Marco Island in a state-administered Critical Wildlife Area adjacent to the City of Marco Island, Florida, a barrier island community with over 16,000 full-time residents that rises to over 40,000 during winter months. The project restored the three-kilometer-long sand spit, a coastal lagoon, and mangrove shorelines by reestablishing an adequate flow channel. Restoration of the sand spit and lagoon provides continued and enhanced coastal protection to over a quarter of the Gulf-facing shoreline while maintaining a large and productive natural coastal ecosystem that is accessible to the public. Adaptive management of this area will ensure that the natural environmental functions of this dynamic coastal system will remain in place, providing habitat and coastal protection into the future.

Producing Efficiencies

The highly productive lagoon habitat, consisting of hectares of mangroves, seagrass beds, and shallow foraging areas, was in decline as the Sand Dollar Island spit migrated landward, covering seagrasses and eventually reaching the mangroves. Restoration of this ecological system included relocating the existing spit seaward to where it was approximately five years ago. This enlarged the existing waterway to prior conditions and provided enhanced sediment management at the Big Marco River, where excess shoaling required frequent maintenance dredging. The project established a sand trap where nuisance sediment is accumulating, using that to reconstruct the thinning and retreating Sand Dollar Island spit.

Using Natural Processes

The project relocated nuisance sediment shoaling to areas where it provides enhanced protection from wave and coastal storm impacts. Sand from Sand Dollar Island erodes either toward the sand trap or adjacent Marco Island Beaches, providing supply to that area, creating a natural cycle and beneficial downdrift effects. This beneficial use of dredged materials will ensure continued supply to downdrift beaches and provide natural recirculation to the sand trap. Periodic maintenance of this sand spit will provide coastal protection that is adaptive to sea level rise.

Previous page: Aerial view of the flow channel and restored wetland. Restoration of over eight hectares of lost tidal wetlands occurred since 2017. A tidal flow channel was established, reconnecting the lagoon south end at Tigertail Beach Park with gulf tidal flow. (Photo by Humiston & Moore Engineers)

Right: Aerial view of flow channel preconstruction. Restoration of the gulf shoreline improved tidal flushing, water quality, and recreational park attractions. (Photo by Humiston & Moore Engineers)

Broadening Benefits

The Tigertail Lagoon and Sand Dollar Island ecosystem is a protected natural preserve and a critical wildlife area that provides valuable habitat for a variety of birds, sea turtles, manatees, and seagrasses and valuable Marco Island recreational resources for residents and tourists for birding, fishing, kayaking, paddle boarding, kitesurfing, and, on the northern half, boating. The project design included enhanced terrestrial habitat for shorebirds and nesting sea turtles. Beneficial use of sediment was applied by taking sediment from the areas of shoaling to be applied to areas of erosion and retreat, providing economic and sustainable adaptability for future management.

Promoting Collaboration

Project design elements included integrated efforts with the upland community, the City of Marco Island, state and federal agencies, Rookery Bay National Estuarine Research Reserve, and Critical Wildlife Area administration to maintain the integrity of the natural barriers system for protection and management of coastal flooding vulnerability and wildlife habitat. Community outreach included engagement and feedback from local groups, such as Friends of Tigertail Beach and the upland property owners. Designs were provided and input solicited from each stakeholder throughout the design and permitting stages. This led to several design modifications to incorporate additional beneficial features.

Top: Aerial view of the lagoon entrance postconstruction. (Photo by Humiston & Moore Engineers)

*Middle: American flamingo (*Phoenicopterus ruber*) present in Tigertail Beach Park. The beach is one of 510 points on the Great Florida Birding and Wildlife Trail and is considered one of the best all-around birding spots in southwest Florida. (Photo by Jack Hartfelder, Turrell Hall & Associates)*

Bottom: Beachgoers enjoying postrestoration conditions along Tigertail Beach Park. (Photo by Mohamed Dabees, Humiston & Moore Engineers, and Jack Hartfelder, Turrell Hall & Associates)

Ohio River Bonanza Bar

Portsmouth, Ohio, United States

Using dredged material beneficially to create ecological habitats and restore the historical footprint. The Bonanza Bar is an ephemeral island near the City of Portsmouth, seated between the banks of the States of Ohio and Kentucky in the Ohio River. Historically, the island has been used for dredged material placement dating back to the early 1980s. In the early 2000s, the U.S. Army Corps of Engineers (USACE)–Huntington District received approval from the Kentucky Division of Water (DOW) to hydraulically "stack" dredged material near the bankline, with the specific intent to leave space sufficient for sustaining back-channel habitat in the slack waters created by the bar. From an agency partnering meeting in 2011, the USACE Huntington District began to develop the island as a beneficial use site by incorporating the back channel between the bar and the Kentucky bankline. The ephemeral island is currently constructed entirely of dredged material and has been restored to mimic its footprint in the river channel documented more than 50 years ago. As successful placements have occurred over the past decade, the creation of the Bonanza Bar has subsequently allowed for more efficient dredged material placement and reduced timing, frequency, and cost of dredging in the adjacent navigation channel while providing valuable ecological habitat and recreational opportunities.

Producing Efficiencies

Since 2016, the number and cost of dredge requirements near the Bonanza Bar reach have declined. This decrease in dredging needs has coincided with the Bonanza Bar island creation. Hypothetically, the islands are concentrating the flow to maintain a more sustainable federal channel. The cross-sectional area of the river had changed due to the deposition of dredged material. The current trend in the Bonanza Bar project area is that there is less shoaling in the region, leading to the decline of dredging demands over the past several years.

Using Natural Processes

The USACE Huntington District is currently interested in stabilizing and growing the bar to serve as additional constriction on the navigation channel (reducing or potentially removing the need for repetitive maintenance dredging) and stabilizing downstream and adjacent ecological resources (i.e., mussel bed habitat). Therefore, placement regions have been informed by historical bar locations, and the current Bonanza Bar footprint, created with dredge placement, mimics the location of the natural bar formation as documented in historical navigation charts. The dredge placement is unconfined, and the energy of the river is used to distribute the sediment and shape the bar.

Previous page: Bonanza Bar island habitat. Ecological benefits observed at the project site include increased mussel populations, the presence of migratory birds, and creation of riverine back-channel habitat. (Photo by USACE Huntington District)

Right: Dredged material placement in 2016. The top cover present on the island is primarily cobble and gravel-sized materials followed by a coarse sand layer beneath. (Photo by USACE Huntington District)

Broadening Benefits

The development of the ephemeral Bonanza Bar has created a riverine back-channel habitat. Migratory birds have been observed on the island, and mussel populations have increased with beds present along the downstream bankline and side channels adjacent to the islands. USACE Huntington District has sponsored nine mussel surveys along the left descending bank at the Bonanza Bar, which shows mussel habitat existing along the Kentucky shoreline there, indicating a thriving population. Located outside of a small town and with a public access boat ramp close by, the island is also regularly used as a popular boating spot by residents and tourists alike.

Promoting Collaboration

A change in philosophy allowed the USACE Huntington District to adapt to a more sustainable approach to dredged material management by using a stakeholder-driven approach to guide its dredge program. The Huntington District collaborated closely with the U.S. Fish and Wildlife Service, the Kentucky Department of Natural Resources, and the DOW on the approach to redirect placement of dredged material away from the bank (to incorporate side channel habitats) and to obtain the related water quality certification permit. At annual stakeholder meetings, the district's proactive approach transformed a contentious atmosphere to one of collaboration.

Top: Placement of dredged material by a clamshell dredge contractor in 2014. (Photo by USACE Huntington District)

Middle: Dredged material being placed on the ephemeral island in 2016. The last dredged material placement occurred in December 2020, and the material remained eight months later following multiple high-water events. (Photo by USACE Huntington District)

Bottom: Migratory birds settling on the island following material placement. Note the clearly defined back channel before the Kentucky bank line in the background. (Photo by USACE Huntington District)

Fort Pierce Island

Fort Pierce, Florida, United States

Creating a large living breakwater system to reduce future coastal storm risk. Most of the City of Fort Pierce's waterfront is public access space that includes a marina and adjacent park. In 2004, Hurricanes Frances and Jeanne destroyed the marina, a vital component of the city's waterfront redevelopment efforts. To provide wave and current protection for the marina, Tetra Tech Inc. worked with the city to develop a six-hectare island breakwater system designed to perform under existing conditions and adapt to projected sea-level rise conditions. The system includes a first-line, nature-based island complex that incorporated beneficial reuse of approximately 114,683 cubic meters of dredged sand and provides structural stability and functional performance enhancement through mangrove plantings, tidal lagoon features, and oyster reefs. The final design consisted of T-head rock groins fronting the largest breakwater island and sand-filled geotextile tubes with circumferences of up to 14 meters creating a perimeter dike that protects the sand fill from the erosive effects of high tidal currents. This design received the Industrial Fabrics Association International's Award of Excellence in the Geosynthetic Projects category in 2014 and two Project Excellence awards from the American Society of Civil Engineers and National Association of Environmental Professionals in 2016 and 2017, respectively. Five years postconstruction, the project has created roughly eight hectares of habitat features that dramatically increased the structural complexity of the benthic communities and the biodiversity within the project area.

Producing Efficiencies

Six hectares of breakwater islands are located in the dynamic flood tidal delta of the Fort Pierce Inlet (where tidal currents of up to four knots occur) and proximate to the Atlantic Intracoastal Waterway. These islands had to be positioned and configured to avoid any disturbance to the area's current and sediment transport patterns. Tetra Tech Inc. performed extensive numerical modeling of currents, sediment transport, and turbidity for the full project configuration and for construction of each island in the complex, including flume testing of critical sections, 3D movable bed physical modeling, CGWAVE (wave prediction) modeling, and multiple marine resource surveys.

Using Natural Processes

The project design included approximately six hectares of habitat components, such as seagrass, mangroves, oysters, dune vegetation, and shorebird nesting, that contributed to the overall environmental enhancement, structural stability, and functional performance, as was demonstrated by mangrove plantings. The project was funded under the Federal Emergency Management Agency's (FEMA's) hazard damage mitigation program, where the operable design criterion is the 100-year storm. FEMA would not fund designs that met more severe conditions than the 100-year flood. To accommodate, the design included mangrove plantings that would over time result in an effective wave attenuating component to protect the islands and prevent overtopping.

Previous page: Placing sand within the perimeter dike of Tern Island. (Photo by Tetra Tech Inc.)

Right: Breakwater Island with intertidal marine mattress as a substrate for oysters. Additionally, nearly 200 macroalgae, sessile invertebrate, and fish species have been documented. (Photo by Tetra Tech Inc.)

Broadening Benefits

Consisting of open, fast-moving water with less than 0.4 hectare of submerged hard substrate and 0.016 hectare of seagrass, the former project area provided no refuge or foraging habitat for marine species. The islands now support a vibrant marine and vegetation ecosystem. The large breakwater island crest hosts habitat for shorebirds and attracts protected species for nesting. Fishing and bird-watching are popular activities in the species-rich area. The breakwater islands provided protection against 100-year storms, allowing rebuilding with reduced concerns over future storm damage and impacts to lost revenue each year the outer marina was out of service.

Promoting Collaboration

The project included an active public participation process with a high-rise residential condominium association in view of the project area, the Marine Industries Association, and the Port of Fort Pierce Advisory Committee to advise on proposed plans and solicit feedback. Collaboration with the Advisory Committee was critical to permitting and a prerequisite to the state approval of the project due to its location within the Port of Fort Pierce Master Plan area. Extensive negotiations with the Florida Department of Environmental Protection were required before the project was finally approved by the Florida governor and cabinet as a pilot project.

Top: Aerial view of the completed project in 2015. The marina and breakwater island complex has endured Hurricanes Matthew (2016), Harvey (2017), and Ian and Nicole (2022) without any significant damage to the marina docks and breakwater islands. (Photo by Bellingham Marine)

Middle: Oysters and mangrove seedlings in the marine mattress. The project created 0.6 hectare of oyster beds, 0.6 hectare of mangrove fringe along the islands' shores, and 12 hectares of seagrass beds. (Photo by Tracy Lybolt, Tetra Tech Inc.)

Bottom: Mangroves growing in the marine mattress layer where none were present before. (Photo by Tracy Lybolt, Tetra Tech Inc.)

Interstate Island

Duluth, Minnesota, and Superior, Wisconsin, United States

Protecting threatened habitat by beneficial use of dredged material. Interstate Island, located in the Duluth Superior Harbor in Lake Superior, was historically 2.5 hectares. However, in 2019, the island was being flooded and washed away during record-high water levels in the Great Lakes. Interstate Island provides valuable and rare habitat to the state-threatened common tern (*Sterna hirundo*) and is home to approximately 200 common terns, which is about half of the entire population in the Lake Superior watershed. In the fall of 2020, using dredged material, the U.S. Army Corps of Engineers (USACE)–Detroit District beneficially placed approximately 51,990 cubic meters of material on the island to significantly expand and protect the island from erosion. This work was done in partnership with the Minnesota Land Trust, the Minnesota Department of Natural Resources, the Wisconsin Department of Natural Resources, and the Environmental Protection Agency (EPA) Great Lakes National Program Office (GLNPO). With placement of dredged material, the areas of the island subject to flooding were elevated, expanding the island from 1 hectare to 2.7 hectares of viable habitat during extreme high-water levels and 3.5 hectares during more regular water-level periods in the Great Lakes.

Producing Efficiencies

As dredging occurs annually in the Duluth-Superior Harbor, the Interstate Island habitat protection and enhancement were completed at no cost to state and federal partners by the beneficial use of this dredged material. This project represented a significant opportunity to not only maximize benefits to the project partners through cost savings but also provided valuable habitat for the threated common tern. In addition, it allowed USACE to beneficially use dredged material, saving space in its confined disposal facility, and showcased the value that dredged material can have as a natural resource.

Using Natural Processes

Rather than place a valuable natural resource in a confined disposal facility, the material is able to be dredged and beneficially used for the expansion of Interstate Island and to provide for and protect habitat for the common tern. The material placed on the island expanded the island's aerial extent, expanded habitat, and provided a buffer for erosion. Placing the material unconfined provides opportunities for natural processes to shape the island's enlarged footprint, thereby enhancing habitat value both above and below water.

Previous page: Interstate Island, post-USACE Detroit District dredged material placement. (Photo by Monica Anderson, USACE Detroit District)

Right: Bulldozer grading during hydraulic placement on Interstate Island with the John G. Munson *freighter in the background. (Photo by Monica Anderson, USACE Detroit District)*

Broadening Benefits

The beneficial use of dredged material at Interstate Island provides much-needed habitat for the threatened common tern in Lake Superior. By helping protect the threatened species, it also provides social and economic benefits for bird-watchers and saves partner funding due to the material being able to be beneficially placed at no additional taxpayer cost as the material is already dredged annually.

Promoting Collaboration

Project partners—the Minnesota Land Trust, the Minnesota and Wisconsin Departments of Natural Resources, and the EPA GLNPO—met regularly to discuss the timing of the dredging, placement methods, design aspects, access to the island, and best management practices. Issues were identified and overcome quickly, and the team was successful because of everyone's willingness to work together for a common goal of restoring habitat on Interstate Island.

Top: Interstate Island, pre-USACE Detroit District dredged material placement. (Photo by Monica Anderson, USACE Detroit District)

Middle: Active hydraulic placement of dredged material at Interstate Island. A baffle plate is attached at the end of the pipe at a 45-degree angle to dissipate the energy from the flow of the dredged material out of the pipe to help minimize turbidity. (Photo by Monica Anderson, USACE Detroit District)

Bottom: After dredged material placement with the John A. Blatnik Bridge in the background. The states of Minnesota and Wisconsin are located on the left and right, respectively, when looking ahead. (Photo by Monica Anderson, USACE Detroit District)

Sand Island

Mobile County, Alabama, United States

Working with nature to build ephemeral islands in an ebb-tidal delta. Mobile Pass is one of the largest ebb-tidal delta systems in the United States. It provides safe and efficient navigation to harbors for the distribution of goods and services, serves as a natural source and sink of sediments for adjacent shoals and ephemeral islands driven by a prevailing wave approach and tidal-flow dynamics, and provides a natural wave break, dissipating wave energy approaching lee-side island beaches and dunes along Dauphin Island, Alabama. Since 1999, sandy material dredged as part of routine maintenance of the Bar Channel has been placed within the Sand Island Beneficial Use Area (SIBUA) by means of bypassing, but the limited placement area restricted dredge equipment and site capacity. In 2019, the SIBUA Northwest Extension was approved to continue the balancing of safe and efficient dredged material placement practices while also using natural transport mechanisms to move sediment westward along the shoal system. As part of the channel improvements and the National Fish and Wildlife Foundation's Alabama Barrier Island Restoration Assessment, the U.S. Army Corps of Engineers (USACE)–Mobile District worked with partners, stakeholders, and industry incorporating lessons learned and design strategies for the placement of over one million cubic meters of dredged material, improving dredge efficiencies and providing migratory bird habitats.

Producing Efficiencies

Revisions to dredged material placement were determined through analysis of long-term sediment transport processes, historical dredge records, and modeling of sediment transport and morphological changes. Historical topographic and bathymetric surveys and dredge records were compared to quantify past and present-day changes in the sand flux to develop sediment budgets that helped to inform modeling tools and placement strategies. This aided in identifying potential operational efficiencies through use of bimodal sand transport pathways for safe and efficient placement practices. To evaluate effectiveness and better understand future placement site capacity, SIBUA is proactively monitored and managed through hydrographic surveys and change analysis.

Using Natural Processes

The project worked with nature to build the ephemeral islands. Regional Sediment Management and beneficial use strategies in conjunction with Engineering With Nature were used to place dredged material along nearshore shoal systems, providing an estimated 401,391 cubic meters of beneficial use sediment placement per year to the downdrift ebb-tidal delta system. A prevailing southeast wave approach and tidal-flow dynamics coupled with ephemeral-island placement strategies maximized efficient dredged material placement and provided natural wave breaks and dynamic transit migratory bird habitats. The islands are the result of sand moving west along the perimeter of the delta shield.

Previous page, top, and bottom: Aerial views of the 2022 SIBUA dredged material placement of ephemeral islands in the foreground looking east toward Sand Island Lighthouse, Alabama. (Photos by Sam St. John, FlyTheCoast)

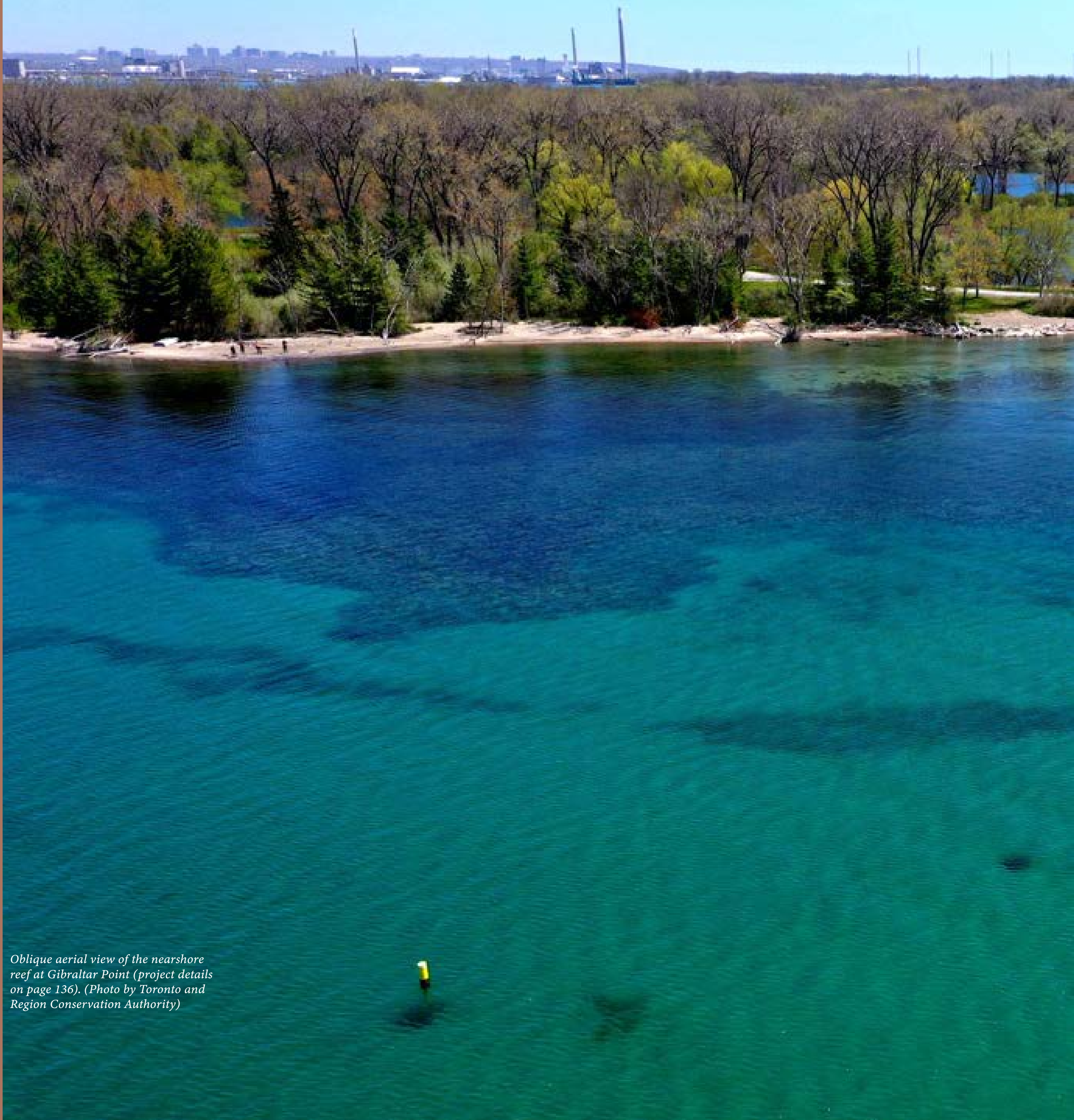
Broadening Benefits

Placement of sediment to mimic ephemeral islands improved dredged material placement efficiencies while providing dynamic transit habitat features for migratory birds, including piping plover (*Charadrius melodus*) critical habitat. The placement provides sediment to the tidal delta shield, which acts as a natural wave break, dissipating wave energy approaching the lee-side island beaches and dunes that serve as second lines of defense for both natural (maritime forests and freshwater lakes) and built infrastructure (cultural resource sites, public educational facilities, campgrounds, and private developments) occurring landward. In addition, the natural wave break of the shoal system allows for recreational boating, kayaking, fishing, and bird-watching.

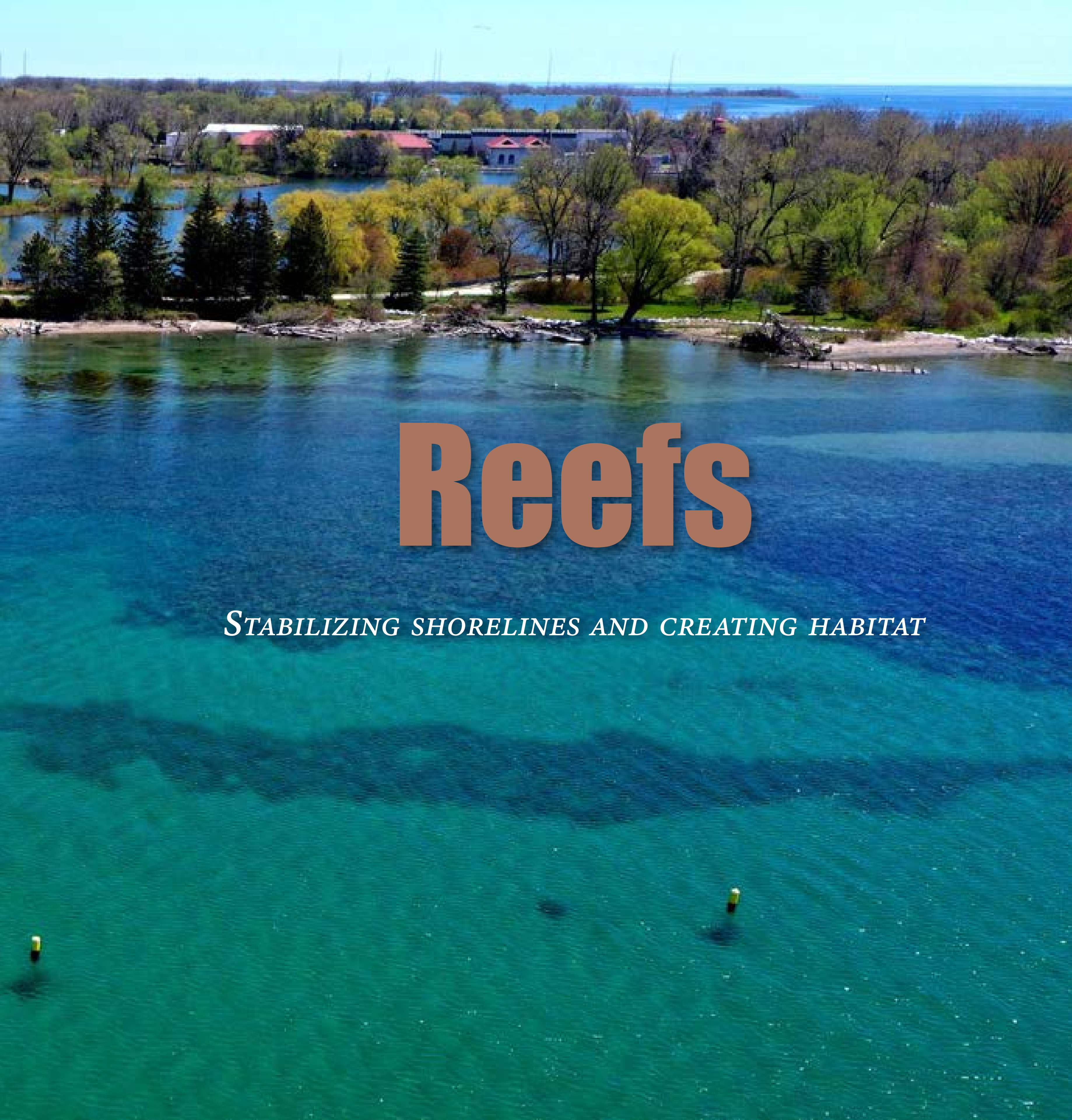
Promoting Collaboration

This effort was built upon decades of data, science, research, and knowledge. Prior work included sediment budget analysis and modeling by Applied Coastal Research and Engineering; coastal data collection and analysis from the University of South Alabama, Geological Survey of Alabama, and South Coast Engineers; sea floor and shoreline change studies by the U.S. Geological Survey (USGS); and updated bathymetric data sets by NOAA, USGS, and USACE. USACE Mobile District worked with partners and stakeholders to gain a fuller understanding of the system and to better define problems, objectives, and opportunities, thereby improving collaboration and leading to continued partnerships and innovative nature-based solutions.

Top to bottom: The C.R. McCaskill *dredge and pipelines placing sediment in the SIBUA ephemeral islands. The project worked with nature to optimize bimodal sand transport pathways and mimic nature through ephemeral-island and shoal placement. (Photos by Sam St. John, FlyTheCoast)*



Oblique aerial view of the nearshore reef at Gibraltar Point (project details on page 136). (Photo by Toronto and Region Conservation Authority)



Reefs

Stabilizing shorelines and creating habitat

Reefs

Introduction

Reefs as natural and nature-based infrastructure are playing key roles in freshwater and marine coastal systems. Highlighted in this chapter are projects to protect built infrastructure, such as roads, while simultaneously providing wave suppression and increasing habitat and economic value in the area. Reefs are also being used in coastal riverine environments not only to restore the historical extent of oyster reef habitat but also to serve as natural infrastructure to reduce the energy from recreational boat wakes. Reefs are being made from locally recycled natural materials, such as bamboo poles and oyster shells discarded by local farmers, to reduce storm and wave impacts on a coastal island and help protect a vast oyster fishery. To combat coastal erosion, reefs constructed from locally sourced rock are also creating bottom habitat features for a plethora of marine life. Reefs designed and constructed in freshwater coastal habitats to protect city shorelines also create recreational opportunities and valuable ecological habitat both above and below the water. Reefs are also being designed and constructed using innovative additive manufacturing and carbon-reduction technologies. Such innovations are being used as nature-based solution demonstrations to evaluate their ability to enhance habitat value and coastal resiliency.

Huon Mundy Oyster Reefs

Noosa, Queensland, Australia

Constructing reefs in an ecological heritage site and urban estuarine environment. Prior to European settlement, the Noosa River estuary was once dominated by rock oyster beds, which provided important ecological services to the river and served as an important food source for First Nations groups for millennia. However, excessive harvesting resulted in the loss of the vast majority of the oyster habitat, leaving a void in both the river's ecosystem and cultural heritage. The Noosa Oyster Ecosystem Restoration Project, a partnership project between The Nature Conservancy (TNC), Noosa Shire Council, The Thomas Foundation, and the Australian Government, was created to restore the rock oyster beds and their ecological services to the river and to help stabilize the riverbank against erosion from recreational boat wakes. In 2022, 30 reef patches were installed at four sites throughout the river before volunteer groups seeded the sites with 600,000 juvenile oysters. The reefs were designed to replicate the complex habitat of the historical oyster reef beds while fitting in with the modern environmental condition of the Noosa River, which now hosts a wide range of human uses and urban development. Following construction, Noosa's traditional custodians, the Kabi Nation, named the reefs the Huon Mundy Reefs after a great Kabi spiritual leader.

Producing Efficiencies

TNC created a restoration suitability model to select the best locations to restore oyster habitat, considering a range of ecological criteria. The reefs, designed by International Coastal Management, primarily operate as effective substrate for the restoration of the oyster ecosystem and protect the riverbank from wind and boat-wake-generated wave energy. The shape and size of the oyster reef patches were designed to provide the greatest environmental outcomes and reflect the bathymetry at each site, minimizing impacts to coastal processes and existing sensitive marine habitats. Each patch was strategically located to ensure public access and public safety. Comprehensive design requirements guided the design of each reef patch, allowing for flexible adaptation of reef patches during construction.

Using Natural Processes

Oysters offer powerful natural processes to estuarine environments by filtering large volumes of water, providing structure for marine species, and dissipating wave energy. The Huon Mundy Reefs offer shoreline protection and promote sediment accretion along the shorelines behind the reef patches. In time, with establishment of the oyster ecosystem, the new reef structure, grown by the oysters and other shellfish, will provide further stability and resilience to the riverbank and allow the reefs to adapt to changes in water level and respond to climate change. The restored ecological processes are also expected to help reestablish other marine habitats within the estuary's ecosystem.

Previous page: The Huon Mundy Reefs are located within a narrow area of Noosa River Estuary near to existing habitat and the developed tourist town of Noosa. The reefs have reduced the level of wave energy impacting the foreshore of the river, which has led to accretion of sediments along the foreshore and the establishment of seagrasses between some of the reef patches. (Photo by Richard Howard, Noosa Integrated Catchment Association)

Right: New rock reef patches at the Noosa Sound West site, replacing the historical oyster beds that once dominated the estuary. (Photo by Sam King, International Coastal Management)

Broadening Benefits

The restored oyster reefs are an important component of the health of the Noosa estuary, creating complex habitat for fish and other marine species and improvements to estuarine water quality through filtration. In addition, the hard reef produced by the oysters and substrate provides great structure for reducing wave energy and stabilizing the shoreline. The reefs provide fishing, recreation, water-based ecotourism, and educational opportunities for the Noosa region, which is a popular tourism destination in Queensland. The restoration of the oyster reefs also represented a significant reconciliation step to renew the cultural links of the Kabi Kabi Traditional Owners to their sea country.

Promoting Collaboration

The project team consulted extensively with various interested parties, including the local Kabi Kabi Traditional Owners, local council and state agencies, local fishing industry representatives, community organizations, residents near the proposed reef sites, and the general public. Community participation was essential throughout, with volunteers assisting with "oyster gardening" and seeding of the reefs on completion. Involvement and collaboration with these groups and the local community was crucial to shaping the direction and outcomes of the project. A multidisciplinary approach brought together the collective expertise and resources of aquatic scientists, planners, coastal engineers, and volunteer groups.

Top: Submerged reef patches at high tide. (Photo by Richard Howard, Noosa Integrated Catchment Association)

Middle: The reefs were seeded with juvenile oysters. Ongoing monitoring preliminarily reports the establishment of a range of shellfish species. (Photo by Craig Bohm, TNC)

Bottom: "Oyster gardening" by local volunteers grew juvenile oysters on recycled oyster shell in the Noosa River. (Photo by Klaus Horner TV Production)

North Carolina Highway 24

Swansboro, North Carolina, United States

Reducing wave energy for salt marsh and highway infrastructure protection. The North Carolina Highway 24 (NC 24) causeway island lies in the Town of Swansboro, North Carolina, within the White Oak River and the Bogue Sound and in eyesight of Bogue Inlet and the Atlantic Ocean. This location, between several waterways, places it in a vulnerable spot, subject to hydrodynamic forces and erosion. The causeway island has been susceptible to wave erosion from extreme storm events and has suffered damage on numerous occasions, most recently during Hurricane Florence in 2018. The NC 24 corridor is also a vital route for hurricane evacuation and acts as a connector between North Carolina's Crystal Coast communities and the local military installations at Camp Lejeune and Cherry Point. Instead of continuing to repair using traditional methods, like armoring the embankment with rock, the North Carolina Department of Transportation (NCDOT) looked to nature-based solutions. NCDOT constructed approximately 260 meters of living shoreline, consisting of granite rock and oyster reef structures and a 0.1-hectare salt marsh. The living shoreline reduces the wave energy impacting the causeway, increasing resiliency while also providing environmental uplift through habitat creation and water-quality improvement. This living shoreline project is the first to be completed by NCDOT, serving as a model for future living shoreline projects along the highways of coastal North Carolina.

Producing Efficiencies

The NC 24 causeway's location is faced with numerous hydrodynamic forces from riverine flows, tidal cycles, storm surge, and wind-blown waves. To make this project successful, all of these forces were considered. The project team collected topographic and bathymetric surveys and current flow data to complete surge and wave analysis, sediment transport, and hydraulic modeling. Although the overall cost for design and construction of this living shoreline is likely similar to a traditional seawall, due to the location and a number of other factors, the anticipated long-term maintenance costs will be much less.

Using Natural Processes

The rock sills and oyster structures offer a stable structural element to reduce wave energy. The oyster structures, made of jute cloth hardened with cement, provide a rough surface that quickly recruits oyster spat and supports oyster growth, creating a natural oyster reef. Theoretically, the growth of the oyster reef may be able to keep up with sea level rise over time, continuing to provide wave-reduction benefits. The smooth cordgrass (*Sporobolus alterinflorus*) marsh plantings further reduce the wave energy, allowing sediments to accrete and building the marsh up along with sea level rise as well.

Previous page: Aerial view of the living shoreline at the end of construction, looking toward the west into the Town of Swansboro, North Carolina. (Photo by NCDOT)

Top: Erosion around the bridge end bent and under the sidewalk from Hurricane Florence and other extreme storm events. (Photo by SWCA Environmental Consultants)

Bottom: Installation of Oyster Catcher tables, a jute fiber and cementitious material matrix that has high oyster spat recruitment, thereby allowing for the creation of a new oyster reef. (Photo by SWCA Environmental Consultants)

Broadening Benefits

The Crystal Coast is a tourism hot spot, with the NC 24 causeway a gateway into the Town of Swansboro, which attracts fishers, boaters, kayakers, beachgoers, and other water-related recreational users. The living shoreline provides a more aesthetically pleasing, environmentally friendly area that blends into the natural beauty of the marshlands and sandbars within the river and sound and also an economic uplift for all of these groups. The combination of tidal salt marsh, deep and shallow water, rock, and oyster structure sills creates a habitat where small crustaceans can thrive and attract larger fish species. The oyster reef will also improve water quality in the area through the oyster's ability to naturally filter water.

Promoting Collaboration

Using National Fish and Wildlife Foundation grant funding, NCDOT partnered with the North Carolina Coastal Federation and multiple consultants, including SWCA Environmental Consultants, Moffatt & Nichol, and RK&K, for the design, data collection, modeling, and monitoring. The project team collaborated with the U.S. Army Corps of Engineers, the North Carolina Division of Coastal Management, and the Division of Marine Fisheries to produce a design that met the needs of NCDOT while providing environmental uplift with minimal impacts. The design was then constructed by the T. A. Loving Company, Native Shoreline, and Sandbar Oyster Company.

Top: Relocating shellfish, oysters, and clams from the project site to neighboring marsh prior to construction. (Photo by North Carolina Coastal Federation)

Middle: Wave energy being dissipated as the tide comes in and begins to inundate the newly planted marsh grasses. (Photo by NCDOT)

Bottom: The saved, existing salt marsh and new granite rock sill. They represent what the entire site will resemble once new marsh grasses mature. (Photo by NCDOT)

Waisanding Sandbar

Dongshi Township, Chiayi County, Taiwan

Mitigating sandbar scouring with natural infrastructure materials. The Waisanding sandbar, located on the western coastal waters of Chiayi County, is the largest detached sandbar in Taiwan. Functioning as a natural barrier, the southern shallow water of the Waisanding sandbar provides an excellent aquaculture environment for oysters and acts as an important resource for oyster farming in Taiwan. Because of storm surge overwash, strong monsoon-wave longshore currents, and land reclamation for coastal structures, the sandbar area had decreased from 2,000 hectares to 1,000 hectares over the past 50 years. In 2022, to mitigate sandbar scouring and reduce wind-wave impact to the shoreline, groins and sand-trapping structures were constructed by the Water Resources Agency, Ministry of Economic Affairs (MOEA), Taiwan. These structures, made with locally sourced bamboo and bagged oyster shells recycled from oyster farming, were designed to be permeable to simultaneously maintain water flow and reduce sediment transport rates. Further, the porous structures would provide habitat for fish, shrimp, and benthic organisms. Additional sand-trapping structures were constructed collaboratively with assistance from the local community and fishing industry in consideration of future coastal protection of the sandbar. Following the Waisanding Sandbar Protection Project completion, local residents and fishers have learned how to effectively and proactively maintain their oyster farms, encouraging community buy-in while protecting and maintaining the sandbar.

Producing Efficiencies

Longshore current sediment transport and wave overwashing are the primary impact factors to the Waisanding sandbar. After assessment, using coastal sediment transport model CCHE2D-Coast, a 300-meter-long groin and two 120-meter-long groins were constructed at the southern shoreline of Waisanding. These structures were expected to increase sand deposition on the northern side of the groins. Bamboo dikes were also installed at the eroded, wave-impacted area of the sandbar to reduce wave energy and current magnitude. Additionally, three sand-trapping structures were constructed behind the sandbar to intercept wash load carried by overtopping waves.

Using Natural Processes

Bamboo oyster racks were continually damaged during typhoon and winter storm events from strong wind and wave energy. The damaged bamboo was being carried by tide currents and moved to the shoreline, creating a coastal environmental problem. To address this issue, the project repurposed the damaged bamboo and discarded oyster shells to make the groins, dikes, and sand-trapping structures. Although both the bamboo and oysters shells were not sufficiently hard enough to withstand strong winds and waves, they met sustainable use requirements and were easily obtainable. Consequently, the project will reduce bamboo and oyster shell placement volumes and increase biological habitats through this reuse.

Previous page: The sand-trapping structure, constructed from bamboo stakes and oyster strings, in August 2022. (Photo by Water Resources Agency, Ministry of Economic Affairs [MOEA], Taiwan)

Top and bottom: In October 2022, half of the oyster strings were buried approximately 20 to 30 centimeters in the sand. By March 2023, the oyster strings were fully buried approximately 40 to 50 centimeters deep. (Photos by Water Resources Agency, MOEA, Taiwan)

Broadening Benefits

The Waisanding Sandbar Protection Project was developed using National Oceanic Atmospheric Administration's Coastal Zone Management Act requirements for biological conservation and coastal environment maintenance. As a result of the project, additional conservation projects were implemented around the sandbar, including a wetland, an artificial reef, no-fishing areas, and a habitat area for the Chinese white dolphin (*Sousa chinensis*). To comply with the conservation plans around Waisanding, natural materials rather than conventional were used to construct engineering structures, thereby reducing the volume of damaged bamboo and unused oyster shells, promoting local tourism, and contributing to an economical and environmentally sustainable model.

Promoting Collaboration

This innovative project successfully united government, coastal residents, and local industry stakeholders to plan and construct the sand-trapping structures for sandbar protection. Early in the project, some residents and stakeholders opposed this effort, but resistance turned into assistance after frequent communication explaining the sandbar protection concept, leading to construction in 2022. The local community collected damaged bamboo and unused oyster shells, and local industry assisted with transporting the materials to the Waisanding beach area. After, participants installed the materials into planned locations. Local residents helped to construct the sandbar, unprompted, lowering project costs.

Top: Aerial view of construction of the Waisanding sandbar bamboo sand-trapping structure. (Photo by Water Resources Agency, MOEA, Taiwan)

Middle: Working together to construct the project's structural features included Taiwan Water Resource Agency staff and local residents of Dongshi Township. (Photo by Water Resources Agency, MOEA, Taiwan)

Bottom: One of the three sand-trapping structures, constructed of bamboo stakes and cages. (Photo by Water Resources Agency, MOEA, Taiwan)

Palm Beach

Gold Coast, Queensland, Australia

Constructing an artificial reef to provide coastal protection and recreational opportunities. For decades, Palm Beach, located on the Gold Coast in southeast Queensland, suffered significant erosion events that threatened beachfront infrastructure, exposing seawalls and impacting the local lifestyle due to the temporary reduction of available recreational shoreline. To find an appropriate solution to address these hazards, the City of Gold Coast developed the Palm Beach Shoreline Project, following a "design with nature approach." After significant investigation, testing, and design, sand nourishment stabilized by an artificial reef was adopted for Palm Beach to provide coastal protection as well as recreational and surfing amenity outcomes. This option was favored for its low visual impact and the long-term retainment of nourished sand. Taking place in two phases, sand nourishment began in 2017, followed by construction of the artificial reef in 2019. Postconstruction monitoring revealed the project is achieving its objectives by sustaining an average of 370,000 cubic meters of sand above the preproject levels within the Palm Beach coastal system, creating a new surf break for the community, generating a positive impact on the local marine ecology, and transforming the site from a barren sandy bottom to a marine ecosystem flourishing with flora and fauna.

Producing Efficiencies

During a comprehensive design process spanning several years, an initial feasibility assessment evaluated 18 management options. Each option was assessed and compared on the basis of cost, coastal protection, and impacts or benefits for a range of aspects, such as coastal processes, ecology, surfing, and beach amenity. The final detailed design phase adopted a "multiple lines of evidence" approach, involving real-world data capture, several forms of sophisticated numerical modeling, and two programs of scaled physical modeling in wave tanks. These investigation methods allowed for crosschecking and calibration between the results of the various design investigations and provided confidence in the unique design.

Using Natural Processes

During nourishment, sand was sourced from deepwater deposits and placed within the surf zone via split hopper dredge. The sand was placed in a unique noncontinuous deposition process that worked with changing bathymetries, minimized beach-user impacts, and provided temporary surfing opportunities. The artificial reef was designed to use the natural northward movement of sand, which is driven by southeast waves arriving oblique to the shoreline. The reef interacts with the waves and currents to slow the northerly sand transport near the reef, promoting an updrift buildup of a portion of the passing sand.

Previous page: Constructed of large rock boulders and located approximately 270 meters offshore, the Palm Beach artificial reef has a 160-meter-long and 80-meter-wide footprint, sitting 1.5 meters below the average water level at its highest point. (Photo by City of Gold Coast)

Top: Marine flora and fauna are now well established at the artificial reef. (Photo by Reef Check Australia)

*Bottom: A green sea turtle (*Chelonia mydas*) enjoying the new habitat created by the artificial reef. (Photo by Ecological Service Professionals)*

Broadening Benefits

The benefits of the project extend beyond coastal protection to include enhancing the local ecology, surfing culture, industry, and community on the Gold Coast. Collected surfing metrics have confirmed that the reef produces a regular rideable wave. Flora and fauna habitat was also created on the previously bare sandy habitat. Ecological monitoring has revealed the establishment of seaweed; sea turtles; several common invertebrates, such as sea squirts (*Ascidiacea*) and feather stars (*Crinoidea*); and schools of yellowtail scad (*Atule mate*), eastern pomfred (*Schuettea scalaripinnis*), bream (*Abramis*), tarwhine (*Rhabdosargus sarb*), sweetlips (*Plectorhinchus*), trevally (*Caranx*), and snapper (*Lutjanidae*).

Promoting Collaboration

The City of Gold Coast collaborated with a team of scientists, coastal management experts, engineers, environmental officers, dredging consultants, and maritime construction experts to find a sustainable solution to protect Palm Beach. Local residents, the surfing community, and other interest groups were also important stakeholders in the project. These groups were consulted regularly throughout the design and construction process to ensure their voices were heard and that the community received the best outcome possible. For its work, the project was twice awarded by the Institute of Public Works Engineering Australasia Queensland Excellence Awards in Innovation in 2019 and Coastal Engineering in 2020.

Top: Construction of the artificial reef involved 60,000 tonnes of rock, each weighing up to eight tonnes, and quarried from southeast Queensland. (Photo by City of Gold Coast)

Middle: Sand rainbow nourishing the nearshore at Palm Beach. Over 470,000 cubic meters of sand were delivered to the nearshore via bottom placement and rainbowing. (Photo by City of Gold Coast)

Bottom: Surfer on the Palm Beach artificial reef. (Photo by Andrew Shield)

Gibraltar Point

Toronto, Ontario, Canada

Placing an innovative nearshore reef and sand dune for shoreline protection. Off the coast of the City of Toronto at the southwesterly tip of the Toronto Islands on Lake Ontario, Gibraltar Point has historically experienced decades of shoreline erosion and storm damage. For decades, the roughly 500-meter-long reach of shoreline from Gibraltar Point to the north has severely retreated by approximately four meters per year. At the request of Toronto and Region Conservation Authority (TRCA), Baird & Associates initiated a study to develop a nature-based design to mitigate erosion and maintain a dynamic beach shore through a long-term, sustainable sand-management approach, using minimal structural intervention and maintaining economic feasibility. In this multiphase project, TRCA initiated development, design, and construction of a nearshore reef concept that would mimic natural coastal features and include improvements in the aquatic habitat. Further improvements and mitigation efforts included construction of a sand dune to provide additional erosion control and develop habitat areas. In 2021, following completion of the reef, 50,000 tonnes of imported sand were barged in and placed to construct a two-hectare sand dune plus additional dune enhancements, including planting 4,200 trees and shrubs, 500 herbaceous species, 7,300 beach marram grass plants (*Ammophila*), and other native plant species. Logs, woody debris, and two songbird boxes were used as natural infrastructure to enhance the habitat value of the dune ecosystem. Construction of the dune was completed in spring 2023.

Producing Efficiencies

Traditionally, natural reefs have been mimicked by designing low-crested structures, or breakwaters, to protect against storm waves without being a visual obstruction. However, low-crested breakwaters do not stop all wave transmission but are efficient when most required, like during storm events. In this project, the reef was defined as a reef breakwater with a wide crest and gentle outer slopes built with rocks in the nearshore area. When there is not enough dissipation of wave energy through wave breaking (such as under higher water levels), the reef's design allowed for additional dissipation via resistance against wave orbital flow through porous media.

Using Natural Processes

Naturally occurring nearshore reefs can mitigate wave transmission and sediment transport. The project's reef mirrors the natural coastal features inherent in nearshore reefs. The submerged nearshore reef uses the natural wave breaking over a submerged structure to dissipate the wave energy before it reaches the shoreline, reducing erosion. Coupled with installation of the sand dune, the nearshore reef has the potential to not only improve coastal resilience to erosion but also enhance local ecology, provide recreational opportunities (e.g., snorkeling), and support desirable aquatic and terrestrial habitats.

Previous page: Aerial view of the completed nearshore reef and beach at Gibraltar Point in summer 2022. (Photo by Toronto and Region Conservation Authority [TRCA])

Top and bottom: Oblique aerial views of the eroding shoreline at Gibraltar Point in August 2003 and June 2017, respectively. (Photos by Baird & Associates and TRCA, respectively)

Broadening Benefits

The City of Toronto is a bustling tourist destination. Only a short ferry ride from Downtown Toronto, the Toronto Islands are a popular location valued for their beaches and other recreational amenities, receiving thousands of visitors each year. The project has created a widened beach for visitor recreational use. Additionally, both terrestrial and aquatic habitats have been created and restored with construction of the submerged nearshore reef and sand dune, providing home to a variety of species.

Promoting Collaboration

Several design alternatives and approaches were considered before settling on the nearshore reef and sand-management concept, which provided the most economical and natural erosion control measures. The project was a collaborative effort that included many meetings and discussions between the design engineers, Baird & Associates, and the TRCA, on behalf of the City of Toronto. These meetings were crucial for aligning goals and objectives and creating a successful project for all stakeholders.

Top: Nearshore reef conditions looking offshore from the shoreline in July 2022. (Photo by Baird & Associates)

Bottom: July 2022 beach conditions behind the nearshore reef looking toward the south. (Photo by Baird & Associates)

SEAHIVE and Concrete 3D Printing

Destin Beach and Wahoo Bay, Florida, United States

Using green engineering to mitigate wave impacts, protect against climate change, and create aquatic habitat. The southeastern United States, and markedly Florida, has been ravaged by frequently occurring catastrophic coastal storms and hurricanes, causing billions of dollars of destruction to the areas in their wake. To protect against future storms and an ever-changing climate, innovative nature-based coastal protection options and solutions are essential. One such option is the use of 3D-printed coastal protection structures. These nature-based structures apply and integrate gray-green infrastructure to mimic natural habitats, mitigate floods, and harness wave energy. In this pilot project, conducted in two locations in North Bay Village, Miami, and Wahoo Bay, Pompano Beach, these gray-green structures, or SEAHIVEs, were deployed to address these municipalities' critical need for sustainable and resilient coastal protection and to safeguard them from flooding and waves while integrating clean electricity generation. These structures were piloted to incorporate a seawall in Wahoo Bay, a nature-based mangrove and coral reef in Pompano Beach, and a hybrid coral reef offshore of Miami Beach.

Producing Efficiencies

SEAHIVE is a modular shoreline-protection system with hexagonal units that, when stacked together, mimic nature, creating beehive-like structures. Hexagons allow continuous tiling of the units and optimize material by maximizing the space for a given amount of concrete. The beehive pattern offers material efficiency and enhances stability. Concrete 3D printing provides design flexibility with precise and customized construction. It also enables clustering—combining SEAHIVE compositions in a single body—which improves stability while facilitating transport and on-site assembly. Sustainable concrete mixtures combined with noncorrosive reinforcement reduce the carbon footprint while increasing durability and compatibility with the marine environment.

Using Natural Processes

Similar to natural reefs and rocky beaches, SEAHIVE structures protect by dissipating wave energy rather than redirecting it like traditional engineering structures such as seawalls. Perforations on the side faces of the hexagonal units and their compositions form interconnected channels in the resulting beehive-like structures, which trap water within the system and slow it down. The channels also provide habitat and protection for fish, while the overall macroscale design can be tailored to create structures for different applications and site conditions. In the University of Miami pilot ECoREEF, SEAHIVE units are in a pyramidal configuration and are populated with corals, while in Wahoo Bay, the units create a sloping structure that reaches the water surface, where units accommodate sediment and mangroves.

Previous page: 1Print SEAHIVE installation at Destin Beach, Florida. (Photo by N. Stills, Okaloosa County)

Right: 1Print concrete 3D printing. (Photo by N. Stills, Okaloosa County, and Arman Alaverdian, 1Print)

Broadening Benefits

Social benefits derived from the deployments enhance their value by providing recreational and educational opportunities for local communities and visitors. Snorkeling and other water activities allow for the exploration and appreciation of the local ecosystems, fostering a sense of connection to nature and promoting environmental awareness. Furthermore, the integration of green-gray infrastructure and the promotion of natural habitats contribute to ecosystem restoration and preservation. SEAHIVE creates a conducive environment for diverse marine life to flourish, supporting biodiversity and the overall health of the coastal ecosystem while increasing resilience to climate change impacts.

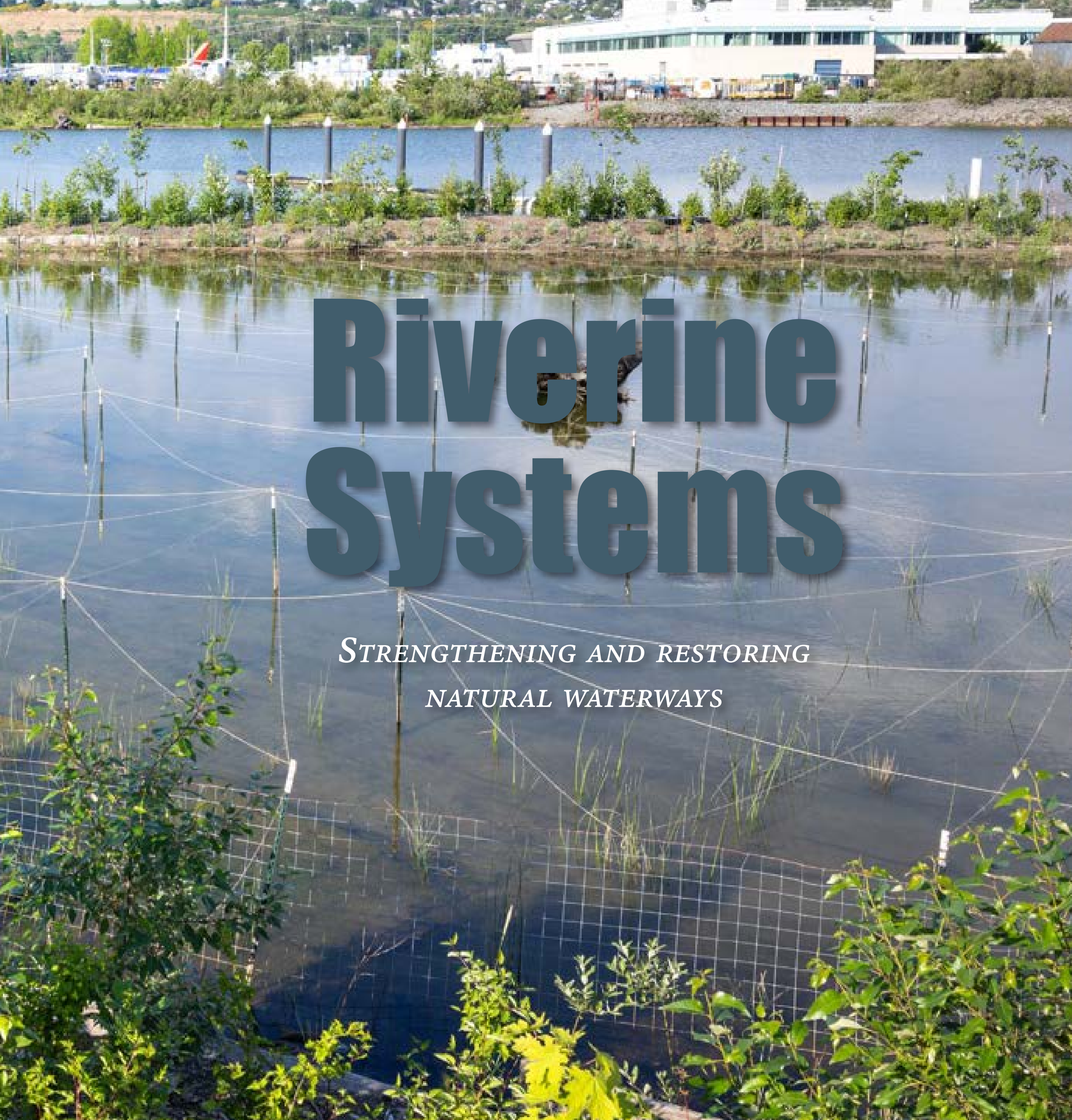
Promoting Collaboration

Concrete 3D printing with novel materials is currently under investigation in the scope of an Army Small Business Innovation Research Phase II grant led by 1Print in collaboration with the University of Miami, Titan Florida, and Carbon Limit. The grant focuses on the design, printing, and deployment of clustered SEAHIVE units and structures using marine-grade concrete and carbon-capture admixtures. The first project using 3D-printed clustered SEAHIVE reef units was deployed in February 2024 in Okaloosa County, Florida. Considering its adaptive features for various coastal and estuarine applications and the potential for habitat creation, the SEAHIVE technology provides a gray-green engineering alternative for coastal solutions codesigned with marine ecologists and local communities.

Top: Destin Beach SEAHIVE deployment. (Photo by N. Stills, Okaloosa County, and Arman Alaverdian, 1Print)

Middle and bottom: ECoREEF and Wahoo Bay SEAHIVE installations, respectively. (Photos by K. Peebles, University of Miami)

The Duwamish River People's Park marsh basin and vegetation nearly one year after cleanup project completion (project details on page 168). (Photo by Port of Seattle)



Riverine Systems

Strengthening and restoring natural waterways

Introduction

EWN principles are being applied in riverine systems around the world to increase the sustainability of infrastructure and to reduce flood risk, restore ecosystems flowing through urban environments, and provide recreational opportunities to local communities, including those considered disadvantaged. EWN is also being implemented to enhance the operation of dams so that downstream habitat and water quality can be improved without affecting the underlying navigation mission of the structures. Other dams are being removed to restore fish passage and increase recreational opportunities. EWN concepts are being combined with built infrastructure in innovative ways that preserve the objectives of that infrastructure while enhancing the ephemeral ecosystem. Strategic placement of dredged material in riverine systems continues to be an increasing means of using nature's energy to enhance habitat value while minimizing effects on navigation in these systems. Many projects in riverine systems are advancing EWN concepts at considerable landscape scales. Nature-based tidal wetlands are being designed and implemented to enhance biodiversity and primary productivity through more resilient ecosystems that also reduce flood risk and provide educational opportunities.

Mission Reach

San Antonio, Texas, United States

Restoring an urban river's riparian and aquatic ecosystem. Throughout the twentieth century, the San Antonio River was heavily modified to mitigate flooding in downtown San Antonio, largely stripping it of its natural ecological function and productivity. A concerted revitalization effort began when Bexar County, the City of San Antonio (CoSA), and the San Antonio River Authority (River Authority) created the San Antonio River Oversight Committee in 1998. The 13-kilometer Mission Reach Ecosystem Restoration and Recreation Project (Mission Reach) was one component of the resulting program that came to be known as the San Antonio River Improvements Project, a $384.1 million investment by CoSA, Bexar County, the River Authority, the San Antonio River Foundation, and the U.S. Army Corps of Engineers (USACE). Completed in 2013, the Mission Reach had three goals: flood conveyance, urban ecosystem restoration (resulting in the largest in the country), and community recreation opportunities. To accomplish this, the team restored the natural pool, riffle, and run sequences; reconnected two historical river remnants; restored natural backwater habitats; and restored the native riparian corridor, including planting over 20,000 young trees. Immediately downstream of the seventh largest city in the country, the Mission Reach is a truly unique amenity where its 500,000-plus annual visitors can see Engineering With Nature in action.

Producing Efficiencies

Historical observations and an extensive network of stream monitoring gauges allowed the project team to evaluate flow conditions in detail prior to design and construction. Knowing the river's flow tendencies through observations and hydrological and hydraulic modeling allowed the team to plan for intense flooding and resulting scouring events. As the river has moved within the project boundaries and additional improvement opportunities have arisen, the team has continued using green infrastructure, including installing toe wood, root wads, and j-hooks to control erosion and provide in-stream habitat. The team eliminated the need for potential future mitigation by disposing of contaminated soils.

Using Natural Processes

Restoration focused on recreating natural riffle, run, and pool sequences and adding embayments for water storage and flood mitigation. The embayments have become much-needed wetland and backwater habitats, capturing sediment from stormwater outfalls and improving water quality through natural filtration processes. Engineered riffle structures aerate the water, providing oxygen for in-stream species and diverting primary flows to encourage smaller microhabitats critical to species like the Guadalupe bass (*Micropterus treculii*). The project also reconnected two historical remnant channels to the main stem, allowing accessibility to these unique habitats that provide further water storage and are home to once-isolated populations of freshwater mussels.

Previous page: The hike and bike trail, paddling trail, and native flowers a few months before the grand opening. Extensive signage is located throughout the site, discussing the importance of the restorative measures employed and various native species. (Photo by River Authority)

Right: Whispers, *a public art installation by Arne Quinze on the west bank of the Mission Reach segment. (Photo by River Authority)*

Broadening Benefits

The Mission Reach was planned, designed, and constructed to provide multiple benefits to an area with tremendous cultural importance; then–Secretary of the Interior Ken Salazar announced support for the project and for the designation of the San Antonio Missions as a UNESCO World Heritage Site. The project channel can contain a 100-year flood event, protecting thousands of residential and commercial properties. Since its opening, more than 200 bird species have been observed at the park, and over five million people have used its trails, pavilions, and picnic areas, providing a major economic boost to an area of town identified as disadvantaged.

Promoting Collaboration

The local leaders appointed to the San Antonio River Oversight Committee oversaw project planning, design, management, construction, and funding. The committee also provided a public forum for citizen input during project development. The most significant partner throughout design and construction was USACE, who funded a substantial portion of the project and worked closely with local engineers and scientists to ensure its success. The San Antonio River Foundation, a nonprofit organization committed to preserving and enhancing the San Antonio River basin, incorporated public art installations along the riverbank. This art recognizes the history of the city, its people, and the river.

Top and middle: Typical scenes of the project site during construction. A traditional trapezoidal channel design was in place for decades. (Photos by River Authority)

Bottom: The project site at dusk. After construction, water quality, habitat, and biological surveys have monitored project performance and documented lessons learned. (Photo by River Authority)

Dahan River

Banqiao District, New Taipei City, Taiwan

Preserving a local ecosystem through a river island approach. The high bank of the Dahan River in metropolitan New Taipei City was the site of a landfill for garbage until 2009, when it was transformed into three artificial wetlands to treat urban sewage prior to discharge into the river. But in recent years, the artificial wetlands have become less effective at purifying that sewage because of dwindling water supplies and various other factors such as land reclamation and the invasion of nonnative species. Furthermore, the high right riverbank has caused the river channel to shift toward the left, affecting riverbank safety. Given the ecological disruptions caused by previous dredging projects, this initiative collaborated with ecological groups and nonprofit organizations through workshops, field surveys, and consultations. This project applied the principles of ecological hydraulics and undertook dredging activities that not only preserved bird habitats but also used local resources to create microhabitats and natural tidal wetlands to minimize its ecological impacts. The experience this project in northern Taiwan provides makes it a valuable reference for other river improvement projects. For its work, the project was given the High Distinction Award at the 4th Engineering Administrative Transparency Awards by the Water Resources Agency, Ministry of Economic Affairs (MOEA), Taiwan.

Producing Efficiencies

Originally constructed as artificial wetlands, the high riverbanks were transformed into natural tidal wetlands upon completion. Dredging and channel widening to preserve the ecologically rich area led to the development of riverine islands planted with cleared vegetation and tree trunks to protect the riverbank for 100 meters, creating a 2-hectare microhabitat. Natural tidal forces were used to create a 4.5-hectare tidal wetland whose gradual slope enhanced connectivity between the main river channel and the high riverbanks, facilitating the movement of living organisms. Two sloping surfaces transformed into vertical cliffs 10 meters long and 2 meters high attract nesting kingfishers (*Alcedo atthis*) and sand martins (*Riparia riparia*).

Using Natural Processes

The project's goal was to enhance local habitats and natural processes. Decaying logs added at the head of an island created to conserve pristine forested areas are exposed at high tide, providing resting and roosting places for birds while stabilizing the shoreline. The natural tidal wetland provides a bare beach for waterfowl and benthos at low tide; the beach floods at high tide, creating a shallow area for fish and other organisms. At low tide, the tidal ditch carries mud and sand to the river's deep main channel, reducing siltation and maintaining habitat for aquatic organisms and waterfowl; the ditch floods at high tide and provides deeper and wider water for fish.

Previous page: Aerial view of the riverine islands—the coexistence of artificial and tidal wetlands. Situated in an urban, population-dense area of New Taipei City, the river channel in this project requires measures to mitigate potential overflow during typhoons or heavy rainfall. (Photo by Water Resources Agency, Ministry of Economic Affairs [MOEA], Taiwan)

Top and bottom: Microhabitat conditions at high tide and low tide, respectively. Debris cleared during dredging is used on site to create microhabitats. (Photos by Water Resources Agency, MOEA, Taiwan)

Broadening Benefits

This project aimed to create a more resilient ecosystem that provides flood prevention, ecological preservation, landscape enhancement, and opportunities for recreation and environmental education. The project cleared 12,000 cubic meters of debris and excavated 200,000 cubic meters of soil from the Dahan River's high riverbank, reducing the risk of flooding and enhancing the river's flood-carrying capacity. The project area's artificial and natural tidal wetlands boast high levels of biodiversity and primary productivity. The forested areas provide resting and roosting places for arboreal birds.

Promoting Collaboration

The project was jointly reviewed and designed by the public and private sectors. During implementation, government agencies, consulting firms, academic institutions, schools, and nongovernmental and nonprofit organizations were invited to participate. Multiple field surveys, ecological assessments, and workshops were organized, and stakeholder feedback was fully considered before proceeding to the planning phase. Progress during construction was shared on a web platform to encourage public participation and address any concerns. Further, local teachers and students were invited to visit for environmental education and community outreach.

Top: A close-up of the microhabitat at the time of completion. (Photo by Water Resources Agency, MOEA, Taiwan)

Bottom: Creation of habitat for kingfishers and sandpipers. Traditionally, dredging projects focused solely on widening the river channel. In contrast, this project implements a river island approach, aiming to preserve the existing local ecosystem to the greatest extent possible. (Photo by Water Resources Agency, MOEA, Taiwan)

Des Moines River

Iowa, United States

Changing navigation infrastructure to improve water quality and fish and wildlife habitat. The Sustainable Rivers Program (SRP) is a national partnership between the U.S. Army Corps of Engineers (USACE)–Rock Island District and The Nature Conservancy (TNC) to improve rivers by changing dam operations to restore and protect ecosystems while maintaining or enhancing authorized uses. For USACE, SRP focuses on environmental opportunities at existing water infrastructures. The Des Moines River (DSMR) SRP sought to apply those goals on the river and at Lake Red Rock and Saylorville Lake, USACE reservoirs in Iowa on the DSMR, a tributary of the Mississippi River. Efforts include flood risk management, recreation, low-flow augmentation, water supply, and fish and wildlife management. DSMR has been active in the SRP since 2015 and has accomplished several projects that advance environmental water management principles. One of the first steps of the DSMR SRP was conducting a literature review and summarizing initial hypotheses and recommendations related to the natural and current deviations in durations, frequencies, and variances from one condition to another for a variety of environmental flow components (e.g., flood pulses and low and high flows).

Producing Efficiencies

The team developed an adaptive management and monitoring plan (AMMP) to address in-lake water-level management strategies and environmental flows downstream of the dams to support bird, fish, and mussel life cycles. Concepts from the AMMP were incorporated into management options for the revised *Lake Red Rock Regulation Manual.* Applying SRP on the DSMR allows reservoir and water control managers to use environmental pool (e-pool) and environmental flow (e-flow) to positively influence the lake or downstream from the dam, improving the aquatic environment. The AMMP achieves ecological benefits through minor modifications in the water regulation strategies of existing infrastructure without incurring additional operations costs.

Using Natural Processes

The project team sought natural aquatic management strategies, e-flows, and e-pool to improve water quality and reduce nutrients going into the lake. The team partnered with Iowa State University (ISU) to evaluate waterbird stopover ecology in the reservoir delta, including tracking shorebirds locally and globally. This work also included assessing vegetation and invertebrate responses to e-flows to further determine wildlife needs. The project also focused on the effects of e-flows on downstream fish and mussel dynamics and included a two-year field study on mussel assemblages and impacts from the Red Rock dam. ISU researchers sought to assess the effects of the experimental flows on fish reproduction in the lower DMSR, with results to be incorporated in an adaptive management framework.

*Previous page: Marbled godwit (*Limosa fedoa*) in the Lake Red Rock delta during summer drawdown. (Photo by Stephen J. Dinsmore, Iowa State University [ISU])*

Right: Shorebird gala at Lake Red Rock delta. In 2021, 2022, and 2023, three "spring pulses" (an intentional pulse of flow from the Red Rock dam to stimulate downstream fish spawning and freshwater mussel recruitment) were conducted. (Photo by Stephen J. Dinsmore, ISU)

Broadening Benefits

DSMR SRP aimed to lower nitrate levels, reduce harm and improve conditions for various animal and fish species, minimize streambank erosion, and improve recreational conditions. Because revision of the reservoir's water control manuals coincided with AMMP's creation, three phases of the SRP process were performed sequentially at no additional cost. The manuals now include flexibility to adopt SRP prescriptions when practicable as well as seasonal conservation bands for pool and outflows to support aspects of the natural flow regime. The Iowa Geological Survey completed a literature review and sampling showing that the reservoir has reduced nitrates by 12.4%.

Promoting Collaboration

Collaboration with partners and stakeholders has been a hallmark of the DSMR SRP since its inception in 2015. In 2016, the SRP team hosted a stakeholder workshop for scientists, biologists, resource managers, and others from state and federal agencies, universities, and conservation-oriented private organizations. The team partnered with the Natural Resources Conservation Service and others to reduce nutrient inputs to the DSMR system. The project benefited from many other partnerships, including those with TNC, the U.S. Geological Survey, ISU, the University of Iowa, the Iowa Department of Natural Resources, and the Engineering With Nature program.

*Top: Tracking least sandpipers (*Calidris minutilla*) in the Lake Red Rock delta. (Photo by Stephen J. Dinsmore, ISU)*

Middle: Least sandpiper tagged with a radio transmitter. (Photo by Stephen J. Dinsmore, ISU)

Bottom: Lake Red Rock delta and emerging vegetation. Vegetation changes were documented to describe diversity and relative abundance of the emerging plant species. (Photo by Nicole Bosco, ISU)

Arden Park

Edina, Minnesota, United States

Restoring fish passage and recreational opportunities through dam removal. Arden Park lies along Minnehaha Creek, a tributary of the Mississippi River, flowing from Gray's Bay Dam on Lake Minnetonka through the first-ring Twin Cities suburb of Edina, which is located just southwest of Minneapolis. Efforts were sought to improve the six-hectare park and to restore a section of the creek, which is included on the State of Minnesota's Impaired Waters List and has been impacted by years of urbanization. The Minnehaha Creek Watershed District and the City of Edina partnered to analyze and design a restoration plan for Arden Park. Working with the design team at Inter-Fluve, the project involved removing a dam to restore fish passage and natural stream function, planting trees, restoring and remeandering over 610 meters of the creek, enhancing wildlife habitat and natural vegetation, improving water quality by treating over 40.5 hectares of untreated urban runoff, and considering a range of potential future flow conditions. Additionally, because of its prominent location in the metropolitan area, the project included significant public outreach efforts to capture community goals and sentiment relative to the existing park and dam. An extensive and well-planned public engagement campaign was key to the planning, design, and construction of the project in 2020. For its work, the project received the 2022 National Recognition Award from the American Council of Engineering Companies–Minnesota Chapter.

Producing Efficiencies

A complex aspect of the new stream design was the promotion of natural geomorphic processes within a channel partially restricted by adjacent site constraints. Through process-based design and natural dynamics, the new design protects infrastructure while fostering a “wild” river that maintains dynamic pools and riffles and promotes aggradation of bars and sediment-transport processes. The creek’s hydraulics—partially regulated by the Gray’s Bay Dam on Lake Minnetonka, the creek’s headwaters, to manage flooding, sustain aquatic habitat, moderate stormwater inputs, and support recreational usage—also required unique design attention to potential current and future flow conditions under the changing climate.

Using Natural Processes

Urban restoration projects often battle pervasive invasive species. In addition to removing existing terrestrial invasive species (and continually treating and managing their removal), this project was specifically designed to allow native species to outcompete them. Changes to light and soil moisture conditions allowed a range of native floodplain vegetation to germinate from the seedbank, replacing monocultures of reed canarygrass (*Phalaris arundinacea*). Additionally, the dam at Arden Park happened to have ideal conditions for invasive carp (*Cyprinus*). By removing the dam and creating a series of smaller pools with moving water, the design now nurtures a full ecosystem for native fishes.

Previous page: Process-based design and natural dynamics were used for the revamped channel at Arden Park. (Photo by Inter-Fluve)

Right: The project included the planting of trees, shrubs, and plugs to restore the native ecology and define boundaries between the landscaped areas and the “wilder” restoration areas. (Photo by Inter-Fluve)

Broadening Benefits

Arden Park is now a thriving park and urban oasis that offers an immersive nature-based experience and provides improved and increased access to a multitude of recreational opportunities, such as kayaking, paddleboarding, tubing, walking, ice-skating, and fishing. The project also enabled the construction and expansion of almost two kilometers of accessible trails and boardwalks, an updated outdoor skating area, and a new park shelter. The restoration aligned with the need for outdoor spaces during the outset of the COVID-19 pandemic, and it was not uncommon for hundreds of people to be enjoying the park's recreational opportunities throughout the year.

Promoting Collaboration

The project necessitated complex coordination and collaboration between various stakeholders. There were several rounds of master planning and conceptual design, including stakeholder and board meetings, city council presentations, and multiple iterative design deliverables and reviews. Concerns and feedback about changes to the beloved park were considered in planning and design, and several skeptical adjacent residents became vocal supporters of the renovated park. All design team members—hydraulic engineer, civil engineer, and landscape architect—were required to understand the full scope of the site restoration plans to work cohesively to progress the design in real time.

Top: A dam was removed to improve paddler passage, fish passage, water quality, and creek geomorphic function. The design incorporated small pools with moving water to remove carp habitat and replace it with native fish habitat. (Photo by Inter-Fluve)

Middle: Construction of the boardwalk that runs through Arden Park. (Photo by Inter-Fluve)

Bottom: The stormwater treatment facility was designed to maintain multiple benefits, including the treatment of previously untreated stormwater and the support of pollinator species. (Photo by Inter-Fluve)

Winfield Locks and Dam

WINFIELD, WEST VIRGINIA, UNITED STATES

Placing dredged material for mussel recruitment. Maintenance at Winfield Locks and Dam on the Kanawha River, a tributary of the Ohio River and a commercially navigable river monitored by the U.S. Army Corps of Engineers (USACE)–Huntington District, is an example of efficient and sustainable use of dredged material. The navigation channel downstream of the locks requires regular maintenance dredging due to continuous shoaling. The dredged material is placed against the opposite bank on the outside bend of the river, creating a velocity shelter that accumulates and maintains preferred substrates for mussels. Before the site was modified in the mid-2000s, the adjacent habitat was dominated by a large section of bedrock and boulders providing poor substrates for various mussel species. This nature-based velocity shelter has helped stabilize the habitat, and the material itself provides a source of clean sands and gravels that migrate downstream to provide the necessary substrates for mussel colonization. Since placement began, survey results have shown an increase in the areas covered by silt, sand, gravel, and cobble. This habitat enhancement has coincided with increases in mussel density and diversity. Because of its habitat transformation and mussel recruitment, the natural resource agency partners have requested that the district prioritize the use of the site.

Producing Efficiencies

The realized efficiencies are notable, especially due to the development of a velocity shed using dredged material from the adjacent navigation channel. Multiple placement efforts have shielded downstream velocities from returning substrates to the previous hard-bottom strata that prevented mussel-bed establishment. Subsequent placements have seeded the area with finer and more beneficial material. The channel's decreased size due to the island bar creates potential for increased velocity and subsequent decreased sedimentation of material shoaled in the channel. Reducing the placement distance of dredged material also reduces transport cost, making placement at the project site the least-cost placement alternative.

Using Natural Processes

The hydrodynamic forces created on the outside bend below Winfield originally resulted in the substrates being stripped to bedrock. When paired with this dredge placement operation, these same forces are now creating sustainable mussel habitat. Five surveys from 2002 to 2023 showed a gradual change in the primary substrate near the Winfield placement area from large boulders and bedrock to areas of silt, sand, gravel, and cobble inhabited by mussels. These data indicate that the dredge placement combined with downstream dispersion of the placed sediment by the river's energy are providing beneficial habitat to promote mussel beds. Early surveys showed only four to seven species present throughout the site, while the most recent survey found diversity had risen to 16 species of native mussels.

Previous page: After construction, the placement pile remains an emergent feature until higher river flows smooth it over. (Photo by USACE Huntington District)

Right: Higher flows smooth the coarse-grained sands of the Winfield Lower Approach disposal area. These coarse materials help to stabilize the feature and provide a source of suitable substrate for downstream mussel beds. (Photo by USACE Huntington District)

Broadening Benefits

Maintenance dredging creates the annual need for placement locations that are cost-efficient, environmentally acceptable, and reusable. The Winfield location demonstrates that, sometimes, dredge placement areas can benefit the local ecology. The material's ability to stabilize and sustain a mussel resource at Winfield has initiated a search along the Kanawha River for similar locations. Local historical characterizations of dredged material placement as harmful have given way to the possibility that significant ecological benefits can come from the careful selection of placement sites. The Winfield site will benefit the continued maintenance of the navigation channel and the river's mussel resources.

Promoting Collaboration

The district's approach to managing dredged material to support and enhance mussel-bed habitat near the project location was substantially advanced through coordination and collaboration with various state and federal stakeholders (West Virginia Department of Natural Resources, West Virginia Department of Environmental Protection, and U.S. Fish and Wildlife Service). Each year, this group of partners discusses recent dredging operations, future plans, water-quality analyses, mussel surveys, protected species, and changing protocols. Effective communication within the group has resulted in a Water Quality Certification from the West Virginia Department of Environmental Protection and the agreement about the continued use of this placement site over others due to its positive impact on mussel habitat in the river.

Top: The Winfield Lower Approach placement area sits along the left descending bank downstream of the Locks and Dam. It is situated just landward of the navigation channel. (Photo by USACE Huntington District)

Bottom: A back channel is maintained behind the placement feature to allow for additional aquatic habitat. (Photo by USACE Huntington District)

Duwamish River People's Park

Seattle, Washington, United States

Restoring a legacy industrial Superfund site. Over two decades ago, the Port of Seattle initiated the largest Duwamish River shoreline restoration project in a generation. A property known as Terminal 117 was transformed from a legacy industrial site with armored shorelines and contaminated soils to an approximately six-hectare habitat site with public shoreline access known as the Duwamish River People's Park and Shoreline Habitat (DRPP). DRPP represents the collaborative power among Duwamish Valley residents, government agencies, and tribes. The project had three critical goals: clean up a highly contaminated site, stabilize the shoreline and restore resilient habitat, and create river access in an environmental-justice neighborhood. A century of industrialization had dramatically reshaped the river and community, and nearly all wetlands and natural resources were lost. At the restored site, critical salt-marsh habitat has increased by 40%, with an encouraging number of juvenile salmon counted. Residents are also enjoying public access. Cleanup removed pavement, structures, and 54,431 tonnes of soil and sediment. Afterward, over 40,000 native plants, a viewpoint pier, trails, art, treaty-fishing piling, and a boat launch were installed. The restored habitat site also serves as a learning lab for youth seeking hands-on experience. As the DRPP flourishes, it will remain a park "for the people."

Producing Efficiencies

The Terminal 117 restoration project included large-scale excavation to remove industrial fill material that had previously displaced estuarine aquatic area. Removal of decades-old fill materials successfully restored intertidal and shoreline elevations at the project site, reestablishing elevations critical to ensuring growth of self-sustaining intertidal marsh vegetation and providing area important for creating riparian buffer resources. Large-scale excavation and grading included installation of anchored large-wood edge logs in fractured rock bolsters along the entire waterward margin of the project. The large wood stabilizes the site while providing habitat complexity.

Using Natural Processes

To create the habitat, the site elevation was excavated approximately four vertical meters, working down from contemporary street level to the historical marsh level of the river to reexpose vital estuarine aquatic area. The goal was to create high-value fish and wildlife habitat, including improved shoreline and off-channel marsh, important for salmon and other fish species. To encourage sediment deposition, coir fabric was placed in the marsh basin. The project is anticipated to provide significant estuarine and aquatic services currently scarce in the waterway. Over 20,000 native marsh plants and almost 20,000 native riparian trees and shrubs were installed.

Previous page: Duwamish River People's Park and Shoreline Habitat (DRPP) shoreline habitat shortly after construction, featuring use of large wood to stabilize the shoreline, with Mount Rainier in the background. (Photo by Port of Seattle)

Right: Use of large wood to stabilize the shoreline along the river channel. (Photo by Port of Seattle)

Broadening Benefits

The river has always been an active cultural area for indigenous people, who continue to practice treaty-fishing rights and harvest returning salmon every season. The universal public access and recreation area creates an important community connection to the river. Environmentally, the DRPP contributes to salmon recovery in the region, which can also support the endangered southern resident orca (*Orcinus orca*) population. Finally, the project applied an innovative financing model and established the Port's first mitigation banking site, enabling third parties to purchase credits to help them comply with federal regulations. Revenue will fund additional habitat-restoration projects.

Promoting Collaboration

Once the lower Duwamish Waterway was designated a Superfund cleanup site, the Port and key interested parties started a decades-long working relationship that grew to include community members and ultimately shaped the transformation of the site. The Port, the Boeing Company, the City of Seattle, and King County formed the Lower Duwamish Waterway Group, a public-private partnership to determine the extent and risks of the contamination. In addition to the planned cleanup and restoration, the community requested green space and a connection to the river, and the Port opened a local field office to collect their feedback and design input.

*Top: Port staff and partners during monitoring and sampling at the DRPP habitat site, where an osprey (*Pandion haliaetus*) nest is visible in the background. The first year of monitoring found promising results and recorded over 7,000 juvenile chum salmon (*Oncorhynchus keta*), 243 juvenile, natural-origin Chinook salmon (*Oncorhynchus tshawytscha*), 922 nonsalmonid fish, and robust marsh vegetation, including bulrush (*Scirpoides holoschoenus*), beachgrass (*Ammophila breviligulata*), and an expanding blanket of wetland emergent plants. (Photo by Port of Seattle)*

Bottom: Duwamish River People's Park 2022 opening celebration. (Photo by Port of Seattle)

Kinzua Dam

Warren, Pennsylvania, United States

Simulating spring pulses for ecological benefits. The Kinzua Dam is part of the National Wild and Scenic Rivers System and home to several threatened and endangered mussel species. The implementation of a "spring pulse" in March 2023 on the Allegheny River in northwestern Pennsylvania provided an environmental flow (e-flow) release that delivered ecosystem benefits for areas downstream of the dam. A collaboration between the U.S. Army Corps of Engineers (USACE)–Pittsburgh District, The Nature Conservancy, the U.S. Geological Survey (USGS), the University of Pittsburgh, and other federal and state partners, the spring pulse was the culmination of years of research into "flow targets" that mimic the timing, quantity, and quality of preimpoundment flow regimes. The e-flows provide numerous riverine and riparian ecological benefits, like supporting habitat conditions for vegetation, fish, and mussels; seed dispersal; moisture regimes; sediment distribution; and nutrient delivery. A recent rain event provided the volume of water of the spring pulse, which water managers used to model the pulse's impacts to the Allegheny Reservoir and downstream reaches of the Allegheny River to ensure no detrimental effects were experienced by either. The increased flows produced by the spring pulse were observed and documented by multiple sampling efforts throughout the event.

Producing Efficiencies

Implementing e-flows provides numerous ecosystem benefits with few additional costs to normal operations. By using existing information sources and technology, water managers can analyze incoming weather events and then model and account for the impacts on the reservoir and downstream river reach to decide whether a pulse event is possible within authorized reservoir operations. The operations that facilitate the e-flows provide benefits that improve ecosystem function, offer more desirable recreation resources, and contribute to the environmental health and economy of the surrounding areas.

Using Natural Processes

E-flows, such as spring pulses, restore ecological function to the river by reestablishing natural processes associated with more significant flows for sustained periods that were part of the natural flow regime before the construction of Kinzua Dam. As a result, e-flows provide numerous riverine and riparian ecological benefits, such as supporting habitat conditions for vegetation establishment and growth, seed dispersal, moisture regimes, sediment distribution, nutrient delivery, increased aquatic habitat and connectivity for riverine fish and mussels, and fish spawning cues.

Previous page: The Kinzua Dam released roughly 425 cubic meters of water per second for 8 hours, resulting in 12 million cubic meters of water released into the river. (Photo by Andrew Byrne, USACE Pittsburgh District)

Right: A section of the Allegheny River is inundated with higher-than-normal water levels from the Kinzua Dam during a "spring pulse" in Tidioute, Pennsylvania, on March 30, 2023, to simulate the natural phenomena that typically occur in temperate climates and during early spring, sending cues to aquatic species and other parts of the ecosystem by moving sediments and nutrients. (Photo by Kristi Dobra, USACE Pittsburgh District)

Broadening Benefits

The social, environmental, and economic benefits of e-flows provide the natural disturbance necessary for healthy and aesthetically pleasing riparian and riverine settings that enhance social recreational opportunities like water sports, camping, and fishing. Environmental benefits and ecosystem services include more habitat opportunities for freshwater mussels that filter the water and increase clarity and the propagation of riparian plant species that buffer and still high-flow events and provide fish habitat and atmospheric oxygen. Economic benefits include making these areas more desirable locations for those seeking recreational tourism opportunities and providing cleaner water that requires less treatment for downstream uses.

Promoting Collaboration

Since 2014, the project has fostered valuable relationships and remarkable cooperation between federal, state, local, and public partners. Coordination between stakeholders at monthly meetings and workshops was critical in developing an adaptive e-flow management and monitoring plan. Collaboration with numerous stakeholders—among them The Nature Conservancy, the Sustainable Rivers Project, the U.S. Fish and Wildlife Service, USGS, the U.S. Forest Service, the Western Pennsylvania Conservancy, the Pennsylvania Fish and Boat Commission, the Pennsylvania Department of Environmental Protection, and the University of Pittsburgh—has been integral to the success of developing and implementing e-flow prescriptions and monitoring techniques.

Top: An inundated section of the Allegheny River during a spring pulse. The district's water management team modeled the operation to ensure the artificial pulse would not impact the reservoir's summer pool or cause flooding. (Photo by Kristi Dobra, USACE Pittsburgh District)

Bottom: USACE Pittsburgh District environmental resources specialist Kristi Dobra holds a freshwater mussel found in the Allegheny River in Warren, Pennsylvania. (Photo by Andrew Byrne, USACE Pittsburgh District)

Lake County Ravine 8

Highland Park, Illinois, United States

Stabilizing a stream's hydrology and restoring habitat. The Ravine 8 project area is about two hectares, primarily consisting of one ravine with an ephemeral stream and smaller areas of Lake Michigan bluff and foredunes. Because of urbanization and storm events, the ravines along the north shore of Lake Michigan have been used as conduits for both open-channel stormwater and piped sanitary sewers, causing erosion and loss of habitat. The City of Highland Park and the U.S. Army Corps of Engineers (USACE)–Chicago District partnered under the Great Lakes Fishery and Ecosystem Restoration program to restore the ecological integrity of Ravine 8 while considering the preservation of critical infrastructure. At the project's outset, the City replaced the broken sanitary sewer and separated the stormwater to discharge into the ravine. The partnered Section 506 project then used Engineering With Nature (EWN) features within the stream channel by installing robust step-pools of glacial and river stone in steep sections and seeded a sediment (coarse sand and pea gravel) source for the new stream to transport during floods. Coupled with native plant restoration, this EWN methodology ensured channel stability for continued human uses while providing native ephemeral stream and riparian woodland habitats. Removal of a small dam and invasive plant species eradication were also included. The project was completed in 2019.

Producing Efficiencies

The project used the most up-to-date science of what riverine ecosystems and species require, coupled with hydraulic engineering to ensure continuation of human use and existing infrastructure. Periodically, about every three to five years, placing a relatively small amount (almost four cubic meters) of coarse sand and small gravel at the head of the ravine ensures sediment transport is satiated to prevent erosion of the downstream ravine banks. This also provides the ravine stream bottom with coarse substrate to help with stability. Clearing out weed trees and shrubs also opened the canopy of the degraded woodland, which allowed for a native understory to establish to further stabilize ravine slopes and banks.

Using Natural Processes

An important part of riverine habitat restoration includes considering sediment input and transport. Sediment primarily enters a river channel via surface erosion. Because of urbanization, there is no longer surface erosion in the Ravine 8 watershed. Surface erosion of the banks and ravine slopes is part of the natural channel evolutionary process, in which a geologically mature ravine with perennial stream would form. This is a positive source of river sedimentation, providing the right amount and types of substrate input typically transported as bedload to form the basis of benthic habitat, substrates, and channel features. Because ravine slopes cannot be allowed to naturally erode, threatening bordering homes, a sediment transport source has ameliorated erosion to date.

Previous page: Sand stream and native vegetation restored with a sanitary sewer underneath. Native plant communities will continue to establish, becoming more active in stabilizing the ravine stream and woodland habitats. (Photo by Robbie Sliwinski, USACE Chicago District)

Top: Preproject surface erosion and sewer blowout. (Photo by Frank Veraldi, USACE Chicago District)

Bottom: Preproject sheetpiled mouth with blown-out best management practices. (Photo by Frank Veraldi, USACE Chicago District)

Broadening Benefits

This project has provided social, environmental, and economic benefits to the residents that live along the ravine. Social benefits include an awareness of who is living on the ravine and how certain individual actions along the ravine affect everyone. Economic benefits include prolonged protection of critical infrastructure, properties, and homes. Values of a land parcel typically increase with beautified nature and ensured stability to home structures. Ecosystem benefits provided by this project include ravine dynamics, stream geomorphology and habitat, native plant communities, invasive species eradication, connectivity, restoration of sloped wetland communities, and increased native species richness and abundance.

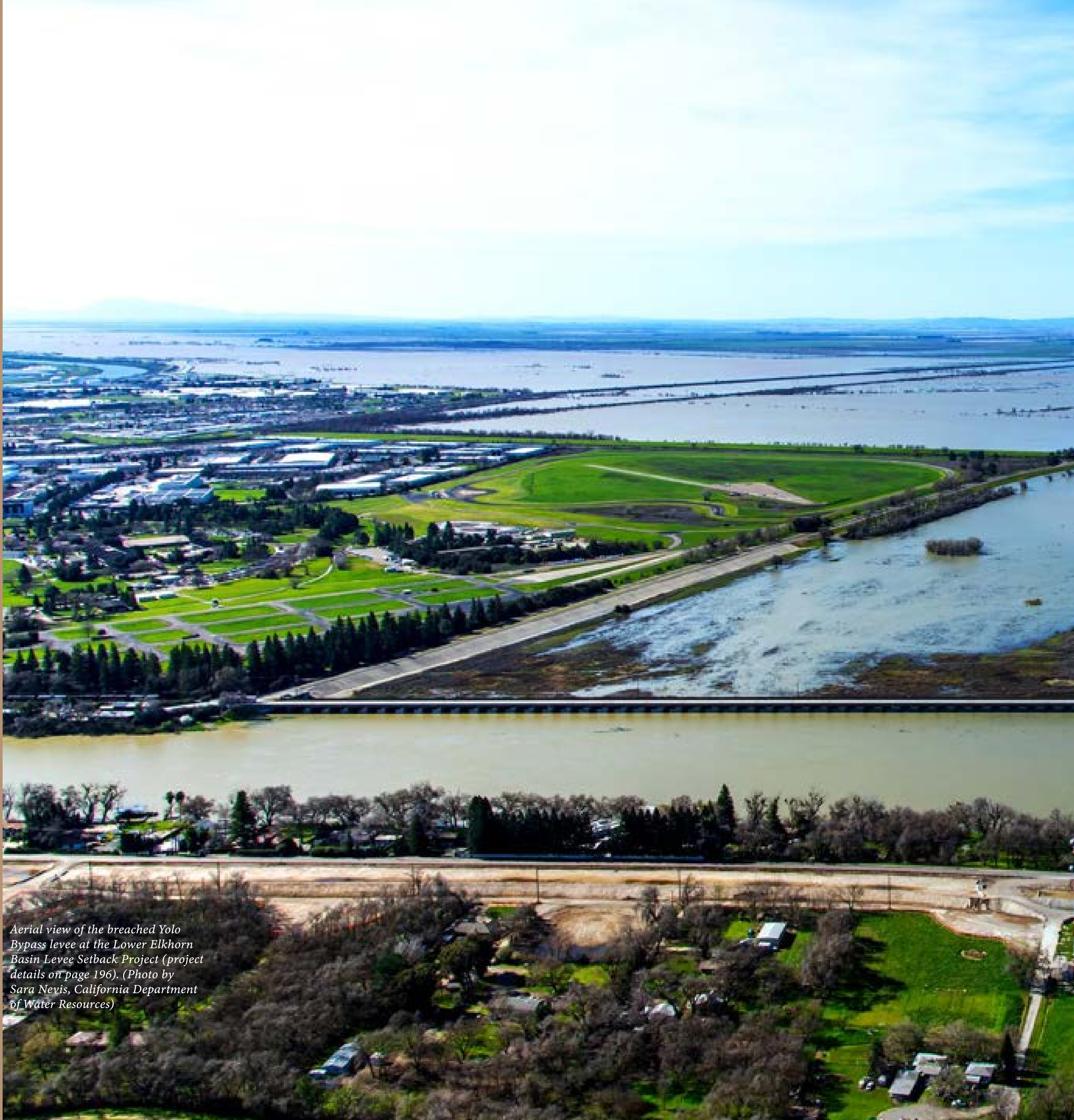
Promoting Collaboration

To accomplish this cost-shared project, temporary easements from over 10 landowners were acquired by the nonfederal sponsor, the City of Highland Park. The city diligently worked to focus the interest of the land- and homeowners along the ravine to foster a consensus that the federally led restoration project was the right action for the ravine ecosystem and the people who live along it. The nonfederal sponsor will continue postconstruction monitoring through 2025.

Top: Nature-based sand transport being restored. (Photo by Frank Veraldi, USACE Chicago District)

Middle: Nature-based step pools and substrates. (Photo by Frank Veraldi, USACE Chicago District)

Bottom: Restored bluff and stream outlet. Since 2016, Ravine 8 has been stable enough to maintain healthy ephemeral stream and woodland habitats while providing a protective layer to the subsurface sanitary sewer system. (Photo by Robbie Sliwinski, USACE Chicago District)



Aerial view of the breached Yolo Bypass levee at the Lower Elkhorn Basin Levee Setback Project (project details on page 196). (Photo by Sara Nevis, California Department of Water Resources)

Floodplains

Reducing flood risk through natural processes

Floodplains

Introduction

Many of this chapter's EWN projects implemented in floodplains in the United States and the United Kingdom seek to enhance environmental benefits. A central focus of these projects is enhancing habitat value for anadromous and other native fish species. Other projects are benefiting from indigenous knowledge to restore floodplains and floodplain islands by using dredged material to reclaim riparian forest habitat function and to increase present and future project value. A key component of floodplain projects is reconnecting streams with their historical floodplains to restore native habitat function. Levee setbacks can be key to the success of such projects. Benefits often achieved when applying EWN principles in floodplains include increasing flood resilience, enhancing biodiversity, reversing past conventional infrastructure practices, restoring habitats, increasing carbon capture, and building awareness of nature-based solutions through education and public access.

Buffalo Slough Island

Welch, Minnesota, United States

Increasing island stability, floodplain forest health, and habitat abundance. Construction of the Mississippi River's almost three-meter navigation channel affected cultural resource sites, including lands belonging to the Prairie Island Indian Community (PIIC). Factors impacting historic properties include natural environmental processes, accelerated geomorphic processes due to altered hydrology, maintenance and operation activities required for the continued management of the Upper Mississippi River for navigation, and population and community growth. Therefore, after the completion of a feasibility study, the U.S. Army Corps of Engineers (USACE)–St. Paul District and the PIIC signed a project partnership agreement in February 2021 to design and construct a project to restore Buffalo Slough Island in Sturgeon Lake. Construction occurred from 2021 to 2023, completed by the district's maintenance and repair crew. It included a rock bullnose at the north end of the island to prevent erosion and rock vanes with an access berm along the eastern side of the island to minimize bank erosion and serve as nesting and shelter habitat for birds, reptiles, and mammals. In addition, the island elevation was raised by placing granular material dredged from the main navigation channel on the island, encouraging the growth of native trees and supporting a floodplain forest habitat.

Producing Efficiencies

Shoreline protection measures were designed to prevent the loss of terrestrial and riparian habitat: a rock bullnose at the north end of the island to prevent erosion; angled rock vanes along the eastern side of the island to redirect flows away from the island, further preventing erosion; and a sand berm to increase the eastern side island's physical size, providing land for planting grasses and trees and serving as nesting shelter and habitat for birds, reptiles, and mammals. The project provided the opportunity for beneficial use of dredged material by dredging the roughly three-meter navigation main channel of the Mississippi River for granular material.

Using Natural Processes

Restoration of floodplains in this portion of the Upper Mississippi River is most commonly accomplished by topographic diversity (ridges and swales in the landscape) and reforestation. To achieve an acceptable elevation that supports a mature forest stand that is flood tolerant and sustains a floodplain forest habitat, the elevation of the island was raised approximately 0.3 to 0.6 meter by placement of dredged material from the Mississippi River. A marina on PIIC's property was also dredged for fine material. The use of dredged material smothered the invasive reed canary grass (*Phalaris arundinacea*) while bringing the island to a suitable elevation.

Previous page: Buffalo Slough Island after completion of construction and subsequent planting of native trees and understory vegetation. (Photo by Lewis Wiechmann, USACE St. Paul District)

Right: USACE St. Paul District Maintenance and Repair crew building the sand bench along the eastern (riverward) side of the island. The sand bench was a necessary feature for tying in rock vanes to deflect flow and prevent island erosion and serves as nesting and shelter habitat for birds, reptiles, and mammals. (Photo by Kimberly Warshaw, USACE St. Paul District)

Broadening Benefits

Preserving and restoring river resources is of national interest due to their scarcity and role in the life cycle of native and protected flora and fauna. The upper Mississippi River ecosystem consists of hundreds of thousands of hectares of forests, islands, waterways, and wetlands, supporting hundreds of animal and plant species. The PIIC identified significant tribal resources in and around Sturgeon Lake and Buffalo Slough Island important to their cultural heritage: a healthy floodplain forest providing nesting trees for bald eagles (*Haliaeetus leucocephalus*), emergent vegetation for the tribe's food and medicine, fisheries for recreation and cultural sustenance, and a healthy waterfowl migratory corridor.

Promoting Collaboration

This is only the second project in the nation to complete design and construction under the USACE Tribal Partnership Program, which aims to identify and assist with water resources projects that will significantly benefit Native tribes. In addition to the USACE St. Paul District, the project team included the PIIC as the project sponsor. The team also engaged the Minnesota Department of Natural Resources and the Wisconsin Department of Natural Resources to provide subject matter expertise in Sturgeon Lake and on ecosystem restoration projects.

Top: The head of Buffalo Slough Island before the bullnose was built. The island was eroding, roots were exposed, killing trees, and the island was overrun with invasive reed canary grass. (Photo by Aaron McFarlane, USACE St. Paul District)

Middle: Rock was placed on the head (north end) of the island to create a bullnose to deflect the river's energy and limit flow erosion. (Photo by Kimberly Warshaw, USACE St. Paul District)

*Bottom: The presence of a healthy floodplain forest providing nesting trees. Mature cottonwoods (*Populus*), particularly, provide habitat for bald eagles, which are an important species to the Prairie Island Indian Community. (Photo by Lewis Wiechmann, USACE St. Paul District)*

Lower Dungeness River

Clallam County, Washington, United States

Restoring a floodplain by using nature-based solutions. Built in the 1960s, the old U.S. Army Corps of Engineers (USACE)–authorized Dungeness River levee created unintended consequences for river processes, flood risk, and aquatic habitat. In response to the original levee being built on the opposite bank, the river became constrained, resulting in a straighter channel, increased water velocities, an aggraded riverbed, reduced habitat for aquatic organisms, and an overall decline in the effectiveness of the levee. A partnership between Clallam County, the Jamestown S'Klallam Tribe, USACE, state and federal agencies, local nonprofits, and the surrounding community, the Lower Dungeness Floodplain Restoration Project sought to remove part of the old levee, build a setback levee, and relocate a road bisecting the floodplain. As envisioned in the late 1990s by the Dungeness River Management Team, a local watershed council, the restoration project took many years to come to fruition. Necessary funds were awarded through grants. Construction occurred in 2021 and 2022. The project reconnects the lower Dungeness River to 71 hectares of historical channels and floodplain, helping restore habitat processes along one of the most important river systems on the Olympic Peninsula in Washington State. The project reduces flood risk and benefits over 100 fish and bird species, including four species of endangered salmon. For its nature-based approach, the project has received awards from the North Olympic Land Trust, Floodplains by Design, American Council of Engineering Consultants, and American Society of Engineers.

Producing Efficiencies

The project addressed high sedimentation rates impacting levee reliability and flood risk by giving the river access to the floodplain. This spreads out the area for deposition and increases conveyance, reducing flood elevations and risks. Nature-based solutions used included levee setbacks to naturally restore the floodplain by letting the river create new side channels and wetlands (that increase storage of fine sediment, nutrients, and carbon), hard infrastructure (road) relocation, and additions of large wood and engineered logjams to manage the rates of bank erosion and floodplain reoccupation by the river. The setback levee also reused portions of the existing levee, reducing the need to import levee fill material and saving on cost.

Using Natural Processes

Providing access to the historical channels and floodplain by removing the old levee and relocating the road has resulted in increased use of the site by fish and wildlife species known to use the river corridor for spawning, nesting, rearing, and migration. Redistribution of water and other materials such as wood and sediment has increased habitat availability and quality by reducing flood velocities during high flows and storing water during low flows, as well as redistributing sediment over a much wider floodplain. River flooding and vegetation recruitment enabled by the project naturally restore existing channels and the reconnected floodplain.

Previous page: Aerial view of project-engineered logjam natural and nature-based features during flooding in December 2022. (Photo by John Gussman)

Right: Panorama of the Dungeness River delta and Lower Dungeness River Floodplain Restoration project. (Photo by John Gussman)

Broadening Benefits

The new levee and restored site are a focal area for recreational activity, including hiking, biking, dog walking, and bird-watching, increasing community involvement and buy-in. The upstream portion of the setback project was enabled by acquiring 26 hectares of floodplain that had been converted to agricultural use. The tribe committed to purchasing agricultural easements on 52 hectares (2:1 ratio) within the area to help provide stability for agricultural producers and offset any perceived impact of restoring the floodplain. The project is expected to improve the Dungeness chinook salmon (*Oncorhynchus tshawytscha*) escapement, likely translating to increased fishing opportunity in marine waters downstream.

Promoting Collaboration

The project required ongoing collaboration between partners, interested groups, and the community. Multiparty meetings were held regularly during the engineering, design, and permitting phases. Monthly meetings of the Dungeness River Management Team offered a forum for regular updates and emerging topics. Subject-specific public meetings were held to gather community input to the project. Informal one-on-one conversations between project partners often occurred and played an important role in a small community. When a specific topic required further investigation, a technical work group convened to study and offer recommendations to the larger group.

Top: Aerial view of Dungeness River and delta, including federal levee (right bank), private levee (left bank), and project area prior to levee setbacks. (Photo by Jamestown S'Klallam Tribe)

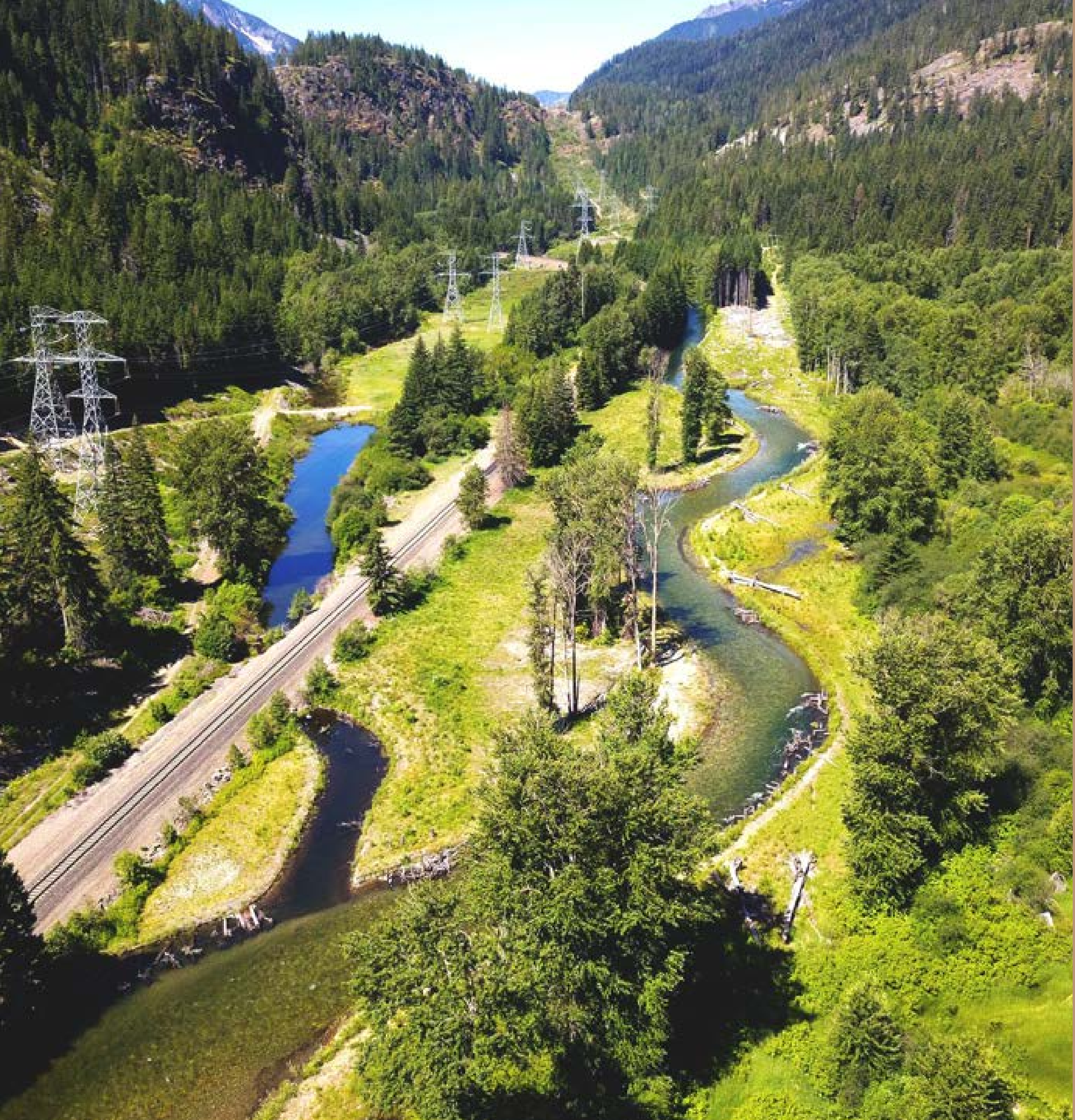
Middle: The channel flowing across the footprint of the old levee upstream of the first engineered logjam complex. (Photo by Randy Johnson)

Bottom: Scour pool located at the engineered logjam complex in May, showing the value of engineered logjams to create deep and extensive pools for fish, especially during years of drought. (Photo by Gus Kays)

Nason Creek

Merritt, Washington, United States

Reconnecting a stream to its historical floodplain. In the 1950s, the formerly meandering Nason Creek was straightened into a confined channel hemmed in by a railroad, a levee, and powerlines. The once-abundant salmon habitat was lost. The river could no longer access its floodplain, severely degrading the ecological conditions that well-connected floodplains provide for fish, wetlands, water quality, and flood control. Therefore, Chelan County initiated a multiphase effort in 2014 to remove and relocate human constraints and to restore the river and floodplain habitats. This included removing a levee, rerouting a power line corridor, and creating almost one kilometer of a new meandering stream channel reconnected to a vegetated floodplain. Construction occurred in multiple phases from 2016 to 2018. Specific project accomplishments included relocating over one kilometer of Chelan Public Utility District's powerlines out of the floodplain, creating a new sinuous 0.6-kilometer channel alignment, removing 0.7 kilometer of levee, creating two backwater alcoves, planting over three hectares of floodplain, and installing 14 large wooden structures for fish habitat. A key objective was to restore the ability of the stream to access its floodplain. The project resulted in a change from 0.4 hectare of connected floodplain to over 5 hectares of reconnected floodplain at the five-year recurrence interval flood event. In 2022, the project received the Silver Award in the Water Resources category from the American Council of Engineering Companies.



Producing Efficiencies

This project demonstrates the intrinsic interdisciplinary nature of large-scale habitat restoration alongside the built environment. The collaboration of engineers, scientists, agencies, public utilities, and a railroad produced a project that restores and reconnects key ecological functions while relocating and protecting essential infrastructure, resulting in a brand-new stream channel emulating natural conditions. A key innovation was the use of a vibratory side grip pile driver to install over 100 timber piles into the channel banks and floodplain to stabilize the large wooden habitat structures. This specialized equipment minimized construction impacts and noise pollution compared to the more traditional approach.

Using Natural Processes

This project required the collaborative ingenuity of multiple disciplines to achieve its goals. Fishery biologists, natural resources specialists, hydrologists, engineers, planners, drafters, environmental regulators, and contractors worked together over multiple years, sharing their insights, perspectives, and interests to help make this project a reality. Design ingenuity included burying rock jetties as a failsafe for railroad protection in case of river erosion toward the rail line, installation of large wood complexes in the floodplain as hydraulic roughness to limit erosion, and the use of vibratory pile-driving to secure large wood habitat structures along the banks for erosion control and habitat enhancement.

Previous page: Aerial view of the project site three years after construction, with the power line corridor and rail line on the left and the remeandered channel and reconnected floodplain on the right. (Photo by Inter-Fluve)

Right: During the second year of construction, builders drove timber piles to support large wood habitat along the new channel banks. (Photo by Inter-Fluve)

Broadening Benefits

This project is a triple win: meeting habitat-restoration goals, the public utility upgrading aging infrastructure, and the railroad reducing its need for long-term maintenance without the creek running along the grade. The project improved the health, safety, and welfare of the public while benefiting the natural environment and the service it provides to the region through a healthy salmon population. The public utility's upgrades and relocation of the power lines provides more reliable distribution of electricity to customers. The relocation of the creek channel away from the railroad grade reduced the risk to this critical transportation corridor from flooding and erosion.

Promoting Collaboration

This project provides an encouraging example for engineers to reevaluate what is possible when confronting seemingly conflicting interests on projects where the natural and the built environment intersect. When engineers perform this type of work, it is critical that they design the project alongside ecologists, fluvial geomorphologists, and fish biologists. This project shows that sorting out these intersections and realigning them (both figuratively and literally) requires redefining classic engineering thinking toward a more open and interdisciplinary approach.

Top: Progress during the second year of construction. Looking up the valley, the remeandered channel connects to the alcove. (Photo by Inter-Fluve)

Middle: Aerial view of the site two years after construction, showing the remeandered channel and floodplain on the left and the filled-in former channel on the right. (Photo by Chelan County, Washington)

Bottom: Aerial view of the site, taken three years after construction, showing the remeandered channel, large wood habitat, and vegetation growth on the new floodplain. (Photo by Inter-Fluve)

Lower Elkhorn Basin

Sacramento, California, United States

Increasing resiliency and capacity through the use of levee setbacks. The Lower Elkhorn Basin Levee Setback (LEBLS) Project is a multibenefit project that provides broad flood risk reduction and ecosystem benefits for a large region within California's Central Valley. For this project, the California Department of Water Resources (DWR) has constructed an approximately 11,500-meter setback levee to expand the Sacramento and Yolo bypasses by about 450 meters. Construction started in August 2020, and the existing levees were breached in summer 2023 for use of the expanded bypass in winter. The expansion of the bypasses significantly reduces the risk of flooding for the Sacramento area; when coupled with the U.S. Army Corps of Engineers (USACE) Sacramento Weir Widening Project, the water surface elevation in the Sacramento River will be reduced by nearly 30 centimeters during high-water events. The expanded bypass footprint area will be used for agriculture and habitat, compatible with seasonal flooding. LEBLS is the first state-led project to be implemented from the Central Valley Flood Protection Plan (CVFPP), which was developed to better manage the risk of flooding in California's Central Valley, specifically in areas classified as protected by the State Plan of Flood Control. LEBLS has been recognized as a well-performing project at state and local levels.

Producing Efficiencies

The project was designed to use on-site soil to comply with air-quality regulations, reduce costs, and create construction and operational efficiencies. The on-site soil is a high-plasticity ("fat") clay not typically suitable for levee construction; however, the levee will have a larger prism and flatter slopes than usual to accommodate this material. To protect the levee from erosive wave wash from the Yolo Bypass while providing ecosystem benefits, the project uses a tied concrete block mat with soil cover and native perennial grass over the mats. This is the first use of the product on state-federal levees in California.

Using Natural Processes

The project expands the inundated Yolo Bypass floodplain and has been designed to inundate the expanded floodplain with frequent flows that will benefit rearing juvenile salmon. The floodplain connects to the Tule Canal riparian corridor, which provides habitat to a variety of fish and wildlife species. The project also creates the opportunity for future habitat improvements to be developed along the Tule Canal corridor that would then allow even greater benefits for aquatic species.

Previous page: Flow from the Yolo Bypass entering the expanded bypass and moving south along the new setback levee in February 2024. The breached Yolo Bypass levee with the tree-lined Tule Canal is visible in the center of the photo. (Photo by Sara Nevis, California DWR)

Right: Aerial view of cured concrete block mats ready to be rolled and placed on the waterside of the new setback levee. The tied concrete block mats are less expensive than placing rock for erosion protection, easier and more efficient to maintain, and more friendly to wildlife. Production of the mats was completed in bulk in approximately 1,219-meter linear increments and cut to size prior to installation. (Photo by Florence Low, California DWR)

Broadening Benefits

The expanded Yolo Bypass area will be used for floodplain-compatible agriculture, like growing rice. This land use allows seasonal flows that benefit the ecosystem and the local economy. For example, the rice paddies will be used by migrating birds, and the nutrients in the paddies can be used during the life cycle of fish in the bypass and downstream. Native grasses will provide foraging habitat for Swainson's hawks (*Buteo swainsoni*), a listed species. The levee degrade plan includes leaving portions of the existing east Yolo Bypass levee intact and spaced at various intervals to provide areas of higher elevation refuge for giant garter snakes (*Thamnophis gigas*) and other species during high water events.

Promoting Collaboration

Identified as a state priority, concept discussions began during the public planning process to develop the 2012 CVFPP, with collaboration continuing through the 2017 CVFPP and Basin-Wide Feasibility Studies, completed in partnership with locals. In 2016, DWR launched a targeted outreach effort that included gathering input from key interested parties, like the local reclamation district (formed and maintained by farmers and landowners for agricultural use), landowners, Yolo County, and Native American tribes. The project has benefited from robust partnerships with other state and local agencies, other special districts (i.e., reclamation districts), and a key partnership with a traditionally and culturally affiliated tribe. These partnerships continue through construction and during future operations, allowing flexibility in implementing and maintaining the project in a cost-effective and timely manner.

Top: Fabrication of the tied concrete block mats before placement on the setback levee. (Photo by Florence Low, California DWR)

Bottom: Pump station with rolls of tied concrete block mats in the foreground and the Sacramento skyline in the background. (Photo by Florence Low, California DWR)

Lower Otter Valley

Budleigh Salterton, East Devon, United Kingdom

Reconnecting an estuarine river to its floodplain through managed realignment. About 200 years ago, the Lower Otter Valley underwent significant manufactured changes, resulting in the disconnection of its river and estuary from their floodplain. The highly modified landscape and occurring agricultural activities were not sustainable in the face of climate change. The Lower Otter Restoration Project (LORP) in Budleigh Salterton, East Devon, is a flagship intertidal habitat restoration, climate adaptation, and infrastructure improvement project delivered by the Environment Agency in partnership with the East Devon Pebblebed Heaths Conservation Trust and Clinton Devon Estates. LORP has been majority funded by the British government, with cofinancing from the European Regional Development Fund through a cross-border initiative called Promoting Adaptation to Changing Coasts (PACCo). LORP is increasing flood resilience through greatly improved infrastructure, reversing biodiversity loss, undoing the negative impacts of human modifications and restoring significant habitat loss, increasing carbon capture, and building awareness of nature-based solutions through educational resources and visits. Beginning in spring 2021, work included removing hundreds of meters of embankments to reconnect the Otter Estuary to its historical floodplain; restoring 55 hectares of wetland habitat; constructing a 500-meter, flood-resilient raised road and bridge plus a 70-meter footbridge over the location of the future breach to ensure continuity of the path; remediating and protecting a former landfill site; relocating the Budleigh Salterton Cricket Club away from the floodplain; raising and improving over three kilometers of public footpaths; and installing seven wildlife viewing areas.

Producing Efficiencies

Through managed realignment, a mix of scientific research, traditional and soft engineering, and more natural solutions and methodologies, LORP has improved local infrastructure and the environment in tandem. Project planning and work was led by extensive consultations, scientific research, citizen science programs (fish and bird monitoring), natural capital reporting, ecologist surveys, carbon capture assessments, historical infrastructure records, fluvial and coastal modeling, and topographic analysis. This included making certain infrastructure resilient to flooding, relocating other infrastructure out of the floodplain, carrying out a 70-meter breach in the main tidal embankment to reconnect the tide, and recreating 55 hectares of wetland habitat.

Using Natural Processes

LORP is returning the Lower Otter Valley and Otter Estuary to a more natural state and function by harnessing nature-based solutions. Without preemptive adaptation, the valley would not be sustainable in the face of further climate change, and many opportunities for environmental benefits would have been lost. The main components of LORP are the reconnection of the River Otter and the reintroduction of wetland habitat, which acts as a natural filter for pollutants, traps carbon, and increases biodiversity by providing feeding and breeding grounds for a variety of wading birds, fish, and invertebrates. By strategically breaching embankments and creating a new network of channels, which can evolve naturally, the tide now flows back into its historical floodplain.

Previous page: Aerial view of the current site showing the newly created natural creek network following the removal of an old and unsightly concrete aqueduct on stilts. (Photo by Jake Newman, KOR Communications)

Top and bottom: Aerial view of the site in March 2021, when work had just begun, and in April 2023, when the landscape was returned to a more natural state to the benefit of wildlife and people alike. (Photos by Jake Newman, KOR Communications).

Floodplains

Broadening Benefits

Through extensive research reports, area and stakeholder analysis, ecological monitoring and surveys, educational engagement and resources, and public consultation, LORP has increased socioeconomic value while improving infrastructure and restoring natural habitats. As the newly created wetlands and woodland develop, biodiversity will increase further. This, along with new infrastructure and improved access to the Otter Valley and natural environment, will increase visitors to the area (which is to be a managed nature reserve) and offer greater opportunities for bird-watching, educational visits, ecological monitoring, and citizen science. The reduction of flood risk will also provide economic benefits.

Promoting Collaboration

LORP is a great example of how international collaboration among cultures, partners, funders, landowners, researchers, contractors, the public, and other stakeholders can provide new solutions to shared challenges. The partners of the PACCo project (including LORP) published a comprehensive guide and other resources, all freely available online, to share lessons learned on adaptation planning, funding and natural capital, stakeholder communications and engagement, design and construction, risk assessment, and long-term monitoring. By building strong relationships through public outreach and events, identifying key aims and audiences, and assigning specific collaborative work packages to project partners, communication and trust with stakeholders was achieved.

Top: The newly restored wetlands at the site as seen through one of the seven new viewing platforms. (Photo by Environment Agency)

Middle: LORP fish monitoring. (Photo by Environment Agency)

Bottom: The LORP and PACCo team at the site. (Photo by Environment Agency)

Mud Creek Confluence

Mills River, North Carolina, United States

Reshaping a floodplain to reduce agricultural impacts and create habitats. The Mud Creek confluence project, situated at the confluence of Mud Creek and the French Broad River in Henderson County, North Carolina, has been highly modified for agricultural production, including crowned fields for row crops, "push-up" berms along the riverbanks constructed of concrete debris and earth, and parallel ditches for drainage. The site also receives urban stormwater runoff, a potential habitat and water-quality stressor, through several pipe outfalls from a neighboring subdivision. The confluence was identified as having excellent potential for restoration and enhancement of aquatic and terrestrial habitats as well as opportunities for recreational access, education, and outreach. The Mud Creek confluence project addresses these needs by restoring a montane alluvial floodplain forest, a rare natural community in North Carolina. Specific vegetation communities and habitat types considered in the restoration design included muskellunge (*Esox masquinongy*) spawning areas, mountain bog wetland, pollinator plots, mountain grasslands, and montane alluvial forest. The project restored over 7 hectares of wetlands using fine and large debris and excavated 0.7 hectares of floodplain pools. Nearly 4 hectares of spawning habitat were created for muskellunge with the removal of a dam and the addition of fine and large woody debris. Pollinator mounds were also established on the tract.

Producing Efficiencies

The project sponsor, Conserving Carolina, identified the site during its yearly watershed review conducted to advance its mission of protecting, restoring, and inspiring appreciation of the local natural world. Agricultural production at the confluence could be challenging due to urban runoff, which degrades water quality and rare fish habitat. Project scientists and engineers collaborated on restoration and enhancement goals, which included natural hydrology, water quality, habitat for breeding muskellunge and other species, wetland habitat, recreational access, and native vegetation. The designer, Jennings Environmental, and the contractor, North State Environmental, conducted joint site reviews to minimize and balance earthwork.

Using Natural Processes

The project used a natural channel design process to determine overbank flowing dynamics into the site and to identify strategic locations within the berm breaches. The design maximized the retention and detention of off-site urban stormwater before it entered the receiving water. Excess material was shaped to blend with the landscape, including hummock areas, which were planted with pollinator vegetation. Fine and large woody debris that were removed along ditches and berm areas were used within the wetland areas to provide habitat for breeding muskellunge, amphibians, reptiles, and birds.

Previous page: Aerial view of the confluence site, showing the French Broad River along with the wetland area and large woody debris piles that provide habitat for amphibians, reptiles, and birds. (Photo by North State Environmental)

Right: Wetland area constructed at the site to provide water-quality and habitat benefits. (Photo by North State Environmental)

Broadening Benefits

Conserving Carolina achieved several social, environmental, and economic benefits from implementing this project. The area, which lies adjacent to a subdivision, has been converted to a nature preserve. In the future, a greenway will be planned through the site, which already includes a paddle camp trail area. The project restored and now protects a rare montane alluvial floodplain forest community with wetlands within it. Further, the muskellunge have been found using the habitat created for them at the site.

Promoting Collaboration

Representatives from U.S. Fish and Wildlife (federal), North Carolina Wildlife Resources (state), and Conserving Carolina (local nongovernment organization) formed a project advisory committee to work with the designer and contractor to create the project objectives and inform design development. Other project partners who participated in the project to make it a success were the North Carolina Land and Water Fund, the North Carolina Department of Environment and Natural Resources, the North Carolina Environmental Enhancement Grant Program, the Natural Resources Conservation Service, SM Soil and Water Solutions, Jennings Environmental, and North State Environmental.

*Top: On-site signage—created in partnership with the Revitalization of Traditional Cherokee Artisan Resources, Cherokee Preservation Foundation, Qualla Arts and Crafts Mutual Inc., and Conserving Carolina—describes the ecological, historical, and cultural significance of river cane (*Arundinaria gigantea*) in English and Cherokee. (Photo by North State Environmental)*

Bottom: The slough created for muskellunge habitat looking toward its confluence with the French Broad River. (Photo by North State Environmental)

The restored channel at Coonamessett River is deeper and narrower to provide cooler water for brook trout (project details on page 216). (Photo by Inter-Fluve)

Use of Vegetation and Natural Materials

Exploring alternative interventions

Introduction

EWN practitioners are using natural and nature-based materials to achieve more sustainable objectives on a variety of projects. For example, two projects strategically placed dredged material along a coastline and allowed natural processes to shape the material in ways that increased its engineering, social, and environmental value. Other examples of locally sourced natural and nature-based materials being used to implement EWN in practice include using NNBF to manage flood risk via leaky dams, low earth bunds, tree plantings, and sediment traps. Repurposed wood (including root wads, sphagnum moss, coir logs, and jute) can be used to manage flood risk at various scales, as seen in a small-scale pilot project to understand how such an approach could be implemented by farms throughout the watershed. Coastal erosion continues to be a natural hazard along freshwater and marine coasts, and practitioners continue to turn to vegetation and other natural materials as features to reduce this natural hazard while improving habitat value of the infrastructure.

Mersea Harbour and Horsey Island

Essex, United Kingdom

Protecting against erosion and creating habitat by beneficially using dredged material. In the United Kingdom, less than 1% of dredged sediment is currently used, particularly as a tool to support estuarine and coastal habitat restoration, with the majority being disposed of offshore. To capitalize on this resource, during winter 2021, a series of beneficial use sites was delivered by the Mersea Harbour Protection Trust (MHPT) and the Royal Society for the Protection of Birds (RSPB) along the Essex coast. The project was designed to create habitat for little terns (*Sternula albifrons*; a protected species), protect local salt marsh from erosion, and help maintain natural harbors by providing shelter from wave action. Using sand and gravel arising from the Harwich Haven Authority (HHA) channel-deepening project, sediments were hydraulically pumped ashore via pipeline and deposited at Horsey Island in the Hamford Water embayment and at four locations across Mersea Harbour in the Blackwater Estuary via pipeline and rainbowing. The material at Horsey Island was an instant success for little terns, with an increase of nests and fledged juveniles from 2021. The shelter afforded by the recharge at Mersea Harbour is already transforming the damaged salt marsh, supporting sediment accretion and vegetation development in the lee of the deposits, which themselves have evolved into a more natural form.

Producing Efficiencies

A nature-based sand and gravel recharge approach was selected, with dredged material that emulates the Pleistocene gravels forming natural beach ridges within Hamford Water and the Blackwater Estuary. Coarser sediments over finer were preferred, as they provide more protection to the eroding marshes and harbors and are favored by the target species of nesting birds. The recharged sediments could also respond to the local tides and waves, creating a more natural and resilient coastal profile. Where safe and navigable access allowed, rainbowing via dredger was used to discharge the sediments. This avoided pipeline costs and reduced the cost of operations.

Using Natural Processes

No reprofiling of the sediments was undertaken once discharged. Instead, coastal processes were allowed to rework them to create a natural morphology. This approach was based on similar beneficial use projects undertaken at the same sites. Following placement, the sediments also help reduce wave energy, encouraging the deposition and accretion of fine, soft sediments. At Mersea, the first-year increase in elevation of the intertidal mudflats landward of the deposits shows the potential, in time, for conditions suitable for the colonization of pioneering salt-marsh vegetation, further stabilizing the sediments and providing ecosystem service benefits associated with salt-marsh habitat.

Previous page: Aerial view of the material postdeposition at Old Hall Point, with Mersea Harbour, Packing Marsh, and Cobmarsh in the background. The project applied Engineering With Nature principles to create multiple benefits. (Photo by Jim Pullen Surveys on behalf of Mersea Harbour Protection Trust [MHPT] and Harwich Haven Authority [HHA])

Right: Aerial view of Horsey Island in September 2023, showing dredged material being shaped by natural processes both landward and westward as predicted. The Thames barges to the right, previously positioned to reduce wave energy on the shore, date from 1988. (Photo by Jim Pullen Surveys on behalf of RSPB and HHA)

Broadening Benefits

The project's primary aims were environmental, providing suitable habitat for bird species and protecting salt-marsh habitat from erosion. The gravel and sand recharge areas have been hugely beneficial to nesting birds like little terns. These benefits have included much-needed winter roosting habitat and the support of marine invertebrates, a year-round food source, by the accreting soft sediments. The project also has significant socioeconomic value. Improved flood defenses increase the sustainability of Mersea Harbour, which directly supports approximately 80 full-time jobs throughout the year. The project also similarly safeguards wildlife and boating interests, supporting area tourism contributing approximately £276 million to the local economy.

Promoting Collaboration

At the project's core was a strong collaboration between MHPT on Blackwater Estuary and RSPB on Horsey Island with funding via the European Union's L'Instrument Financier pour l'Environnement (LIFE) Programme, LIFE on the Edge project. The partner and major funder was HHA, providing the source of gravel and sands and marine construction experience and managing the contractors, Boskalis and Van Oord. As the flood and coastal risk authority, the Environment Agency also provided a financial contribution. Finally, community support was critical. Public talks and exhibitions during design and construction helped identify issues, address concerns, agree on monitoring, and develop solutions, while postrecharge engagement allowed the successes of the project to be shared.

Top: Material being rainbowed onto Packing Marsh Island via the Sospan Dau *dredging vessel, with West Mersea Village in the background. (Photo by Jim Pullen Surveys on behalf of MHPT and HHA)*

Middle: Two of the four deposit locations at Mersea Harbour before the material was pumped ashore—note the eroding edge to Cobmarsh Island and the reduction in size of Packing Marsh Island. (Photo by Jim Pullen)

Bottom: Little terns using Horsey Island to nest in summer 2022. (Photo by Paul Davis, RSPB)

Coonamessett River

Falmouth, Massachusetts, United States

Removing legacy dams to improving fish passage and habitat. The Coonamessett River is a small spring-fed stream on Cape Cod, Massachusetts, that flows south through Falmouth into Vineyard Sound. The Wampanoag people have used the river as a herring fishery since time immemorial, and European settlers used it similarly since the seventeenth century. Cranberry farming has also been part of the fabric of Cape Cod for over 150 years. A long history of mill construction and cranberry cultivation caused declines in fish populations and degradation to aquatic habitat. In the 1970s, the Town of Falmouth acquired more than 81 hectares of bottomlands and uplands, with the intention of using some for conservation and some for organic cranberry farming. Following a geomorphic assessment, topographic survey, sediment analysis, and hydraulic model development, a series of design alternatives was developed. They included the removal of one of the dams on the river, the restoration of one bog to historical channel and wetland conditions, the replacement of two undersized culverts, and the rerouting of flows around another dam. Construction was completed in 2020, with design work continuing on the upper Coonamessett River.

Producing Efficiencies

In the 1800s, some farmers began intentionally spreading sand over their cranberry bogs after noticing that harvests improved when the wind blew sand across their crops. The practice quickly spread across Cape Cod, making the area synonymous with cranberries in American culture but damaging river habitat. The sand prevented native plant growth and resulted in a wider, shallower channel. Excavating the sand, nearly a meter deep in places, improved habitat by making the river deeper and cooler. Potential sediment removal complications and costs were avoided by placing the excavated sand on adjacent hillslopes, where it provides nesting habitat for turtles.

Using Natural Processes

Large root wads placed along the newly restored riverbank help stabilize the channel and extend underwater to provide colder, sheltered areas for fish. Over time, the flow of water will form deep pools around the large wood structures, further enhancing fish habitat. As these structures naturally decay, insects will eat the roots, providing a food source for brook trout. Scientists studying the wetlands have noticed the emergence of native plants from seeds likely buried for centuries and exposed to rain and sunlight by project construction. Over time, these native plants will complement the large wood structures and native riparian plantings, adding further complexity to the ecosystem.

Previous page: Aerial view of the bog shows the remeandered channel as it empties into Vineyard Sound. The river was historically an important herring run. The restored channel is deeper and narrower to provide cooler water for brook trout. (Photo by Inter-Fluve)

Right: A system of raised boardwalks provides recreational access to the bogs while allowing fish passage. Previously, the river had been routed through a series of culverts. (Photo by Inter-Fluve)

Broadening Benefits

Removal of the legacy dams on the Coonamessett River and restoration of the associated floodplain and wetlands have several benefits, the most immediate being improved fish passage. Just a year after construction, herring (*Alosa* sp.) were migrating up the river, likely for the first time in over 300 years in an area historically used as a herring fishery. The restored channel's deep pools and cooler water provide habitat for brook trout (*Salvelinus fontinalis*), a species once found in the river and prized by anglers. And removing in-stream barriers, replacing undersized culverts, and restoring wetlands will help protect neighboring communities against flooding, especially as sea levels rise.

Promoting Collaboration

Some residents saw the proposed restoration as a major loss for Cape Cod, famous for its cranberries for over 150 years. Early in the feasibility process, there was a farmer still harvesting in two of the bogs. This led to design alternatives that included fish passage improvements while maintaining active farming in those two bogs. By the time the lower bog was constructed, the farmer no longer found it viable to farm organically (as required by the Conservation Commission) and had stopped, which allowed for the full restoration of the two additional bogs. Despite some remaining community opposition, most residents had already begun enjoying the paths and restored ecology of the lower bog.

Top: A school of herring was spotted in the river just a year after construction. (Photo by Inter-Fluve)

Middle: Sand excavated from the bog was used to create turtle nesting habitat alongside newly constructed ponds. (Photo by Inter-Fluve)

Bottom: A new road crossing replaced three undersized pipes. (Photo by Inter-Fluve)

Marlfield Farm

Earby, Lancashire, United Kingdom

Applying a pilot flood risk management technique on a smaller farm scale. Situated in the foothills of the Pennines, the City of Leeds, United Kingdom, is predicted to be impacted significantly by ongoing climate change between 2039 and 2069. To offset these impacts, a natural flood management (NFM) project was piloted to provide climate resilience using nature-based solutions. Marlfield Farm, in the catchment of the River Aire upstream of Leeds, was identified as a suitable pilot site to test and trial the implementation of NFM on a traditional upland family farm. It enabled the project team to learn lessons and facilitated upscaling of NFM delivery to hundreds of sites across the 700-square-kilometer River Aire catchment. The Environment Agency led the project on behalf of the Leeds City Council, who worked together with the Procter family (the farm owners), Mott MacDonald (the designers), and the River Stewardship Company (the contractors). The objective was to deliver a range of NFM measures to slow the flow of rainwater before it enters a local tributary of the River Aire and to improve habitat for local wildlife. Works have included creating wetlands, forming seasonal habitat ponds using earth bunds to hold surface-water runoff, planting hedges and trees, installing a leaky barrier, and fencing off field corners from grazing to promote vegetation growth. The project was completed in 2019.

Producing Efficiencies

The Marlfield Farm pilot site was used to understand how the Environment Agency, which normally delivers large flood alleviation schemes, could approach NFM on a smaller farm scale, providing operational efficiencies while maintaining a robust procedure to manage environmental, health, and safety risks. Design drawings were produced using a modular approach; a single standard design could be used for multiple NFM features across the site, saving on cost and time. Hydrological analysis was undertaken to estimate the predicted flood risk benefits from the NFM on Marlfield Farm, which helped inform wider hydraulic modeling and monitoring strategies for the whole Leeds NFM project.

Using Natural Processes

The project team consulted with the farmer, whose family has worked the site for generations, to form a plan to enhance natural processes and reconnect fragmented habitats. Features were positioned to intercept overland flows across the site's main drainage routes and direct runoff to storage features. Marl (clay) was sourced on site to build an earth bund. Existing boundary drystone wall material was repurposed to form a leaky barrier, with a strengthened wall fitted with high-level overflow pipes passing excess flows to other NFM features. Within the woodland where runoff occurred, locally sourced hazel was used to make a woven leaky barrier.

Previous page: The pilot natural flood management (NFM) project was completed at Marlfield Farm in Lancashire in 2019 to help protect the Aire catchment from flooding. (Photo by Mott MacDonald)

Top: A completed cross-slope hedgerow, planted to reduce soil erosion and surface water runoff as well as provide biodiversity benefits. (Photo by Mott MacDonald)

Bottom: Completed seasonal habitat ponds following Storm Ciara in February 2020. (Photo by Daniel Procter)

Broadening Benefits

Along with other pilot sites on the Leeds NFM project, Marlfield Farm has been used to show stakeholders and the community a practical example of NFM. The farm owners have led group tours of the site, including an NFM community group in 2022, where they discussed how well the NFM works had established during the three-year period since installation. The team used local contractors during construction wherever possible, reinvesting the project funds into the local economy. Since construction, the farm owners have observed the performance of the NFM works during storm events and noted a range of wildlife using the new habitats.

Promoting Collaboration

Work on the Marlfield Farm pilot site was concurrent with Mott MacDonald leading a partnership for the Construction Industry Research and Information Association Natural Flood Management (CIRIA NFM) Manual. This work collated a wide range of research and engagement to bring together NFM best practices. The CIRIA NFM Manual delivery process was applied to project development; working with others was central, and project initiation started with understanding the catchment. Measures were selected in discussion with the landowners and designed and constructed by the project team. Future monitoring and maintenance of the features will be undertaken by the landowner.

Top: Excavation of a seasonal habitat pond. (Photo by Daniel Procter)

Middle: Completed in-channel leaky barriers, slowing the flow during Storm Ciara in February 2020. (Photo by Daniel Procter)

Bottom: A site visit held by the local NFM community group in 2022 to see the NFM installations. (Photo by Mott MacDonald)

Illinois Beach State Park

Zion, Illinois, United States

Using an innovative approach to address coastal erosion. Erosion threatens rare habitat in the Illinois Beach State Park's (IBSP's) unique beach-ridge geology. In response to the ongoing challenges of coastal erosion along the northern areas of the IBSP coastline, the Illinois Department of Natural Resources (IDNR) and the Healthy Port Futures Initiative (funded by the Great Lakes Protection Fund) codeveloped rubble ridges for coastal protection and habitat creation. Construction was funded by the Great Lakes Restoration Initiative through grant funding available to IDNR and completed by the U.S. Army Corps of Engineers (USACE). As a series of underwater ridges constructed of smaller stones, the feature is designed to reduce wave energy before it reaches the shore and induces further erosion. As a collection of features, the ridges work together to roughen the lakebed and encourage waves to break offshore. This new lakebed is also designed to serve as fish habitat, offering rocky shelter in an environment that has very little. Because it is a novel pilot project, there are many unknowns regarding final performance, but initial findings are positive. This pilot project showcases the continued need for similarly experimental projects that further the ability to work more productively and collaboratively with coastal processes.

Producing Efficiencies

As a pilot project, the rubble ridges were not overtly motivated by operational efficiency. That said, at the project outset, several considerations aimed to streamline construction. Most obvious was the use of smaller stones than would be typical of an offshore breakwater, making sourcing and transport somewhat easier. In addition, these stones were more casually dumped to form the features (as opposed to being meticulously placed and fit together, as would be the case in a traditional breakwater) in a process that would save time during construction.

Using Natural Processes

At IBSP, the natural processes are actually causing the problematic erosion and longshore sediment transport. Most engineering responses would attempt to halt this, but this approach tends to produce a wide range of collateral effects, both known and unknown. The rubble ridges are designed to simply slow these processes and encourage positive work. Sand continues to move, but in an offshore ridge of slowly moving sediment created by the lower-energy area between the ridges and the shore, providing another barrier to wave energy.

Previous page: Rubble ridges protecting the habitat of Illinois Beach State Park. (Photo by Healthy Port Futures)

Right: Material is placed from the barge with a crane and grapple to form the underwater ridges. The rubble ridges are constructed with smaller stones than would traditionally be used in breakwater construction. (Photo by Healthy Port Futures)

Broadening Benefits

The rubble ridges protect the ecological, cultural, and economic value of IBSP as a rare coastal habitat, a public landscape, and a popular tourism destination. They serve as an accessible habitat for various fish species, as they can swim over and around the ridges in a way that would be impossible with a standard breakwater. The rubble ridges are also intended to remain underwater at most, if not all, water levels. This allows IBSP to serve its cultural role as a public landscape affording beautiful views of Lake Michigan and its infinite horizon, which would be marred by traditional offshore structures.

Promoting Collaboration

The rubble ridge project was the product of a strong collaboration between the IDNR and Healthy Port Futures. The IDNR team conducts robust outreach programs that organize stakeholders around issues of coastal management, including what is known as the "sand-management working group." It was with the help of IDNR that the project focused on addressing the concerns of partners and incorporated local feedback. For its efforts, the project (as part of the larger Healthy Port Futures Initiative and supported by Anchor QEA) received an Honor Award from the American Society of Landscape Architects in 2020 under the category of Analysis and Planning.

Top: A USACE floating plant constructing the rubble ridges in summer 2021. (Photo by Healthy Port Futures)

Middle: Construction of the second row of material for the rubble ridges, looking north at the unique beach ridge geology of the Illinois Beach State Park. (Photo by Healthy Port Futures)

Bottom: Panne wetlands, located between beach ridges, are rare coastal ecosystems in the Great Lakes that are at risk due to coastal erosion and that the rubble ridges are designed to protect. (Photo by Healthy Port Futures)

Littlestock Brook

Milton-under-Wychwood, Oxfordshire, United Kingdom

Reducing flood risk by using natural flood management measures. The village of Milton-under-Wychwood was flooded in 2007 during a flood event that affected large parts of southern England, with subsequent floods occurring in 2011. The Littlestock Brook project was initiated by the Environment Agency in 2016 after identifying the potential to reduce flood risk by deploying more natural flood management measures rather than using conventional "hard engineering." To understand how a small, rural community could manage its flood risk, a partnership project was created with Wild Oxfordshire, Milton Parish Council, Bruern Estate, and West Oxfordshire District Council. The project was initiated and funded by the Environment Agency, which also oversaw its delivery. Wild Oxfordshire, as hosts of the Evenlode Catchment Partnership (ECP), managed the delivery of the project with support from HR Wallingford, UK Center for Ecology and Hydrology, Windrush AEC, and Whitehorse contractors. In a catchment upstream of the village, the Environment Agency and ECP developed natural flood management measures, including leaky dams, low earth bunds, tree planting, and sediment traps. Through detailed hydraulic modeling and extracting flood depths, it was possible to assess the effectiveness of the measures in reducing flood risk and undertake a cost-benefit analysis for the reduction in flood damages to properties affected by historic flooding. Phase 1 of the project was completed in 2019 and proved effective in December 2020 when the measures reduced flooding during a heavy rainfall event.

Producing Efficiencies

The project was supported by a detailed 2D hydraulic model that identified areas where flows could be intercepted and measures implemented. It also demonstrated the efficacy of some existing measures and tested options for water retention and the design of outlet structures, with modeling for a range of rainfall extremes. The materials used in the low earth bunds were sourced from the site, minimizing transportation costs and disruption to the local community. The study revealed that optimal design of the low earth bunds in combination with leaky dams was critical, as significant water retention was required for flood risk reduction.

Using Natural Processes

The watercourses upstream of Milton-under-Wychwood have been modified over the years to increase agricultural production and allow for construction of a water mill. This has enlarged the channel unnaturally and "perched" it above the natural valley. The project has used natural processes to provide flood mitigation, including leaky dams to reduce the in-channel bankfull flow to a more natural one and allow more water to flow out onto the natural floodplains. The project also incorporated long-term land management with features like the planting of trees in the catchment intended to intercept rainfall and slow overland flows, thus reducing flood flows in the watercourses.

Previous page: The Littlestock Brook as it flows through the Bruern Estate. (Photo by HR Wallingford)

Top: Planting around one of the low earth bunds showing a mix of trees and wildflower meadows. (Photo by Wild Oxfordshire)

Bottom: Close-up of a storage area and habitat in the Littlestock Brook catchment. (Photo by Wild Oxfordshire)

Broadening Benefits

The project is very much owned by the local community. The principal landowner, the Bruern Estate, was supportive from the outset, willing to donate land and effort. Community groups were involved with tree planting activities, and the ECP facilitated many project updates to the local residents. The project introduced nutrient retention ponds as well as field margin sediment and nutrient traps to limit diffuse phosphate and sediment in Littlestock Brook, planted around 14 hectares of riparian woodland to bolster wildlife habitat, and built a footpath to promote recreation. The newly created low earth bunds were planted with wildflower meadows, encouraging insect communities to thrive.

Promoting Collaboration

The project was initiated by the Environment Agency working with the local parish council and delivered in partnership with Wild Oxfordshire. Other key stakeholders included the West Oxfordshire District Council; Thames Regional Flood and Coastal Committee, who provided £230,000 of funding; and numerous research organizations interested in expanding the NFM evidence base. The community was actively involved and encouraged to document the new landscape features, and the project includes public access and information boards. The majority of the measures are located within the Bruern Estate, who worked with the project to develop solutions that met flood risk reduction, water quality, and habitat creation requirements without detriment to the estate's agricultural work.

Top: Construction of one of the new bunds. Note the use of material from the site and the sculpting of the bunds to fit in with the natural landscape. (Photo by White Horse Constructors)

Middle: Natural flood management measures including a mixture of in-line storage, field corner bunds, and tree planting. (Photo by Environment Agency)

Bottom: One of the newly constructed bunds doing its job in January 2021. (Photo by the Bruern Estate)

Kinder Scout

Kinder, Derbyshire, United Kingdom

Using natural materials to protect vulnerable communities and reduce flood risk. Six years ago, over 50,000 *Sphagnum* spp. moss plug plants were planted into previously revegetated areas on Kinder Scout, the highest peak in the Peak District National Park. This area now forms part of the newly extended National Nature Reserve (NNR), looked after by the National Trust. Sphagnum moss is a key component of blanket bogs and can hold up to 20 times its weight in water. The source material for the sphagnum was harvested locally and nursery grown in a polytunnel. Each plug contained a mix of 11 species of sphagnum commonly found in the Peak District. After planting, the impact was closely monitored and has been proven to significantly slow water running off the hills after rainfall, reducing peak streamflow (the maximum amount of water at any one time in a river after a storm) by 65%. There is a similarly remarkable increase in the lag time (the time it takes the water to enter the river system). This has important benefits for downstream communities vulnerable to flooding, as water is less likely to overtop riverbanks. The findings of the six-year study—implemented by the Moors for the Future Partnership as part of the MoorLIFE 2020 project, funded by the European Union's L'Instrument Financier pour l'Environnement (EU LIFE)—confirm the vital part sphagnum moss could play in widespread and effective flood-risk reduction for downstream communities.

Producing Efficiencies

The site has formed part of an "outdoor laboratory" created to study the impacts of peat restoration, including its important role in natural flood management (NFM). The reintroduction of sphagnum has significant benefits, which are improving with time. As it grows and thickens, it creates a dense, rough surface over the peat, slowing down water flowing across the catchment and into the streams. Stormwater is fed into the river system more gradually, reducing flood risk and severity in the valleys. On a landscape scale, the impact would be global in terms of climate change, water quality, and flood severity.

Using Natural Processes

NFM uses natural processes to reduce the risk of floods and droughts, making catchment areas more resilient to the impacts of climate change and extreme storm events. Sphagnum plug plants introduced four years after revegetation and gully blocking made a significant difference in peak discharge and lag times. Six years after its addition, the sphagnum has decreased peak discharge by 65 percentage points (compared to the untreated control) and drastically increased lag time by 680 percentage points. The most abundant sphagnum species in the stream channels today are *S. cuspidatum*, *S. fallax*, *S. fimbriatum*, and *S. palustre*.

Previous page: Across the streamflow network in the experimental catchment, sphagnum has reached 85% cover in total and 100% in many places. (Photo by Moors for the Future Partnership)

Top: Leaky timber dams were installed to attenuate streamflow during storm events. These dams have created pools where sphagnum has thrived, increasing hydraulic roughness and leading to increased lag times and reduced peak discharge. (Photo by Moors for the Future Partnership)

Bottom: During planting in 2015, the sphagnum plugs were about 30 millimeters in diameter. By 2018, some had grown to around 300 millimeters, and those in the wettest areas had coalesced, forming patches more than 1,000 millimeters across. (Photo by Moors for the Future Partnership)

Broadening Benefits

This most recent study shows that upland restoration can cost-effectively minimize flood risk in compromised rural areas while maximizing the many benefits of NFM restoration work. If the Kinder Scout restoration was replicated across the landscape, peak river levels would be lowered—even in the biggest flood-relevant storms—significantly reducing the likelihood and severity of flooding for communities in its shadow. The effects of introducing sphagnum on peatlands with dominant native moorland plant species were also observed. Monitoring has shown that sphagnum planting into dense heather (*Calluna vulgaris*) may have slowed the flow of water from the hills. This effect will likely increase as it continues to grow and spread.

Promoting Collaboration

MoorLIFE 2020 was a Moors for the Future Partnership project in the European Union–designated South Pennine Moors Special Area of Conservation funded by EU LIFE with support from Severn Trent, Yorkshire Water, and United Utilities. For Protect NFM, Moors for the Future Partnership worked alongside the University of Manchester on the findings. The outdoor laboratories are situated on land managed by the National Trust. The project benefited immensely from extensive stakeholder and community engagement. Much of the planting was accomplished with the help of volunteers, and hundreds of presentations and events promoted the project and raised awareness around environmental and conservation efforts.

Top: The gullies were blocked with a combination of leaky timber and stone dams, which have now been completely covered by vegetation. The timber dams are still visible, but many are being colonized by sphagnum. (Photo by Moors for the Future Partnership)

Bottom: Volunteers assisting with planting sphagnum. The sphagnum trial site on Kinder Scout is a relatively small area, but extensive sphagnum planting has also occurred across the Peak District, South Pennines, and West Pennines. (Photo by Moors for the Future Partnership)

Port Bay Cobble Bell

Port Bay, New York, United States

Emulating natural condition through long-term adaptive management. The Port Bay cobble bell is located on Lake Ontario in a geologic context that has created a series of embayments protected by sandbars traditionally formed and fed by eroded drumlins (glacially deposited till left in linear hills). Reduction of erosion has minimized the inputs of the sediments that fed these protective sandbars and, in this case, has led to their breach, exposing the bay communities to ice and waves that can be highly destructive to property. Compounding the issue is the maintenance of community access from the bay to the lake, which requires the continual dredging of a channel though the bar. The removed material is typically placed on the channel's east side, either upland or on the nearby beach. Funding to move the material farther is limited, as it is derived solely from fees paid by the community. The cobble bell is a sediment management project drawing inspiration from international Engineering With Nature concepts like the Dutch Sand Engine (but on a smaller scale). As such, it is intended to be a recurring, adaptively managed landform, reconstructed regularly to mimic the local conditions of bluff erosion and sediment input that characterizes the region. The cobble bell was designed by Healthy Port Futures with funding from the Great Lakes Protection Fund. Partners at the Wayne County Soil and Water District and the New York State Department of Environmental Conservation (NYSDEC) were fundamental to the success of the project, aiding considerably in its design and implementation.

Producing Efficiencies

The cobble bell works by harnessing the energy of the waves and winds of Lake Ontario to transport sediment dredged annually from the boat channel downsystem to weak and failing areas of the sandbar, all without incurring costs beyond what was traditionally spent to place the material at an adjacent upland area where it is removed from the coastal system. This was achieved through long-term site observations, case studies, and physical models to assess just how the system worked and how it could function in a way that maximized operational efficiencies without increasing costs.

Using Natural Processes

The cobble bell is a form of adaptive coastal management, where information gathered from previous years can inform future decisions on an annual basis. And while the natural processes of wind and wave energy were studied and modeled to inform the initial design, the efficiency and adaptability of this process come from the ability to respond yearly based on what was observed and monitored in previous years. In this way, the cobble bell can continue to calibrate its relationship with the natural processes that drive it, allowing it to harness them for maximum benefit.

Previous page: The material transported from the cobble bell helps bolster the barrier sandbar that protects the homes around Port Bay from the waves and ice of Lake Ontario. (Photo by Healthy Port Futures)

Right: At Port Bay, the cobble bell form is created by removing sediment from the adjacent navigation channel and grading it out into the nearshore to be shaped by natural processes. (Photo by Healthy Port Futures)

Broadening Benefits

The sandbar protecting Port Bay from volatile Lake Ontario is an essential piece of natural infrastructure for the community. Without it, ice and waves batter homes and docks, exacerbating erosive property loss around the bay. The sandbar has also been a habitat for the state-listed spiny softshell turtle (*Apalone spinifera*). The community's economy relies heavily on water-based tourism, and access to Lake Ontario through the sandbar from the bay is essential. The project serves as a receiving area for dredged sediment that contributes to the local coastal ecosystem by keeping the sediment in the longshore system.

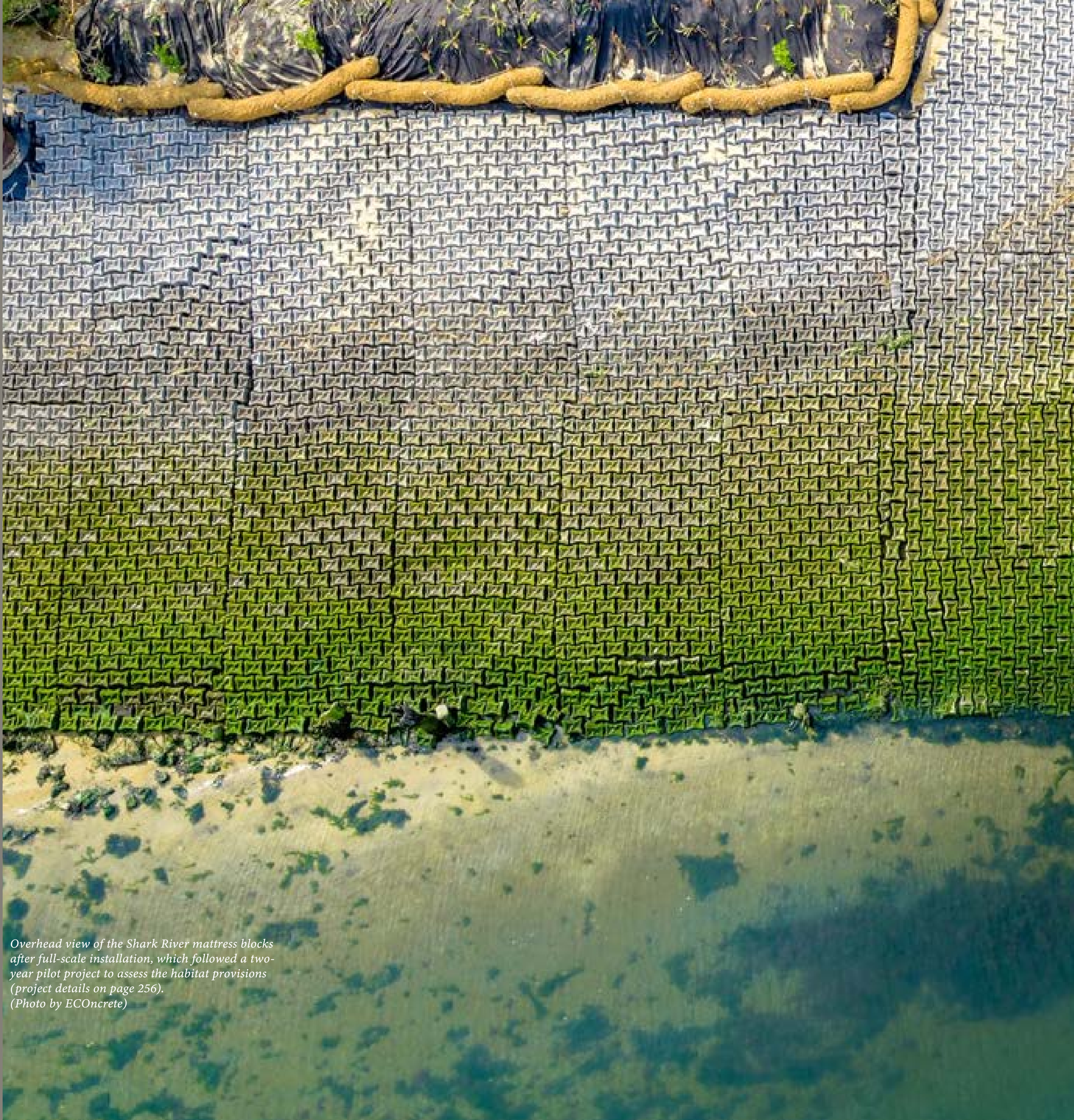
Promoting Collaboration

The cobble bell is the result of a highly productive collaboration between the design team, the local county soil and water conservation district, and the larger NYSDEC. With the help of the county representatives, the team was able to explain the project to the local community, who understood the value of both the long-term maintenance of the channel and the bolstering of the protective sandbar and saw the potential of the project to serve both of those roles simultaneously.

Top: In a typical year, the cobble bell is eroded and transported within one or two weeks. (Photo by Healthy Port Futures)

Middle: Typically completed with an excavator and bulldozer over one or two days, the cobble bell is intended to limit the time and funds needed to renourish the protective shoreline and its habitat. (Photo by Healthy Port Futures)

Bottom: Located just beyond the wave shadow of the jetty, the cobble bell works with the complex system of waves and currents at the mouth of the Port Bay navigation channel. (Photo by Healthy Port Futures)



Overhead view of the Shark River mattress blocks after full-scale installation, which followed a two-year pilot project to assess the habitat provisions (project details on page 256).
(Photo by ECOncrete)

Environmental Enhancement of Infrastructure

Engineering structures to include beneficial habitat

Environmental Enhancement of Infrastructure

Introduction

The abundance of aging conventional coastal, navigation, and other infrastructure around the world in need of repair or modification provides an opportunity to apply EWN principles globally. In this chapter, EWN principles are being deployed at a superyacht facility using biomimicry to enhance a vertical breakwater structure. The implemented design increased habitat heterogeneity and surface complexity while enhancing the biodiversity of marine species on the bioenhanced structures compared to conventional concrete blocks. Eco-armor units are being designed and placed to modify existing port infrastructure and maximize learning, reduce the project's carbon footprint, make use of local materials, and support a circular economy; using native materials is also increasing the growth of native marine species on the units. Another project is enhancing the benefits of reservoirs via a sea change in the way water levels are managed by an upstream lock and dam. The purpose of the reservoirs—flood control, recreation, navigation, and water supply—are not affected when water flowing through the system is managed more sustainably to concomitantly improve water quality and conserve fish and wildlife. Finally, EWN principles are transforming and enhancing former industrial lands into ones that are less flood prone, uplifting both the economy and the habitat features integrated into the project design.

Newlyn

Newlyn, Cornwall, United Kingdom

Implementing nature-inclusive design to deliver multiple benefits. Situated on the shores of Mount's Bay in southwest England, Newlyn's heavily developed coastline relies on hard seawalls and breakwaters to manage flood risk and has limited foreshore space to implement nature-based solutions, such as dune restoration. With a fixed line of hard defenses competing with sea levels at the cost of intertidal habitat, innovation to protect coastal communities and biodiversity is needed. The Newlyn Coastal Research and Development project, a partnership between the Environment Agency and Kier and Atkins, trialed 88 eco-armor units around the existing breakwater to investigate the ability of this innovative technology to enhance intertidal biodiversity while fulfilling its primary function as coastal armor. This pilot was among the first to use the technology, typically used in moderate and subtidal environments, in an intertidal, high-energy setting. Four suppliers were used: Exo Engineering, ECOncrete, ARC Marine, and JP Concrete. The low-carbon element of the concrete mixes saved 41 tonnes of embodied carbon in material alone compared to standard CEM I ordinary Portland cement mix concrete units. The project received the Concrete Society's Devon & Cornwall Region Sustainable Concrete Award in 2022 for its innovative practices.

Producing Efficiencies

The eco-armor units, which have been evenly distributed around the apron of the existing rock breakwater to maximize performance learning, feature low-carbon concrete mixes, have an altered pH similar to seawater, and make use of local aggregate, supporting a local circular economy. One aggregate is a byproduct from a quarry, which is regulated if excess aggregate enters the local watercourse. Using this byproduct reduces pollution risk. Growth of marine species on the units can create a carbon sink while protecting the breakwater asset. Radio frequency ID tags and scanners are used to monitor specific units without removing growth.

Using Natural Processes

Surface texturing, water retention features, and an altered pH to match that of seawater encourage the growth of marine flora and fauna on the units. This delivers biodiversity enhancements, providing a space for the migration of coastal species in a location suffering coastal squeeze. Flora will sequester carbon to the point that the project could become carbon neutral in the future. Natural environments have been enhanced by providing space for rocky shore species to thrive and migrate to. The eco-units will be monitored for at least five years to investigate asset condition and habitat creation, with results considered in future coastal projects.

Previous page: Eco-armor units from four suppliers were evenly distributed around an existing rock breakwater to maximize learning opportunities from the project. (Photo by Environment Agency)

Right: Nooks and crevices have been designed into the eco-armor units to provide shelter for marine life. The original granite rock breakwater has been in situ since 1992 and had supported very little marine life due to its smooth characteristic. Since completion of the pilot in February 2023, growth of algae on the rocks has been observed for the first time, along with attached bivalves. (Photo by Environment Agency)

Broadening Benefits

This project has saved tonnes of carbon dioxide in material due to the low-carbon concrete mixes. Some units comprise local aggregate from rock-quarrying byproduct like granite dust, diverting a pollution risk. The use of native materials means local marine species are more likely to grow on the units. Though suppliers were not local, they agreed to fabricate within the southwest region, significantly reducing transport carbon costs. This pilot has engaged the community around coastal-change messaging, sustainable coastal defenses, and habitat-restoration opportunities. School children have participated in an educational roadshow and a coastal-themed art competition.

Promoting Collaboration

With a widespread team, online meeting platforms and data-sharing sites were used to ensure accessibility and eliminate travel time and carbon. Valuable community engagement was achieved via advertised daytime and evening events as well as multiple feedback methods. Concern was raised about impact to a heritage feature, resulting in an update to the construction methodology and a heritage survey. Units from each supplier were evenly distributed around the breakwater, ensuring comparable monitoring. Suppliers demonstrated "bigger-picture" culture by offering to fabricate at each other's yards and collaborating while being industry competitors.

Top: Each unit is around 4.8 tonnes and 1.3 cubic meters, providing new intertidal habitat as well as protection to existing infrastructure. (Photo by Environment Agency)

Middle: Designs incorporated water-retaining features, identified as a key factor in encouraging colonization by marine species. (Photo by Environment Agency)

Bottom: Rough surface texturing increases surface area for accumulation of biofilm, promoting succession and increasing intertidal biodiversity. (Photo by Environment Agency)

Cape Cod

Chatham, Massachusetts, United States

Stabilizing an eroding coastline with a system of natural materials and native plants. Coastal communities on Cape Cod have suffered from increasing damage due to sea level rise, growing storm intensity and frequency, and worsening erosion. One property had experienced erosion along the bottom of the bank, and in 2010, a coir fiber roll array was installed to slow this erosion. The array quickly fell into disrepair and required replacement due to inadequate installation techniques and materials not designed for the coastal environment. Wilkinson Ecological Design proposed a nature-based approach that included a properly installed and maintained coir fiber roll array to stabilize the eroding toe of the bank and a reinforced transitional high marsh to provide a second layer of stabilization that would also restore salt marsh species where none existed. The union of these techniques maximizes the stabilizing capabilities of a living shoreline while enhancing the ecological benefits and protective aspects of a salt marsh. After extensive permitting beginning in 2014, the protective bioengineering structures were installed in 2018.

Producing Efficiencies

The project restored an eroding coastline with a healthy and functioning plant community via the fully vegetated coir fiber roll array and reinforced transitional high marsh. This nature-based solution uses the restored native plant communities to attenuate wave action and reduce the likelihood of future erosion while preserving the natural shoreline's aesthetics. This nature-forward initiative vastly differs from the traditional coastal engineering structures used today—seawalls, bulkheads, and revetments—that can change sediment distribution and hinder salt marsh migration.

Using Natural Processes

Naturally vegetated coastlines provide ecological and protective benefits, including wave attenuation, habitat creation, and water filtration. This intervention champions the restoration of salt marsh and maritime shrubland to reestablish a healthy coastal ecosystem and naturally anchor these ecosystem services back into the land. The restoration of these native plant communities not only is integral to the system's projected life span but also improves the shore's ability to withstand erosion and provides salt marsh an area to retreat from sea level rise.

Previous page: After four seasons of growth, the native plant communities have become well established, providing wildlife benefits and stabilizing soils while conserving the natural beauty of this Cape Cod shoreline. (Photo by Wilkinson Ecological Design)

Top: Preconstruction visits to the site revealed the largely eroded bank was in great need of stabilization. (Photo by Wilkinson Ecological Design)

Middle: The base row of the fiber roll is laid out and the first rows of helical anchors are driven, ensuring the fiber rolls can withstand storm energy and wave action. (Photo by Wilkinson Ecological Design)

Bottom: The fiber roll array has been installed and nourished, the trench for the reinforced transitional high marsh has been excavated, and coir and jute blanket materials are being set in place. (Photo by Wilkinson Ecological Design)

Broadening Benefits

Cape Cod faces increasing coastal flooding due to more frequent storms and sea level rise caused by anthropogenic climate change. Living shorelines like this offer a physical buffer to vulnerable coastal communities while increasing the area's ecological value and preserving the natural aesthetic. This effort is one of a host of reinforced-marsh projects across Cape Cod designed by Wilkinson Ecological Design to stabilize eroding shorelines without sacrificing the iconic ecological identity that fuels tourism in Cape Cod.

Promoting Collaboration

The design of a reinforced high marsh was a collaborative project in consultation with the Massachusetts Department of Environmental Protection, the Coastal Engineering Company, and the primary stakeholders on site. The process allowed a novel approach, using a multilayered method to increase the stabilization capabilities of a living shoreline while complying with all local and state regulatory requirements.

Top: The outer envelope of coir and jute material is being hand-sewn after the cobble and planting medium was added to the reinforced transitional high marsh. (Photo by Wilkinson Ecological Design)

Middle: The transitional high marsh species are being planted into the completed installation. (Photo by Wilkinson Ecological Design)

Bottom: The planted native species are seen establishing during the first season, expanding their root systems while the coir materials hold soils in place. (Photo by Wilkinson Ecological Design)

Port Lands

Toronto, Ontario, Canada

Future-proofing a former industrial urban area against flooding. The Port Lands consist of low-lying infill with a legacy of industrial uses, overlying what once was one of the largest wetlands on Lake Ontario. They are bounded to the north by the Keating Channel and the Don River, to the west by the Toronto Inner Harbour, to the east by Ashbridges Bay, and to the south by Lake Ontario and Tommy Thompson Park. The Port Lands are among the highest flood risk areas in Toronto. During an event the size of 1954's Hurricane Hazel—the flood standard for floodplain management in the Greater Toronto Area—approximately 290 hectares of land are in the floodplain. Providing flood protection for the Port Lands and naturalizing the river mouth have long been objectives of the City of Toronto and were prioritized when the government established Waterfront Toronto in 2001. The multi-award-winning Port Lands Flood Protection project transformed and revitalized the underused postindustrial area into a natural asset supporting Toronto's growth and economic competitiveness, creating a new mouth for the Don River and two new urban islands with associated municipal infrastructure. The new mouth's multiple outlets will provide expanded waterfront access while creating natural habitats that provide social and environmental benefits locally and regionally.

Producing Efficiencies

The project undertook studies to characterize soil conditions and develop a reuse strategy for most of the excavated soils, reducing placement costs and minimizing the volume of contaminated soil requiring maintenance. Local river-mouth area surveys were conducted to inform the design for the new naturalized mouth of the Don River. Bioengineered bank protection measures stabilize the riverbanks while providing wildlife habitat. The constructed wetlands emulate abandoned oxbow channels and were reinforced with preventative carp and flood gates. These passive and active management features in an otherwise "static" river system ensure the long-term functionality of its design.

Using Natural Processes

Land farming of soils by optimizing moisture content, aeration, and nutrient addition reduced contaminant levels to ranges that permit reuse within the project. To ensure that flowing ice does not destroy the new river channel during significant winter-thaw flood events, an ice management area has been reinforced with armor stone. Various complex flow adjustments will trigger enhanced sediment deposition upstream of the new river system. Subsequently, dredging activities will move north of the bridge at the newly established Sediment and Debris Management Area. This will reduce sediment deposition downstream in the new channel and the frequency and extent of dredging required.

Previous page: An aerial view of the Port Lands Flood Protection project (looking east). (Photo by Waterfront Toronto)

Top: Crib walls with logs and root wads were installed on the outside curves of the river. (Photo by Waterfront Toronto / Vid Ingelevics / Ryan Walker)

Bottom: Some areas of the riverbank were reinforced with fiber-encapsulated lifts made of soil and seeds wrapped in a coconut coir fabric. (Photo by Waterfront Toronto / Vid Ingelevics / Ryan Walker)

Broadening Benefits

The project has the potential to deliver wide economic benefits, including billions of dollars in value to the Canadian economy as well as in tax revenues to all orders of government and tens of thousands of person-years of employment. Pulling 240 hectares of underused land out of the floodplain unlocks a prime area that will allow Toronto to grow sustainably and improve its resiliency through one kilometer of new river channel and hectares of new coastal wetland and terrestrial habitat. Social benefits to residents and visitors are a number of new recreational opportunities in the park. The project has received multiple awards recognizing its work and approach.

Promoting Collaboration

The project is the result of a decades-long planning process that launched the City's Interim Task Force to Bring Back the Don, a citizen-led advisory committee. Their final report in 1991 galvanized support for the Don River as a natural space, ultimately leading to the project currently underway. Public consultation occurred throughout project planning, design, and construction via meetings and events. The project team also regularly consults a Stakeholder Advisory Committee and a Construction Liaison Committee. Close collaboration with indigenous communities, consultants, and designers ensures that the new environment will reflect their interests, history, culture, and traditions.

Top: The new river, built with some already-dead and decaying organic materials, is flanked by wetlands to provide habitat and green space. (Photo by Waterfront Toronto / Vid Ingelevics / Ryan Walker)

Middle: The design mimics local coastal river conditions. (Photo by Waterfront Toronto / Vid Ingelevics / Ryan Walker)

Bottom: After excavation, this area was left alone for several months. During that time, seeds buried beneath industrial land used for over a century germinated into hundreds of native plants. (Photo by Waterfront Toronto / Vid Ingelevics / Ryan Walker)

Shark River

Neptune, New Jersey, United States

Using ecological concrete materials to create a hybrid living shoreline. Seaview at Shark River Island is an active boating and waterfront community in the Shark River Inlet in Neptune, New Jersey. The highly eroded northwest corner of the island is subject to continuous wave action and boat wakes from the adjacent navigation channel; significant flooding of the nearby homes occurred during Hurricane Sandy in 2012. A bulkhead lining the project site to maintain the shoreline's position had degraded severely, allowing for major erosion of the marsh along the western shoreline. Charged with the property, the island's homeowners association (HOA) sought to stabilize the highly exposed shoreline while providing it with ecological benefits. After a comprehensive site analysis, the selected design included the creation of a hybrid living shoreline using ECOncrete's ecologically enhanced articulated concrete block mattresses to stabilize the northwest corner of the island. A nearshore sill was placed along the adjacent western shoreline to protect the marsh area, with the area shoreward of the sill being replanted in an effort to restore the eroded marsh. The promising results allowed for the hybrid solution to qualify for general permits from the New Jersey Department of Environmental Protection (NJDEP) and the U.S. Army Corps of Engineers (USACE).

Producing Efficiencies

The northwest corner's high level of erosion required a novel robust solution by using the ecologically beneficial articulated concrete block mattress. The area was covered with a geotextile filter fabric and stabilized with marine mattresses running the length of the shoreline, offering erosion control along the inter- and subtidal areas. A berm was planted with upland vegetation to mitigate erosion during extreme weather events and to further stabilize the area's slope, with a coir log placed to prevent damage along its toe. For the western shoreline's less exposed marsh, a more traditional living shorelines approach was taken. A marsh sill was constructed for shoreline stabilization and habitat restoration.

Using Natural Processes

The project's hybrid solution creates habitat opportunities while maintaining shoreline protection. The ecological marine mattresses include a scientifically proven bioenhancing admixture, retaining features, and a unique surface texture that allow the structure to serve as a substrate for marine flora and fauna and promote sedimentation and the growth of terrestrial flora. In a two-year pilot study to evaluate ecological and structural performance, ECOncrete blocks had significantly higher species richness and diversity than traditional control blocks. Monitoring of the full installation will take place over several years to evaluate the project's overall performance, with preliminary results already showing 19 species colonizing the ecological concrete units.

Previous page: The living shoreline a month after installation. (Photo by ECOncrete)

Right: Aerial view of the site area postconstruction. The project functioned as a true hybrid living shoreline, which integrated ecological concrete materials that complemented native upland plantings for erosion and sediment control. (Photo by ECOncrete)

Broadening Benefits

The HOA wanted a holistic design approach to improve the physical condition of the shoreline while providing ecological uplift. Objectives included creating a hybrid living shoreline to prevent ongoing erosion at the island's northwest corner, mitigating potential damage to the pump station and condos along the island's northwestern shoreline during extreme weather events, incorporating nature-based elements for ecological uplift, and providing community access for recreation like fishing and kayaking. Under the NJDEP General Permit 24 for living shorelines and the USACE Living Shorelines General Permit, project designers expedited the permitting process, which provided cost savings.

Promoting Collaboration

The project is an excellent showcase for stakeholder engagement and collaboration. ECOncrete worked with the HOA on design. Financial support was provided by the HOA and Neptune Township, in addition to a grant from The Nature Conservancy to mitigate design and permitting costs. Renova Environmental Services, the project's contractor, was responsible for the regrading of the shoreline, placement of the marine mattresses, construction of the nearshore sill, marsh restoration, and creation of the terrestrial upland habitat. The American Littoral Society provided ecological consulting and logistical support toward completing restoration, organizing a volunteer planting event. Fill material was provided by Neptune Township.

Top: An aerial view of the installation. (Photo by ECOncrete)

Middle: Marine growth layer observed during biological monitoring. (Photo by ECOncrete)

Bottom: Biological monitoring showing the ECOncrete mattress (right) compared to control units (left). ECOncrete blocks had extensive growth of both Ulva *and* Fucus *algae, alongside* Sabellidae *worms and bivalves, whereas the control blocks were almost completely barren. (Photo by ECOncrete)*

Big River at Calico Creek

Fletcher, Missouri, United States

Restoring a river to its historical natural form and function. Until the early 1970s, the Southeast Missouri Lead District was the world leader in lead production for nearly 100 years. Mining operations introduced gravel, sand, and silt-sized mine waste material into the Big River. During elevated flows, this material is transported downstream, depositing into both the channel and floodplain. Most impacted areas of the watershed are now designated as a U.S. Environmental Protection Agency (USEPA) Superfund site. In coordination with state partners, the U.S. Army Corps of Engineers (USACE)–St. Louis District entered into an agreement with USEPA to design and construct a series of bank stabilization features in the Big River watershed near the confluence of the Calico Creek tributary. Historical imagery and topographic maps suggest that heavy equipment severely altered Calico Creek, creating an undesirable configuration near its confluence with the Big River. This project reconfigured the creek channel to its assumed previous layout and dimension, restoring it to a more natural form and function more conducive to balanced sediment transport through the reach.

Producing Efficiencies

Sediment excavated from Calico Creek's new channel was reused as a "plug" for the old channel, greatly reducing haul distances and the need for bringing in new material. Similarly, in the construction of the three bank stabilization features within the Big River, excavated in-channel material was reused landward of the new layout to fill the old channel (as opposed to being hauled off site with new fill material needing to be delivered). Nearby cleared trees were also selectively used as root-wad revetment. Finally, scour calculations and velocity modeling optimized the rock placement rate for bank toe protection with an approach that balanced cost with the desired level of security.

Using Natural Processes

Bank stabilization features were constructed using root-wad revetment, weirs, and longitudinal peaked stone toe protection (LPSTP) offset from the eroded bank. Root-wad revetment provides energy dissipation at the bank's toe while creating extensive in-stream cover for aquatic species. Weirs throughout the site provide additional stabilization while creating hydraulic and bathymetric diversity in the channel. LPSTP provides a fixed channel border while recruiting sediment deposition between itself and the eroded bankline. Native vegetation was planted throughout the site. Species were selected to provide rooting to hold soil in place long-term while withstanding flooding at the elevation at which they were planted.

Previous page: Bank 1 postconstruction, facing downstream, sloped and vegetated. A constructed containment area allows excess sediment to deposit and be retained. (Photo by USACE St. Louis District)

Top: Bank 1 preconstruction, facing downstream. Vertical bank erosion progresses steadily through the lead-contaminated floodplain. (Photo by USACE St. Louis District)

Bottom: Bank 3 preconstruction, facing upstream. Vertical bank erosion progresses steadily toward a narrowing access road to the floodplain bottoms. (Photo by USACE St. Louis District)

Broadening Benefits

At Bank 1, the large offset between the new channel and the old bankline provides a sink for lead-laden soil to deposit and lock in place outside of the channel, which improves the habitat for aquatic species highly sensitive to lead levels. At Bank 3, the use of root-wad revetment provides additional aquatic habitat, which is beneficial for the environment and for fishing. The new orientation of the river channel provides a clearer and easier path for recreational users, with fewer obstacles and snags than before this project.

Promoting Collaboration

The USACE St. Louis District coordinated with USEPA, the U.S. Fish and Wildlife Service, and Missouri Department of Natural Resources to balance agency authorities, funding limitations, and project objectives. Ultimately, a project was constructed to address environmental concerns while providing value to three adjacent landowners who were losing their banklines.

Top: Calico Creek realigned into a more natural configuration that is more conducive to balanced sediment transport through the reach. (Photo by USACE St. Louis District)

Middle: Bank 2 stabilized using weirs, which push the energy from the river away from the bankline and toward the thalweg. (Photo by USACE St. Louis District)

Bottom: Bank 3 postconstruction, facing upstream, sloped and vegetated. A constructed bench extends into the river and terminates with root-wad revetment. (Photo by USACE St. Louis District)

Port of Málaga

Málaga, Spain

Placing ecological blocks for structural integrity and sustainability. Recent studies have proven that slight structural modifications to increase habitat heterogeneity and surface complexity increase colonization and enhance biodiversity of marine species on different forms of coastal and marine infrastructure (CMI). This improvement can be encouraged through science-based, cost-effective enhancements in accordance with ecological engineering principles. These design approaches have been proven to provide not only significant ecological advantages over traditionally engineered CMI but also valuable structural advantages, contributing to a structure's strength, stability, and lifespan. Island Global Yachting (IGY) Marinas turned the harbor located in Málaga in Southern Spain into a superyacht marina and ecologically enhanced it by incorporating ECOncrete into a vertical breakwater. The bioenhancing solution was integrated into eight-cubic-meter concrete blocks, applying the specified concrete composition and surface design. The result is a healthy ecosystem developing on the concrete, quickly generating a layer of bioprotection to strengthen the structure and reduce maintenance. The increased biodiversity also improved water quality and serves as a natural carbon sink, actively sequestering carbon dioxide during the lifetime of the structure. The applied technology meets internationally recognized concrete standards, and neither the manufacturing nor the installation required modification of standard construction processes.


Trasmediterránea

Producing Efficiencies

The ecological blocks, developed to mitigate the pier's ecological impact and improve the durability of marine structures, consisted of multiple elements working together to decrease the ecological footprint and enable the growth of marine life on concrete structures. The admixture—a key component of the patented bioenhancing concrete solution—seals the concrete internally to improve impermeability, chloride penetration, and structural lifespan. Customized, locally produced reusable liners were fitted to the existing breakwater formwork by project contractors. These liners, coupled with mold-modifying agents and coatings, create complex surface textures that allow rich, diverse marine life to develop.

Using Natural Processes

Addressing the chemical composition and surface of the concrete on a micro and macro level has promoted the growth of organisms like oysters, coral, and barnacles, which act as biological glue to enhance structural strength, durability, stability, and longevity. A proprietary bioenhancing admixture produces a chemically balanced concrete, creating a neutralized surface and environment that enables healthy and diverse marine ecosystems to develop. The surface complexity of the concrete blocks is based on biomimicry design principles and adapted to support the natural development of local species.

Previous page: Port of Málaga marina pier installation. Integration of ECOncrete technology during the construction of a vertical breakwater to include nature-inclusive engineering features that are designed to promote marine biodiversity and limit project impact. (Photo by ECOncrete Inc.)

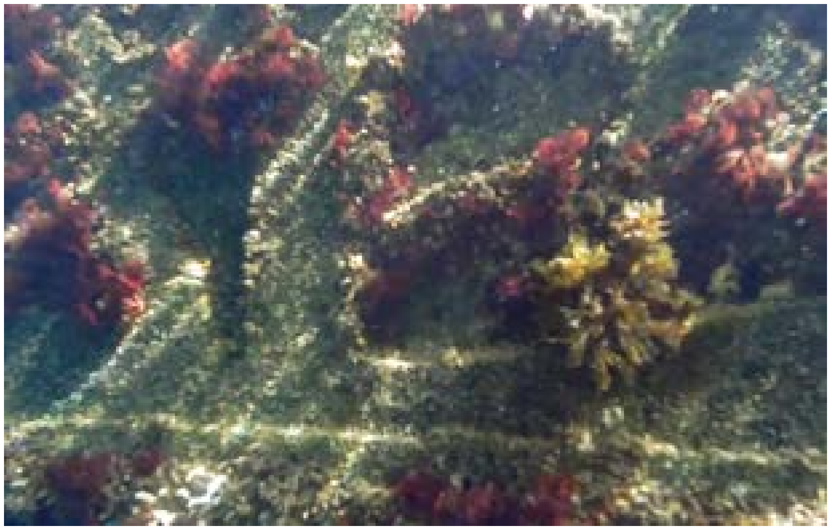
Right: Alternate view of the ecological block installation. The technology is inspired by and works with nature to provide ecological benefits while still achieving structural integrity and sustainability. (Photo by ECOncrete Inc.)

Broadening Benefits

With the marina's location in a heavily trafficked maritime region, the incorporation of ECOncrete structures into the project design has created marine life and habitat opportunities traditionally unavailable in the marina. The structures will now foster local species settlement, minimize typical invasive species dominance found at marinas, and improve overall water quality throughout the harbor. Within less than a year postinstallation, local species were seen proliferating on the top part of the structure, and fan worms (*Sabella*), calcareous sponges (*Calcarea*), snakelocks (*Anemonia viridis*), sea anemones (*Actiniaria*), and brown algae (*Phaeophyceae*) have been identified.

Promoting Collaboration

The enhanced vertical breakwater has encouraged and enhanced biodiversity, enabling important ecosystem services and strengthening the structure. Through ECOncrete's partnership with IGY Marinas, the project has enabled IGY Marinas to promote environmental stewardship and the value of working with nature to achieve analogous structural objectives. The marina was motivated to develop greener alternatives for their operations and identify applicable market solutions. For its sustainable approach, the project received the Excelencias Turísticas Azul Award in 2021.



Top: Biological growth developing on the new structure, which created a habitat area for native species and promoted improvements to overall water quality. (Photo by ECOncrete Inc.)

Middle: Biological growth 10 months post deployment. A variety of algaes and tubeworms were observed, which, amongst other ecosystem services, contribute to water filtration in the marina basin. (Photo by ECOncrete Inc.)

Bottom: ECOncrete marine biodiversity growth versus a control unit below. The top of the quay block was modified with ECOncrete, and the lower portion was left as a control, displaying a staunch biological difference. (Photo by ECOncrete Inc.)

Kaskaskia River Basin

Modoc, Carlyle, and Shelbyville, Illinois, United States

Promoting revegetation through the use of drawdowns. With a total of 15,126 square kilometers of drainage and a presence in 22 counties, the Kaskaskia River Basin is the main tributary of the Mississippi River, flowing southwest through Illinois. The Jerry Costello Lock and Dam, previously called the Kaskaskia Lock and Dam, is located on the lower end of the basin, about one kilometer from the river. Lake Shelbyville and Carlyle Lake are two multipurpose reservoirs working cooperatively in the basin. Project purposes for each reservoir are flood control, recreation, navigation, water quality, fish and wildlife conservation, and water supply. Several years ago, the U.S. Army Corps of Engineers (USACE)–St. Louis District started to explore changes in water-level management that would continue to support flood control and navigation while enhancing wildlife conservation and recreational purposes. USACE St. Louis District successfully implemented 15-centimeter late-summer pool drawdowns at each of the locations in 2021 and 2022 to promote the revegetation of banklines, backwaters, and coves. The district will continue to work with agency partners and host public meetings to discuss project implementation and address questions.

Producing Efficiencies

USACE St. Louis District, Office of Water Control, uses the newer Corps Water Management Systems models to produce daily forecasts with and without precipitation for decision-making and upward reporting. Capable of using 16-day precipitation grids in six-hour increments, this technology enables the office to help plan drawdowns using real-time data and alternatives analysis. Additionally, DigitalGlobe aerial imagery data sets at both normal summer pool and drawdown elevations at each site were used to delineate water lines and calculate area exposed. These data were later combined with predicted seedhead production to estimate the number of waterfowl that could be supported as a result of the drawdowns.

Using Natural Processes

When conditions for the growing season are favorable, the Office of Water Control will draw down the pools throughout the basin at Lake Shelbyville, Carlyle Lake, and the lock and dam to let the aquatic vegetation establish growth. The office will then bring water levels up slowly to ensure that vegetation is not overtopped. Fluctuations at these project sites are a natural occurrence. In 2022, the drawdown on the lower Kaskaskia resulted in approximately 1,009 kilograms of seed per hectare of emergent vegetation. This is comparable to intensively managed moist-soil units, which depend on water-level management and periodic disturbance.

Previous page: A backwater on the Lower Kaskaskia River. Bands of color help to illustrate how vegetation established in zones as conditions became favorable for germination. (Photo by USACE St. Louis District)

Top: A tributary corridor and cove in Lake Shelbyville that germinated as a result of the 15-centimeter environmental pool drawdown in August and September 2022. (Photo by USACE St. Louis District)

Bottom: The shorter vegetation, growing 61 to 91 centimeters, is the result of the 15-centimeter drawdown in this oxbow of the Kaskaskia River. (Photo by USACE St. Louis District)

Broadening Benefits

The improved plant production and habitat structure increased the wildlife that can be supported, leading to improved recreational opportunities through nature viewing, hunting, and fishing. A drawdown of pool elevations to 15 centimeters below normal has been used to expose mudflats and banklines, providing shallow hunting areas for waterbirds. As the exposed sediment dries, its structure reduces erosion and allows emergent wetland plants to establish. This vegetation improves water clarity by slowing water movement and trapping sediment and often serves as an important food source for migratory waterfowl.

Promoting Collaboration

The district hosts an annual public meeting at each location to facilitate communication around general project operation, safety, and any additional initiatives, such as the 15-centimeter growing-season drawdown to enhance environmental benefits. Discussion includes a summary of current-year drawdown results and the tentative plan for the coming year, with feedback from local businesses and the public. Coordination calls with USACE operations and the Illinois Department of Natural Resources (the primary agency partner) are initiated as conditions become suitable to begin a drawdown. At season's end, a call is held to discuss results and any potential future changes.

*Top: Shorebirds and egrets (*Ardea *sp.) hunt in the shallow water created by the drawdown by environmental pool management in late summer 2021 at Carlyle Lake. (Photo by USACE St. Louis District)*

Middle: Environmental pool management promotes primarily native, annual emergent vegetation. These species are highly productive and produce an abundance of seed favored by waterfowl. (Photo by USACE St. Louis District)

*Bottom: In addition to native annual emergent vegetation, some perennial aquatic species, such as arrowhead (*Sagittaria latifolia*), can be promoted by drawdowns occurring in consecutive years. (Photo by USACE St. Louis District)*

Mayer Ranch

Ottawa County, Oklahoma, United States

Implementing a region's first-of-its-kind, full-scale mine water quality improvement system. Mining and mineral processing around the world have resulted in massive disturbances to and the degradation of land and water. Surface water and groundwater at the Tar Creek Superfund site in Oklahoma's Tri-State Lead-Zinc District were deemed "irreversibly damaged" decades ago, and elevated concentrations of trace metals have severely degraded local streams. In 2008 the University of Oklahoma Center for Restoration of Ecosystems and Watersheds, the U.S. Environmental Protection Agency, the Oklahoma Department of Environmental Quality, and the Quapaw Nation implemented the Mayer Ranch passive treatment system at the site. By merging ecosystem ecology and engineering design, the system uses natural processes to efficiently produce treated water that meets in-stream quality criteria and maximizes diverse benefits, including a recovered fish community and reestablished populations of beavers, otters, and other fauna. Now that initial construction and planting of select process units have been completed, operation and maintenance commitments are minimal. Mayer Ranch has been the site of several university research projects and class visits, and dozens of public outreach tours are conducted there every year. The collaboration of state, local, and tribal partners has been fundamental to the project's success, and the university's community-engaged, service-learning approach has led to the installation of another passive treatment system and plans to further address other polluted water sources.

Producing Efficiencies

The passive treatment approach is based on decades of research to thoroughly understand naturally occurring biogeochemical mechanisms and optimize an Engineering With Nature (EWN) approach. Although conventional methods of improving water quality are available, they often are neither financially nor operationally feasible at abandoned industrial sites. Successful operation of the passive treatment system requires efficient coupling of natural ecosystem processes with a thorough site-specific environmental characterization to design, build, and operate multiple ecosystem-type process units addressing a mix of environmental risk drivers. Coproduction of benefits is efficiently enhanced by allowing ecological self-design to dictate and modify system configurations.

Using Natural Processes

Active treatment approaches to improve water quality require the regular addition of refined chemicals, constant use of fossil fuels, and consistent operation and maintenance oversight. Passive treatment approaches rely on environmental conditions to optimize natural processes and maximize benefits. At Mayer Ranch, aerobic (requiring oxygen) and anaerobic (requiring no oxygen) biogeochemical mechanisms are maximized in different process units to address distinct objectives. All hydrologic flows are driven by hydraulic head differences, and solar and wind energies are used to enhance physical, chemical, and biological performance. Operationally, the implemented system requires no fossil fuel commitment and only minimal maintenance.

Previous page: University of Oklahoma (OU) Center for Restoration of Ecosystems and Watersheds (CREW) researchers collecting vegetation samples from the surface-flow wetland process units in summer 2023. (Photo by OU CREW)

Right: OU CREW researchers filtering water samples at the final outflow in spring 2017. (Photo by OU CREW)

Broadening Benefits

The passive treatment system has improved water quality, aided the ecological recovery of the receiving stream, and provided wildlife habitat and a broad suite of ecosystem services. Located on the historic treaty lands of the Quapaw Nation and in a region of economic and environmental decline, the project's social benefits include promising ecological restoration alternatives, evidence of the critical role of traditional ecological knowledge in solving environmental challenges, significant opportunities for public outreach, education, and research, demonstration of effective nature-based solutions, and provision of optimistic future expectations. Economic benefits include providing a foundation for economic recovery by demonstrating that intractable environmental problems are solvable.

Promoting Collaboration

The project demonstrates the power of collaboration to address recalcitrant problems. In addition to state and federal agencies, the role of multiple academic, tribal, local government, and nonprofit partners cannot be overstated. Despite the myriad challenges presented by conducting innovative work on a Superfund site on Native land, the diverse partners recognized the many cobenefits of an EWN approach and provided direct and indirect support to university-led efforts. Most important, because the project is on private land, it required the nurturing and maintenance of trustworthy relationships with agricultural producers.

Top: Sampling one of the mine water inflows to the Mayer Ranch passive treatment system in fall 2022. (Photo by OU CREW)

*Bottom: A North American river otter (*Lontra canadensis*) captured at the Mayer Ranch outflow by a remote wildlife camera in 2023. River otter were not seen in this watershed until after the return of fish populations in 2009 and beaver (*Castor*) populations in 2013. (Photo by OU CREW)*

*A great egret (*Ardea alba*) feeding in the Teaneck Creek Park shallows along the edge of one of the sand seepage pools, which supports prey species, including various fish, water snakes, frogs, and others (project details on page 52). (Photo by David Ike Photography)*

Conclusion

Recognizing EWN opportunities and encouraging action

Looking to the Future

Those who contemplate the beauty of the earth find reserves of strength that will endure as long as life lasts.
—Rachel Carson

The journey through these Engineering With Nature (EWN) projects stands as a testament to the boundless potential of partnership between human innovation and the natural world. As we close this volume, we are reminded of Rachel Carson's words:

> There is symbolic as well as actual beauty in the migration of the birds, the ebb and flow of the tides, the folded bud ready for the spring. There is something infinitely healing in the repeated refrains of nature—the assurance that dawn comes after night, and spring after winter.[1]

Just as the achievements of engineering have shaped the past century, so too can they shape the next. Yet, the question arises: What expanded value can human engineering create in a partnership with nature? The answer lies in our collective commitment to innovation, collaboration, and stewardship.

As we embark on this journey, we must also embrace the development of new science, engineering, and methods of working. Focused research and development, coupled with interdisciplinary collaboration, will unlock the full potential of nature-based solutions.

Introducing new ideas and methods into practice requires a concerted effort to bridge the gap between theory and application. By fostering dialogue and exchange among researchers and practitioners, we can ensure that cutting-edge innovations find practical implementation.

[1] Rachel Carson, *The Sense of Wonder: A Celebration of Nature for Parents and Children* (1965; repr., New York: Harper Perennial, 1998), 98. Citations refer to Kindle edition.

*Clockwise: Habitat reef installation in the Lake Michigan nearshore via crane and barge at Fort Sheridan (project details on page 16) (photo by FadeOut Media); marking a biological monitoring location on the breakwaters at the Hancock County living shoreline (project details on page 44) (photo by Sarah Ballard, Anchor QEA); Mayer Ranch final outflow after successful passive treatment of mine water in fall 2021 (project details on page 272) (photo by University of Oklahoma Center for Restoration of Ecosystems and Watersheds); and boulders along the edge of the river at the Mission Reach project provide bank stability while increasing habitat for fish, freshwater mussels (*Margaritifera*), and other aquatic organisms (project details on page 148) (photo by San Antonio River Authority).*

Through deliberate efforts to engage across sectors, we can harness diverse perspectives and experiences to advance sustainable infrastructure. The Network for EWN stands as a beacon for such collaboration.

Education and training are paramount to preparing future generations for the challenges and opportunities ahead. By equipping professionals and communities with the knowledge and skills needed to embrace nature-based solutions, we ensure a sustainable legacy for generations to come.

Strategic communication will be the linchpin of our success. Through channels like the EWN website, the *Atlas* series, and the podcast series, we can share best practices, inspire action, and foster confidence in our collective vision. Documenting the diverse benefits of EWN approaches is essential for driving progress. Understanding and quantifying the economic, environmental, and social benefits of our endeavors will guide future decision-making and investment.

In the coming years, the EWN Initiative will continue to collaborate and collectively share in success. Together, we will build a future where nature and engineering are partners and allies, creating a world of endless possibilities. Let us embrace this journey with optimism, determination, and a profound respect for the beauty and wonders of the natural world, and in doing so, "find reserves of strength that will endure as long as life lasts."

Over 5,000 trees, 77,000 shrubs, and 2 million herbaceous plants will be planted as part of the Port Lands Flood Protection Project—most by hand (project details on page 252). (Photo by Waterfront Toronto / Vid Ingelevics / Ryan Walker)

A split hopper dredge rainbowing sand onto Palm Beach, where over 470,000 cubic meters of sand were delivered to the nearshore via bottom placement and rainbowing (project details on page 132). (Photo by City of Gold Coast)

Acknowledgments

The following individuals were members of the ERDC project team responsible for developing Engineering With Nature: An Atlas, Volume 3: Amanda Tritinger, Courtney Chambers, Burton Suedel, Michelle Bourne, Emily Moynihan, and Jeffrey King. Anchor QEA provided technical support, editorial review, and production of *EWN Atlas, Volume 3*, under contract to ERDC. The Anchor QEA team members consisted of Zelini Hubbard, Lydia Pudzianowski, Ken Mayo, Ram Mohan, Christopher Overcash, and Zheng Fang. Portions of the "Introduction" have been modified and reprinted from T. S. Bridges, E. M. Bourne, B. C. Suedel, E. B. Moynihan, and J. K. King, *Engineering With Nature: An Atlas®, Volume 2*, ERDC SR-21-2 (Vicksburg, MS: U.S. Army Engineer Research and Development Center, 2021), http://dx.doi.org/10.21079/11681/40124, public domain. The team wishes to thank the following individuals and their respective organizations for contributing the project information and photos that ultimately resulted in this publication:

Beaches and Dunes

Fort Sheridan is located in Lake Forest, Highland Park, and Fort Sheridan, Illinois, United States. Project information and photos courtesy of Samantha Belcik, U.S. Army Corps of Engineers–Chicago District. For more information concerning this project, please contact Samantha Belcik by email at samantha.d.belcik@usace.army.mil.

North Sandy Pond is located in Sandy Creek, New York, United States. Project information and photos courtesy of Thomas Hart, Hart Environmental Science & Planning, and David Klein, The Nature Conservancy. For more information concerning this project, please contact Thomas Hart by email at thomashart109@gmail.com.

Oranjestad Shoreline is located in Oranjestad, Aruba. Project information and photos courtesy of Joseph Little, PE, Little Environments, PLLC. For more information concerning this project, please contact Joseph Little by email at joseph.little@littleenvironments.com.

Sodus Point Beach is located in Sodus Point, New York, United States. Project information and photos courtesy of Thomas Hart, Hart Environmental Science & Planning. For more information concerning this project, please contact Thomas Hart by email at thomashart109@gmail.com.

Ameland Inlet is located in Ameland, Friesland, the Netherlands. Project information and photos courtesy of Quirijn Lodder, Stefan Pluis, and Thijs van Rhijn, Rijkswaterstaat. For more information concerning this project, please contact Stefan Pluis by email at Stefan.Pluis@rws.nl or Quirijn Lodder by email at Quirijn.Lodder@rws.nl. Some images have been adapted from Sentinel Hub, Sinergise Solutions d.o.o, https://www.sentinel-hub.com/explore/eobrowser/. Web application.

Wetlands

Lower Brule is located in Lower Brule, South Dakota, United States. Project information and photos courtesy of Drew Minert, U.S. Army Corps of Engineers–Omaha District. For more information concerning this project, please contact Drew Minert by email at Drew.D.Minert@usace.army.mil.

Hancock County Marsh is located in Hancock County, Mississippi, United States. Project information and photos courtesy of Wendell Mears and Sarah Ballard, Anchor QEA. For more information concerning this project, please contact Wendell Mears by email at wmears@anchorqea.com.

Lightning Point is located in Bayou La Batre, Alabama, United States. Project information and photos courtesy of Mary Kate Brown, The Nature Conservancy. For more information concerning this project, please contact Mary Kate Brown by email at mkbrown@tnc.org.

Teaneck Creek Park is located in Teaneck, New Jersey, United States. Project information and photos courtesy of Joseph Berg, Biohabitats, Inc. For more information concerning this project, please contact Joseph Berg by email at jberg@biohabitats.com.

Amoco is located in Muskegon, Michigan, United States. Project information and photos courtesy of Dusty Tazelaar, Ramboll. Funding by the Great Lakes Restoration Initiative and U.S. Environmental Protection Agency was provided via a regional partnership between the grantors, the National Oceanic and Atmospheric Administration, and the Great Lakes Commission. The project was administered by the West Michigan Shoreline Regional Development Commission. For more information concerning this project, please contact Dusty Tazelaar by email at dusty.tazelaar@ramboll.com.

Belcher Street Marsh is located in Kentville, Nova Scotia, Canada. Project information and photos courtesy of Jane Heeney, TransCoastal Adaptations: Centre for Nature-Based Solutions at Saint Mary's University. For more information concerning this project, please contact Jane Heeney by email at jane.heeney@smu.ca.

Spicer Creek is located in Grand Island, New York, United States. Project information and photos courtesy of Mark Filipski, New York State Department of Environmental Conservation. For more information concerning this project, please contact Mark Filipski by email at mark.filipski@dec.ny.gov.

Baptiste Collette Bayou is located in Venice, Louisiana, United States. Project information and photos courtesy of Jeff Corbino, U.S. Army Corps of Engineers–New Orleans District. For more information concerning this project, please contact Jeff Corbino by email at jeffrey.m.corbino@usace.army.mil. Portions of this project's text have been modified and reprinted from P. E. Whitfield, B. C. Suedel, K. A. Egan, J. M. Corbino, J. L. Davis, D. C. Carson, A. S. Tritinger, D. M. Szimanski, William L. Balthis, Joe Z. Gailani, and Jeffrey K. King, *Engineering With Nature® Principles in Action: Islands*, ERDC TR-22-9, (Vicksburg, MS: U.S. Army Engineer Research and Development Center, 2022), http://dx.doi.org/10.21079/11681/44940. Public domain.

Wagon Hill Farm is located in Durham, New Hampshire, United States. Project information and photos courtesy of Thomas Ballestero, University of New Hampshire, Coastal Habitat Research Team. For more information concerning this project, please contact Thomas Ballestero by email at tom.ballestero@unh.edu.

LIFE adapto is located in Authie Bay, Orne Estuary, Lancieux Bay, Moëze Marsh, Gironde Estuary, Leyre Delta, Petit et Grand Travers, Vieux-Salins d'Hyères, and Golo Delta, France, and in Mana, French Guiana. Project information and photos courtesy of Adrien Privat, Conservatoire du littoral. For more information concerning this project, please contact Adrien Privat by email at a.privat@conservatoire-du-littoral.fr.

Great Lakes Wetland is located in Defiance, Ohio, United States. Project information and photographs courtesy of the Jacob Berkowitz, U.S. Army Engineer Research and Development Center. For more information about this project, please contact Jacob Berkowitz by email at Jacob.F.Berkowitz@usace.army.mil.

Crumpmeadow is located in Cinderford, England, United Kingdom. Project information and photos courtesy of Helen Leyshon, Mott MacDonald Bentley. For more information concerning this project, please contact Helen Leyshon by email at helen.leyshon@mottmac.com.

Islands

Mubbaraz Island is located in Mubarraz Island, Abu Dhabi, United Arab Emirates. Project information and photos courtesy of Paul Erftemeijer, University of Western Australia Oceans Institute and School of Biological Sciences, and Manimaram Ramamoorthy and Rauda Al Nuaimi, Abu Dhabi Oil Co. Ltd (Japan). For more information concerning this project, please contact Paul Erftemeijer by email at paul.erftemeijer@uwa.edu.au. Portions of this project's text have been modified and reprinted with permission from P. Erftemeijer, S. Ito, and H. Yamamoto, "Creating Mangrove Habitat for Shoreline Protection: Working with Nature in the Arabian Gulf," *Terra et Aqua* 162 (2021): 16–27, https://www.iadc-dredging.com/article/creating-mangrove-shoreline-protection/. Copyright © 2020 International Association of Dredging Companies and individual contributors.

Tigertail Lagoon and Sand Dollar Island are located in Marco Island, Florida, United States. Project information and photos courtesy of Mohamed Dabees, Humiston & Moore Engineers. For more information concerning this project, please contact Mohamed Dabees by email at md@humistonandmoore.com. Portions of this project's text have been modified and reprinted from M. A. Dabees, M. Fleming, and M. Damon, "Natural and Nature Based Features for Environmental Enhancement and Coastal Storm Risk Management: A Case Study on Marco Island, Florida, United States," *Frontiers in Built Environment* 29 (2022), https://doi.org/10.3389/fbuil.2022.884692. Copyright © 2022 Dabees, Fleming, and Damon. Licensed under CC BY 4.0, https://creativecommons.org/licenses/by/4.0/.

Ohio River Bonanza Bar is located in Portsmouth, Ohio, United States. Project information and photos courtesy of David Johnston, Christopher (Blake) Chadwick, and Jamie Sunderland, U.S. Army Corps of Engineers–Huntington District. For more information concerning this project, please contact David Johnston by email at David.L.Johnston@usace.army.mil. Portions of this project's text have been modified and reprinted from A. D. McQueen, B. C. Suedel, K. E. Harris, A. S. Murray, D. P. May,

C. B. Chadwick, A. N. Johnson, J. L. Sunderland, D. L. Johnston, and J. T. Whipkey, "Sustainable Dredged Material Management on the Ohio and Kanawha Rivers to Achieve Multiple Benefits," in Proceedings of the Dredging Summit & Expo 2023 (Western Dredging Association, 2023), https://www.westerndredging.org/phocadownload/2023_Las_Vegas/Proceedings/WEDA%202023%20Conference%20Proceedings.pdf. Public domain.

Fort Pierce Island is located in Fort Pierce, Florida, United States. Project information and photos courtesy of Erin Hague and Tracy Lybolt, Tetra Tech Inc. For more information concerning this project, please contact Erin Hague by email at erin.hague@tetratech.com. Portions of this project's text have been modified and reprinted with permission from Tetra Tech Inc., "Designing a Stronger, Resilient Marina to Provide Storm Protection in Florida," https://www.tetratech.com/projects/designing-a-stronger-resilient-marina-to-provide-storm-protection-in-florida/. Copyright 2024 Tetra Tech Inc.

Interstate Island is located in Duluth, Minnesota, and Superior, Wisconsin, United States. Project information and photos courtesy of James Luke and Monica Anderson, U.S. Army Corps of Engineers–Detroit District. For more information concerning this project, please contact James Luke by email at james.d.luke@usace.army.mil.

Sand Island is located in Mobile County, Alabama, United States. Project information and photos courtesy of Elizabeth Godsey, U.S. Army Corps of Engineers–Mobile District. For more information concerning this project, please contact Elizabeth Godsey by email at elizabeth.s.godsey@usace.army.mil.

Reefs

Huon Mundy Oyster Reefs are located in Noosa, Queensland, Australia. Project information and photos courtesy of Sam King, International Coastal Management. For more information concerning this project, please contact Sam King by email at sam@coastalmanagement.com.au.

North Carolina Highway 24 is located in Swansboro, North Carolina, United States. Project information and photos courtesy of Brian Lipscomb, North Carolina Department of Transportation. For more information concerning this project, please contact Brian Lipscomb by email at blipscomb@ncdot.gov.

Waisanding Sandbar is located in Dongshi Township, Chiayi County, Taiwan. Project information and photos courtesy of Ching-Wen Chen, Water Resources Agency, Ministry of Economic Affairs, Taiwan. For more information concerning this project, please contact Ching-Wen Chen by email at cwchen@wra.gov.tw.

Palm Beach is located in Palm Beach, Queensland, Australia. Project information and photos courtesy of Zoe Elliott-Perkins, City of Gold Coast. For more information concerning this project, please contact Zoe Elliott-Perkins by email at zelliott-perkins@goldcoast.qld.gov.au. Portions of this project's text have been modified and reprinted with permission from Z. Elliott-Perkins, "Palm Beach Artificial Reef Transforms Sandy Substrate to Underwater Wonderland," *Engineering for Public Works* 19 (2020): 49–54, https://issuu.com/ipweaqld/docs/3660___epw_september_2020_final/49, copyright Institute of Public Works Engineering Australasia, Queensland & Northern Territory; Z. Elliott-Perkins, C. Wharton, P. Prenzler, E. Watterson, and L. De Lucia, "Palm Beach Shoreline Project: Post-Project Outcomes Measured Through Key Performance Indicators," abstract, 2023 Australasian Coasts & Ports Conference, August 15–18, 2023, copyright East Coast Conferences; and City of Gold Coast, *Palm Beach Shoreline Project: Project Overview*, brochure (Gold Coast, Australia: City of Gold Coast, 2020), https://www.goldcoast.qld.gov.au/files/sharedassets/public/v/1/pdfs/environment/palm-beach-shoreline-project-brochure-a4.pdf, copyright City of Gold Coast.

Gibraltar Point is located in Toronto, Ontario, Canada. Project information and photos courtesy of Mohammad Dibajnia, Baird & Associates. For more information concerning this project, please contact Mohammad Dibajnia by email at mdibajnia@baird.com.

SEAHIVE and Concrete 3D Printing are located in Destin Beach and Wahoo Bay, Florida, United States. Project information and photos courtesy of Adam Friedman, 1Print, LLC, and University of Miami, Rosenstiel School of Marine, Atmospheric, and Earth Science. For more information concerning this project, please contact Adam Friedman by email at info@1print.one.

Riverine Systems

Mission Reach is located in San Antonio, Texas, United States. Project information and photos courtesy of the Shaun Donovan, San Antonio River Authority. For more information concerning this project, please contact Shaun Donovan by email at sdonovan@sariverauthority.org.

*Clockwise: Marbled godwits (*Limosa fedoa*) on the Lake Red Rock delta (project details on page 156) (photo by Stephen Dinsmore, Iowa State University); giant hermit crab (*Petrochirus diogenes*) present at enhanced habitat (project details on page 96) (photo by Marielle Nageon de Lestang, Turrell Hall & Associates); Huon Mundy reef patches were designed specifically for each site and surveyed during construction to ensure the substrate was being placed correctly (project details on page 120) (photo by Craig Bohm, The Nature Conservancy); and Buffalo Slough Island was planted using the bare root method, containerized trees, and by seed casting (project details on page 184) (photo by Lewis Wiechmann, USACE St. Paul District).*

Dahan River is located in Banqiao District, New Taipei City, Taiwan. Project information and photos courtesy of Ching-Wen Chen, Water Resources Agency, Ministry of Economic Affairs, Taiwan. For more information concerning this project, please contact Ching-Wen Chen by email at cwchen@wra.gov.tw.

Des Moines River is located in Iowa, United States. Project information and photos courtesy of Perry Thostenson, U.S. Army Corps of Engineers–Environmental Stewardship & Sustainable Rivers Program, and Stephen J. Dinsmore and Nicole Bosco, Iowa State University. For more information concerning this project, please contact Perry Thostenson by email at Perry.M.Thostenson@usace.army.mil. Portions of this project's text have been modified and reprinted from U.S. Army Corps of Engineers, *Stewardship* 6, no. 1 (2023), https://corpslakes.erdc.dren.mil/employees/envsteward/pdfs/news/V6N1-0323.pdf. Public domain.

Arden Park is located in Edina, Minnesota, United States. Project information and photos courtesy of Michael Chergosky, Inter-Fluve. For more information concerning this project, please contact Michael Chergosky by email at mchergosky@interfluve.com.

Winfield Locks and Dam are located in Winfield, West Virginia, United States. Project information and photos courtesy of Andrew Johnson, U.S. Army Corps of Engineers–Huntington District. For more information concerning this project, please contact Andrew Johnson by email at andrew.n.johnson@usace.army.mil. Portions of this project's text have been modified and reprinted from A. D. McQueen, B. C. Suedel, K. E. Harris, A. S. Murray, D. P. May, C. B. Chadwick, A. N. Johnson, J. L. Sunderland, D. L. Johnston, and J. T. Whipkey, "Sustainable Dredged Material Management on the Ohio and Kanawha Rivers to Achieve Multiple Benefits," in Proceedings of the Dredging Summit & Expo 2023 (Western Dredging Association, 2023), https://www.westerndredging.org/phocadownload/2023_Las_Vegas/Proceedings/WEDA%202023%20Conference%20Proceedings.pdf. Public domain.

Duwamish River People's Park is located in Seattle, Washington, United States. Project information and photos courtesy of the Kathleen Hurley and Mallory Hauser, Port of Seattle. For more information concerning this project, please contact Kathleen Hurley by email at Hurley.K@portseattle.org. Portions of this project's text have been modified and reprinted with permission from World Port Sustainability Program, "Port of Seattle – Duwamish River People's Park and Shoreline Habitat," https://sustainableworldports.org/project/port-of-seattle-duwamish-river-peoples-park-and-shoreline-habitat. Copyright © 2024 World Port Sustainability Program.

Kinzua Dam is located in Warren, Pennsylvania, United States. Project information and photos courtesy of Carol Vernon and Andrew Byrne, U.S. Army Corps of Engineers–Pittsburgh District. For more information concerning this project, please contact Carol Vernon by email at carol.e.vernon@usace.army.mil. Portions of this project's text have been modified and reprinted from U.S. Army Corps of Engineers–Pittsburgh District, "Pittsburgh District's Water Quality Team Conducts First 'Spring Pulse'" (Pittsburgh, PA: U.S. Army Corps of Engineers–Pittsburgh District), 17 April 2023, https://www.lrp.usace.army.mil/Media/News-Stories/Article/3364635/pittsburgh-districts-water-quality-team-conducts-first-spring-pulse/. Public domain.

Lake County Ravine 8 is located in Highland Park, Illinois, United States. Project information and photos courtesy of Frank Veraldi and Robbie Sliwinski, U.S. Army Corps of Engineers–Chicago District. For more information concerning this project, please contact Frank Veraldi by email at Frank.M.Veraldi@usace.army.mil.

Floodplains

Buffalo Slough Island is located in Welch, Minnesota, United States. Project information and photos courtesy of Kimberly Warshaw, Lewis Wiechmann, and Aaron McFarlane, U.S. Army Corps of Engineers–St. Paul District. For more information concerning this project, please contact Kimberly Warshaw by email at kimberly.a.warshaw@usace.army.mil.

Lower Dungeness River is located in Clallam County, Washington, United States. Project information and photos courtesy of Cathy Lear, Clallam County. For more information concerning this project, please contact Cathy Lear by email at cathy.lear@clallamcountywa.gov.

Nason Creek is located in Merritt, Washington, United States. Project information and photos courtesy of Michael Chergosky, Inter-Fluve. For more information concerning this project, please contact Michael Chergosky by email at mchergosky@interfluve.com.

Lower Elkhorn Basin is located in Sacramento, California, United States. Project information and photos courtesy of David Pesavento, California Department of Water Resources. For more information concerning this project, please contact David Pesavento by email at david.pesavento@water.ca.gov.

Lower Otter Valley is located in the Budleigh Salterton, East Devon, United Kingdom. Project information and photos courtesy of Jasmine van der Eijk, Environment Agency. For more information concerning this project, please contact Jasmine van der Eijk by email at jasmine.vandereijk@defra.gov.uk. Portions of this project's text have been modified and reprinted from Environment Agency, "New Trees to Benefit Community, Wildlife and Environment in the Lower Otter," press release, April 17, 2023, https://www.gov.uk/government/news/new-trees-to-benefit-community-wildlife-and-environment-in-the-lower-otter. Contains public sector information licensed under the Open Government Licence v3.0, https://www.nationalarchives.gov.uk/doc/open-government-licence/version/3/.

Mud Creek Confluence is located in Mills River, North Carolina, United States. Project information and photos courtesy of Brandon Spaugh, North State Environmental, Inc., and Greg Jennings, Jennings Environmental, PLLC. For more information concerning this project, please contact Brandon Spaugh by email at b.spaugh@nsenv.com.

Use of Vegetation and Natural Materials

Mersea Harbour and Horsey Island are located in Essex, United Kingdom. Project information and photos courtesy of Kieren Alexander, Royal Society for the Protection of Birds. For more information concerning this project, please contact Kieren Alexander by email at kieren.alexander@rspb.org.uk.

Coonamessett River is located in Falmouth, Massachusetts, United States. Project information and photos courtesy of Michael Chergosky, Inter-Fluve. For more information concerning this project, please contact Michael Chergosky by email at mchergosky@interfluve.com.

Marlfield Farm is located in Earby, Lancashire, United Kingdom. Project information and photos courtesy of Paul Millard, Mott MacDonald. For more information concerning this project, please contact Paul Millard by email at paul.millard@mottmac.com.

Illinois Beach State Park is located in Zion, Illinois, United States. Project information and photos courtesy of Sean Burkholder, Healthy Port Futures / University of Pennsylvania / Proof Projects. For more information concerning this project, please contact Sean Burkholder by email at seanburk@design.upenn.edu.

Littlestock Brook is located in Milton-under-Wychwood, Oxfordshire, United Kingdom. Project information and photos courtesy of Richard Body, HR Wallingford, and Ann Berkeley, Wild Oxfordshire. For more information concerning this project, please contact Richard Body by email at r.m.body@hrwallingford.com or Ann Berkeley at ann@wildoxfordshire.org.uk.

Kinder Scout is located in Kinder, Derbyshire, United Kingdom. Project information and photos courtesy of Robbie Carnegie and Tom Spencer, Moors for the Future Partnership. For more information concerning this project, please contact Robbie Carnegie by email at robbie.carnegie@peakdistrict.gov.uk. Portions of this project's text have been modified and reprinted from Moors for the Future Partnership, "Superhero Sphagnum Moss Reduces Flood Risk" (United Kingdom: Moors for the Future Partnership), 28 September 2022, https://www.pressreleasepoint.com/superhero-sphagnum-moss-reduces-flood-risk. Licensed under CC BY 3.0 DEED, https://creativecommons.org/licenses/by/3.0/.

Port Bay Cobble Bell is located in Port Bay, New York, United States. Project information and photos courtesy of Sean Burkholder, Healthy Port Futures / University of Pennsylvania / Proof Projects. For more information concerning this project, please contact Sean Burkholder by email at seanburk@design.upenn.edu.

Environmental Enhancement of Infrastructure

Newlyn is located in Newlyn, Cornwall, United Kingdom. Project information and photos courtesy of Harriet Googe, Environment Agency. For more information concerning this project, please contact Harriet Googe by email at Harriet.Googe1@environment-agency.gov.uk.

Cape Cod is located in Chatham, Massachusetts, United States. Project information and photos courtesy of Seth Wilkinson and Jeremy Schaub, Wilkinson Ecological Design, Inc. For more information concerning this project, please contact Seth Wilkinson by email at info@wilkinsonecological.com.

Port Lands are located in Toronto, Ontario, Canada. Project information and photos courtesy of Steve Desrocher and Michela Comparey, Waterfront Toronto. For more information concerning this project, please contact Waterfront Toronto by email at info@waterfrontoronto.ca.

Shark River is located in Neptune, New Jersey, United States. Project information and photos courtesy of Andrew Rella, ECOncrete. For more information concerning this project, please contact Andrew Rella by email at andrew@econcrete.us.

Big River at Calico Creek is located in Fletcher, Missouri, United States. Project information and photos courtesy of Joe Collum, U.S. Army Corps of Engineers–St. Louis District. For more information concerning this project, please contact Joe Collum by email at joseph.b.collum@usace.army.mil. Portions of this project's text have been modified and reprinted from J. Collum, "Implementing Diverse Bank Stabilization Measures to Contain and Capture Lead-Contaminated Sediment," in *Proceedings SEDHYD 2023 Conference* (SEDHYD, 2023), https://www.sedhyd.org/2023Program/1/124.pdf. Public domain.

Port of Málaga is located in Málaga, Spain. Project information and photos courtesy of Andrew Rella, ECOncrete. For more information concerning this project, please contact Andrew Rella by email at andrew@econcrete.us. Portions of this project's text have been modified and reprinted with permission from A. Rella, I. Sella, and S. Finkel, "Bringing Concrete to Life – Enhancing Natural Processes on Concrete Based Coastal and Marine Infrastructure (CMI)," abstract, 2019 National Coastal Conference Abstracts (American Shore & Beach Preservation Association, 2019), https://asbpa.org/conferences-draft/2019-national-coastal-conference-program/2019-national-coastal-conference-abstracts/. Copyright American Shore & Beach Preservation Association.

Kaskaskia River Basin is located in Modoc, Carlyle, and Shelbyville, Illinois, United States. Project information and photos courtesy of Lane Richter, U.S. Army Corps of Engineers–St. Louis District. For more information concerning this project, please contact Lane Richter by email at lane.a.richter@usace.army.mil.

Mayer Ranch is located in Ottawa County, Oklahoma, United States. Project information and photos courtesy of Robert Nairn, University of Oklahoma, Center for Restoration of Ecosystems and Watersheds. For more information concerning this project, please contact Robert Nairn by email at nairn@ou.edu.

The restored marsh and native riparian areas awaiting plant installation at the Duwamish River People's Park (project details on page 168). (Photo by Port of Seattle)

REPORT DOCUMENTATION PAGE

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED	
		START DATE	END DATE
May 2024	Final / Special Report	FY22	FY24

4. TITLE AND SUBTITLE
Engineering With Nature:
An Atlas, Volume 3

5a. CONTRACT NUMBER	5b. GRANT NUMBER	5c. PROGRAM ELEMENT
5d. PROJECT NUMBER	**5e. TASK NUMBER**	**5f. WORK UNIT NUMBER**

6. AUTHOR(S)
A. Tritinger, Z. Hubbard, C. E. Chambers, B. C. Suedel, E. M. Bourne, E. B. Moynihan, R. K. Mohan, and J. K. King

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	8. PERFORMING ORGANIZATION REPORT NUMBER
See reverse.	ERDC SR-24-2

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)	11. SPONSOR/MONITOR'S REPORT NUMBER(S)
U.S. Army Engineer Research and Development Center Environmental Laboratory 3909 Halls Ferry Rd. Vicksburg, MS 39180		

12. DISTRIBUTION/AVAILABILITY STATEMENT
Distribution Statement A. Approved for public release: distribution is unlimited.

13. SUPPLEMENTARY NOTES
The AMSCO for this work is 1090119; the funding account is U4396577.

14. ABSTRACT
Engineering With Nature: An Atlas, Volume 3 showcases EWN principles and practices “in action” through 58 projects from around the world. These exemplary projects demonstrate what it means to partner with nature to deliver engineering solutions with triple-win benefits. The collection of projects included were developed and constructed by a large number of government, private sector, nongovernmental organizations, and other organizations. Through the use of photographs and narrative descriptions, the EWN Atlas was developed to inspire interested readers and practitioners with the potential to engineer with nature.

15. SUBJECT TERMS
Beaches, Environmental engineering, Environmental monitoring, Environmental management, Environmentalism, Floodplains, Infrastructure (Economics), Islands, Levees, Reefs, Sand dunes, Technology transfer, Wetlands

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES
a. REPORT	b. ABSTRACT	C. THIS PAGE	SAR	315
Unclassified	Unclassified	Unclassified		

19a. NAME OF RESPONSIBLE PERSON	19b. TELEPHONE NUMBER (include area code)

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) (concluded)

U.S. Army Engineer Research and Development Center
Coastal and Hydraulics Laboratory
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

U.S. Army Engineer Research and Development Center
Environmental Laboratory
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

U.S. Army Engineer Research and Development Center
Information Technology Laboratory
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

Anchor QEA
755 Business Center Drive, Suite 220
Horsham, PA 19044

Engineering With Nature® An Atlas, Volume 3

ISBN: 978-1-7378868-5-3