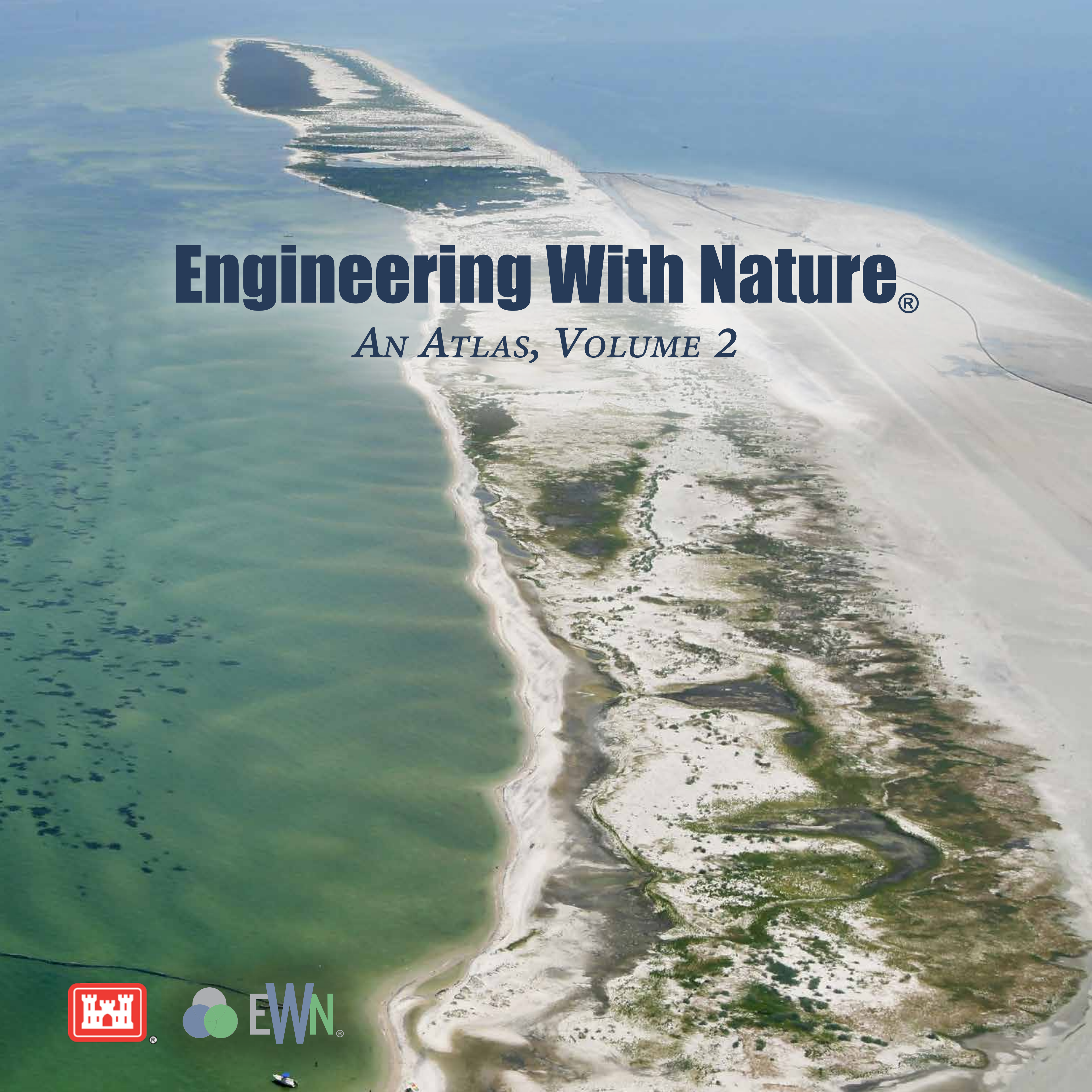
Engineering With Nature®

An Atlas, Volume 2



Engineering With Nature®

An Atlas, Volume 2

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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

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Project Team Project Lead: Todd Bridges
Project Managers: Michelle Bourne and Jeff King
Designer and Editor: Emily Moynihan
Technical Advisor: Burton Suedel

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Cover Photo Aerial image of East Ship Island, in the Mississippi Sound, during Phase I of construction, 3 August 2018 (project details on page 96). (Photo by U.S. Army Corps of Engineers–Mobile District)

Foreword

Creating Value by Innovating and Collaborating with Nature

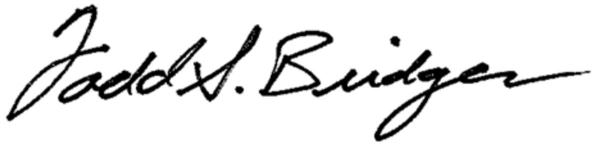
We celebrated the tenth anniversary of the U.S. Army Corps of Engineers' Engineering With Nature® (EWN®) Initiative in 2020. Over the last 10 years, EWN has grown to encompass a broad collaboration among sectors—public, private, academic, and nonprofit—both in the United States and internationally (www.engineeringwithnature.org).

Looking back on the progression in collaboration, I am excited to imagine where we will be in the next 10 years. The pursuit of nature-based solutions continues to accelerate, with more organizations and people applying EWN principles and practices to achieve engineering outcomes with diverse economic, environmental, and social benefits. The complex landscape of challenges and opportunities continues to evolve as a worldwide pandemic and a diversity of natural hazards intersect with the desire to develop twenty-first-century engineering solutions that deliver energy, water resources, food, and sustainable infrastructure. Advancing the integration of natural and human systems is the key to providing these solutions.

The EWN Initiative, with its partners and collaborators, is committed to facilitating the innovation that is necessary to advancing technical practice and to creating diverse, holistic value through nature-based solutions and infrastructure. And it is this central theme—growth and innovation through collaboration—that allows us to share a diverse set of projects embodying worldwide progress.

With that premise as the backdrop, I am pleased to introduce the next volume in our *EWN Atlas* series chronicling the potential for engineering with nature: *Engineering With Nature: An Atlas, Volume 2*. In *EWN Atlas, Volume 1* in 2018, we took the approach of "seeing is believing" to emphasize the importance of visual depictions of projects to communicate the elements of EWN and the value these projects provide. We have continued this approach for *EWN Atlas, Volume 2* as we showcase the work of the many talented organizations and people represented in this volume while seeking to inspire others to do the same. Interest in *EWN Atlas, Volume 2* has been overwhelming, and I am grateful to all the people and organizations that nominated projects for us to consider. The growing interest in EWN and the quality of nature-based projects being developed and built around the world fuels our commitment to publish future volumes so that the international community can continue to share practices, learn from each other, and build the momentum for sustainable infrastructure.

I hope you enjoy *Engineering With Nature: An Atlas, Volume 2* and the opportunity to consider this impressive assemblage of projects from around the world. It is my sincere hope that in doing so you will be further inspired to engineer with nature!



Todd S. Bridges, Ph.D.
Senior Research Scientist, Environmental Science
National Lead for Engineering With Nature®

Collaborating for Resilience

The mission of the U.S. Army Corps of Engineers (USACE) is to deliver vital public and military engineering services, partnering in peace and war to strengthen our nation's security, energize the economy, and reduce risks from disasters. Engineering With Nature supports this mission, which is why it will always be an important initiative for USACE.

Developing and operating infrastructure to support and sustain our communities, economy, and environment in the twenty-first century calls upon us to innovate, modernize, and even revolutionize our approach to infrastructure development. The challenges are relevant across all sectors and organizations that contribute to the engineering enterprise.

Developing our collective readiness to meet the needs and opportunities that present themselves as we enter the third decade of the century requires world-class organizations to look ahead in order to develop future practice and capabilities. We must strengthen our relationships and partnerships across organizations, mandates, and missions to fully realize the potential of integrating infrastructure engineering with natural systems. To create lasting value for the nation, we must deliver affordable and timely projects that produce a broad spectrum of economic, social, and environmental benefits.

The project examples in *Engineering With Nature: An Atlas, Volume 2* illustrate the future of infrastructure development. Multiorganizational teams are collaborating and codeveloping modern solutions that deliver diversified value for both public and private investment. USACE is proud to showcase 23 such projects on the following pages, alongside best-practice examples from around the world.

My hope is that while reading and learning about these projects, you will discover new inspiration and share your ideas across the growing Engineering With Nature community that supports and sustains resilient communities, the economy, and the environment.

LTG Scott A. Spellmon
55th Chief of Engineers
Commanding General, USACE

Creating Solutions Today for Resilience Tomorrow

Engineering With Nature is an increasingly important tool for the Environment Agency and its partners to create better places for people and wildlife. Indeed, our recently published National Flood and Coastal Erosion Risk Management Strategy for England demonstrates clearly how *engineering with nature* can benefit the economy, society, and the environment.

Economic assessments completed to develop our long-term investment scenarios have identified the significant role natural flood management has to deliver this strategy over the next 50 years—by slowing flow and storing floodwaters. It is also becoming increasingly clear that nature-based solutions to reduce flood risk also bring water quality and quantity benefits and may even reduce fire risk in some upland catchments—themes repeated across the case studies in the pages of this *Atlas*. These are solutions that we are using today to deliver resilience for tomorrow.

The Environment Agency is once again delighted to be able to contribute to a large number of the ten schemes from the United Kingdom that are presented here in *Engineering With Nature: An Atlas, Volume 2*. Positive outcomes from collaborative partnerships underscore these case studies to deliver not only flood risk management but also much more for so many more.

Working together internationally allows us to both share and learn from best practice. The inherent benefits for people and wildlife positively encourages the mainstreaming of these techniques.

John Curtin
Executive Director, Flood and Coastal Risk Management
Environment Agency of England

Shaping a Better Place: Engineer with Nature!

The Netherlands is a densely populated low-lying country with an abundance of water. About 30% of our surface area is below sea level, and about 60% is flood-prone. Our Dutch Delta Program stipulates the Dutch national policy and associated programs, supported by a Delta Law and a Delta Fund. This program firmly connects our adaptive flood security approach with spatial quality, as we need to continuously increase our nation's resiliency to predicted sea level rise and more extreme weather events. More than ever before, we must take into account such issues as droughts, heat waves, flooding, and flood risks when planning and selecting current and future land use. Therefore, nature, agriculture, industry, housing, energy, and water must all become part of our spatial considerations: "water directs" instead of "water follows."

In the Netherlands, Engineering With Nature is one of our innovative approaches and has become the preferred option in many projects. Its application also involves a different project approach as we are working *in* and *with* an inherently dynamic natural system. Advanced adaptive modeling tools, full-scale testing, intensive stakeholder consultations, a multiagency approach to project management, monitoring of a project's effects, and periodic maintenance have all become essential elements of success.

Rijkswaterstaat, the Dutch Regional Water Authorities, and many other Dutch stakeholders are proud that several Dutch case studies have been included in this *EWN Atlas, Volume 2*. With this *Atlas*, we would like to keep inspiring other countries and other interested parties to keep an "open eye" and to increase our common scientific understanding of the immense challenge to adapt our nations to the effects of climate change, while at the same time shaping a "better place to live."

Marlouke Durville
Managing Director for Water, Transport, and the Environment
Rijkswaterstaat

After the removal of three dams, the Boardman River has been restored to a more natural state, providing a variety of habitat for aquatic and terrestrial species (project details on page 140). (Photo by Inter-Fluve)

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At Horsetail Creek, former gravel borrow pits were partially filled and disconnected from low summer stream flows to improve summer thermal characteristics while still providing important winter rearing habitat for endangered salmonids (project details on page 232). (Photo by Inter-Fluve)

Aquatic vegetation growing in a protected nook of the Mississippi River (project details on page 104). (Photo by Andrew Hannes, U.S. Army Corps of Engineers–Buffalo District)

Introduction

Connecting projects around the world

Background

Nature does nothing in vain.
—Aristotle

There is tremendous value in nature. People are drawn to different aspects of that value, depending on their perspectives and purposes. For millennia, humans have extracted resources from nature through hunting, mining, damming, and logging. However, nature's value includes more than material resources. To be sure, trees can provide fuel, lumber, and cellulose. But trees are also beautiful (aesthetic value). Children—and some adults—climb trees (social value). Trees are habitat for animals (environmental value). And trees can also be infrastructure, in that they can provide services associated with engineering functions. Trees near buildings can reduce the costs of cooling those buildings in the summer (e.g., by shading) and heating those same buildings in the winter (e.g., by buffering winds). Trees and their root systems can provide hydrologic value by increasing surface water infiltration that reduces flooding and increases groundwater recharge. Trees can also improve air quality by filtering particulate matter and other pollutants, in addition to sequestering carbon.

Humanity faces many challenges in the twenty-first century related to supporting a human population that is expected to exceed 10 billion by the end of the century, mitigating the increasing risks posed by natural hazards, and climate change. Whether we frame the future in terms of problems to resolve or opportunities to develop, nature will figure prominently in the outcomes of our pursuits. The overarching need before us is to *figure out* how to discover, preserve, expand, and apply nature's value. Engineering that extracts value can leave *marks* on nature. Engineering to *control* nature has resulted in a combination of partial successes and dramatic failures. Engineering that *partners* with nature holds great promise in the twenty-first century, building on lessons developed through recent and distant experiences. Partnering with nature to produce expanded and diversified value is the central motivation for Engineering With Nature® (EWN®) and the growing movement to develop and implement nature-based solutions.

The timeline marking the conceptualization, methodological development, and application of nature-based solutions is long and passes through many technical fields. Different definitions of *nature-based solutions* and related terms (e.g., ecosystem-based

A constructed side channel habitat in the Clackamas River provides cold groundwater flow for juvenile salmonids during the summer heat *(project details on page 228).* *(Photo by Inter-Fluve)* approaches and natural infrastructure) have been used by many organizations pursuing the approach. However, the predominant element among these definitions is the focus on conserving, restoring, and engineering nature for the benefit of people *and* the ecosystems we inhabit. It is difficult to pinpoint the very beginning of the nature-based-solutions timeline, but it stretches across several decades. In the 1960s, the ecologist Howard T. Odum and others developed a foundation for *ecological engineering*; and in 1969, the landscape architect Ian McHarg published his seminal book *Design with Nature*. The introduction to *Design with Nature* was written by the prolific polymath Lewis Mumford, who wrote

> McHarg's emphasis is not on either design or nature by itself, but upon the preposition *with*, which implies human cooperation and biological partnership. He seeks, not arbitrarily to impose design, but to use to the fullest the potentialities—and with them, necessarily, the restrictive conditions—that nature offers.[1]

It is worthwhile to note that among other awards, Mumford and McHarg were recognized for their respective accomplishments by three different Presidents of the United States. Mumford received the Presidential Medal of Freedom from President Johnson in 1964 and the National Medal of Arts from President Reagan in 1986. In 1990, McHarg received the National Medal of Arts from President George H. W. Bush who said when conferring the award that "I hope that in the twenty-first century the largest accomplishment of art will be to restore the earth."[2]

Discovering the full value of nature and developing and delivering projects that apply that value will involve engineering across a range of scales. A single tree can be a source of pleasure for a group of children. A copse of trees can reduce energy usage for a building. An entire forest and networks of forests can reduce flood risks and damage from hurricanes. A recent study found that mangrove forests along the coast of Florida in the U.S. are averting billions of dollars in flood damages from extreme storms by attenuating storm surge and waves.[3] A small pocket of wetlands can provide an afternoon

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[1] Ian L. McHarg, *Design with Nature* (New York: Wiley, 1992), viii.
[2] McHarg, vi.
[3] Siddharth Narayan, Christopher Thomas, Joss Matthewman, Christine C. Shepard, Laura Geselbracht, Kechi Nzerem, and Michael W. Beck, *Valuing the Flood Risk Reduction Benefits of Florida's Mangroves* (The Nature Conservancy, Gulf of Mexico Program, 2019), 2–4.

of adventure for birdwatchers, productive outings for a local community of anglers, and water-quality improvements associated with land-based nutrient discharges. A network of natural and nature-based wetlands across an entire watershed or bay can reduce flood damages from small and large storms, including hurricanes.[4] Many other examples, ranging the full scope of nature's landscapes, could be used to illustrate the fact that nature holds tremendous value; and many such examples are illustrated within the pages of this *Atlas*. The challenge and opportunity before us is to *figure out* how to integrate this value into our collective engineering of infrastructure in the twenty-first century and beyond.

The EWN Initiative

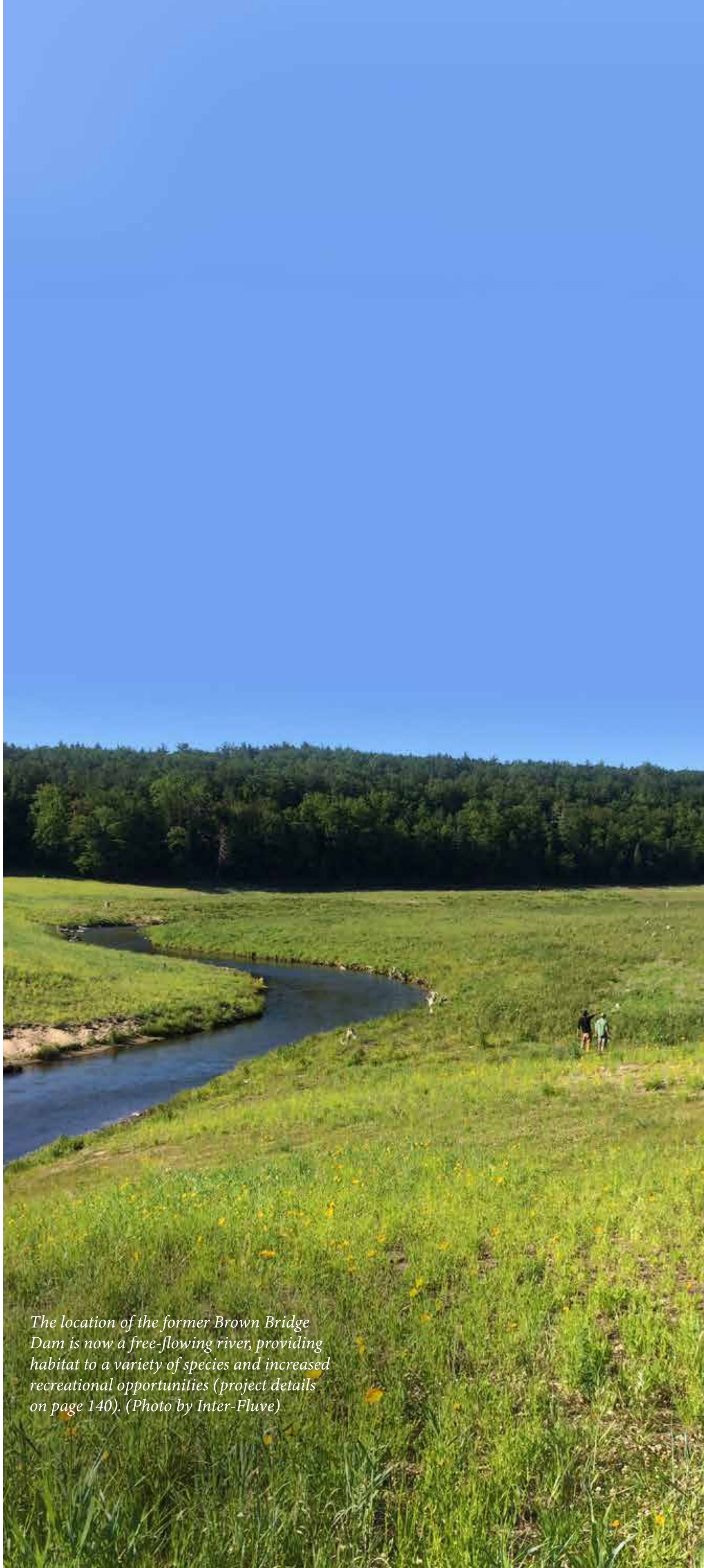
The Engineering With Nature Initiative formally began in 2010 within the U.S. Army Corps of Engineers as a way to highlight good-past-practice examples, while advancing current and future capabilities, for integrating nature's value into engineering projects. In the last 10 years, the initiative has grown to include many partner organizations and collaborators. The initiative supports more sustainable water resources and infrastructure practices, projects, and outcomes by pursuing the *intentional alignment of natural and engineering processes to efficiently and sustainably deliver economic, environmental, and social benefits through collaboration* (www.engineeringwithnature.org).

[4] Siddharth Narayan, Michael W. Beck, Paul Wilson, Christopher J. Thomas, Alexandra Guerrero, Christine C. Shepard, Borja G. Reguero, Guillermo Franco, Jane Carter Ingram, and Dania Trespalacios, "The Value of Coastal Wetlands for Flood Damage Reduction in the Northeastern USA," *Scientific Reports* 7 (2017): 9463, https://doi.org/10.1038/s41598-017-09269-z.

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

As with the original book, *EWN Atlas, Volume 2* uses these four critical elements to define progress and success related to EWN and to provide the structure for describing each of the representative projects. With this, we can more easily highlight the efficiencies produced, the natural processes used, the project benefits provided, and the collaborative partners engaged.



The location of the former Brown Bridge Dam is now a free-flowing river, providing habitat to a variety of species and increased recreational opportunities (project details on page 140). (Photo by Inter-Fluve)

A Global Community of Collaboration on Nature-Based Solutions

Sharing examples of EWN practice and learning from project examples around the world is the motivation for the *EWN Atlas* series. As with the first volume of the *Atlas*, we chose the current collection of projects to illustrate a diverse portfolio of circumstances, inspirations, obstacles, and achievements. All of the projects in this Atlas highlight the importance of collaboration to innovating and creating diversified 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.

Over the last 10 years, there has been a growing wave of interest and progress in developing nature-based approaches. One can attempt to quantify this interest in different ways, including the significant growth in publications on the topic in peer-reviewed and other technical literature. At the time of this writing, a simple Google search on the term "nature-based solutions" provided more than 2 million results. For those actively involved in the effort to advance nature-based solutions, the forward movement has been both obvious and meaningful.

Today, an increasing number of organizations across both the public and private sectors are investing in nature-based solutions, as demonstrated by the more than 26 organizations that nominated projects to appear in this Atlas. These contributions illustrate that government organizations with infrastructure responsibilities are increasingly investing in nature-based solutions (e.g., U.S. Army Corps of Engineers; Environment Agency in England; Rijkswaterstaat in the Netherlands; Scottish Environment Protection Agency; Pierce County, Washington, U.S.; among others). Public agencies with environmental and conservation missions are incorporating engineering and social value into projects to complement the environmental benefits created (e.g., U.S. National Oceanic and

Atmospheric Administration, U.S. Fish and Wildlife Service, and the Flemish Agency for Nature and Forest). A range of private companies are investing in nature-based solutions to either support their own physical assets and landscapes or by supporting such projects with materials and engineering design and construction services (e.g., Dow Inc., Boskalis, ECOncrete, Inter-Fluve, Van Oord, Atlantic Reef Maker, and more). Knowledge institutions, universities, and technical associations are also actively engaged in advancing nature-based practice (e.g., EcoShape, University of Glasgow, University of Kansas, University of Dundee, etc.). Nonprofit and nongovernmental organizations are partnering across sectors to deliver nature-based solutions (e.g., The Nature Conservancy, Natuurmonumenten, the Woodland Trust, the West Cumbria River Trust, Restore the Earth Foundation, and others).

Work on nature-based solutions is expanding on both national and international scales. While context and specifics can vary among communities and countries, the commonalities that exist are a significant driver of progress at the international level. To draw attention to widespread progress being made in integrating nature into planning, design, construction, and operation of engineering projects, we have used the globe symbol (below) to identify projects outside of the United States.

Engineered logjams at Smithills function as leaky dams, which intercept flood flows but allow lower flows to pass through (project details on page 180). (Photo by Photo by Woodland Trust, Environment Agency, and Mersey Forest)

Connectivity to Natural Hazards and Flood Risk Management

Natural hazards result in thousands of lost lives and many billions of dollars in damage worldwide every year. The toll taken by natural hazards varies across time, regions, and countries. The U.S. can be used as a specific example of the scope of the problem. Between 1980 and 2020, the U.S. experienced 285 weather and climate disasters where damages reached or exceeded $1 billion (consumer price index adjusted to 2020). The total amount of damages produced across all of these events exceeds $1.8 trillion.[5]

Flooding is responsible for a significant amount of the annual loss of life and economic damages caused by natural hazards in the U.S. and worldwide. Future improvements and investments in conventional engineering solutions for flooding offer some promise for "buying down" these damages. However, expanding application of nature-based solutions arguably offers even greater potential for achieving long-term risk mitigation for flooding and other natural hazards. It has been estimated that between 2020 and midcentury, $100 trillion will be invested in infrastructure development worldwide, including infrastructure related to flood risk management and natural hazards.[6] There are some "big" questions to consider with respect to that investment: What will that infrastructure look like? How will nature be incorporated as a part of the solution? How will it work? What range of value will the infrastructure produce?

Natural and nature-based features (NNBF) is a term used to describe the use of landscape features to provide engineering functions relevant to flood risk management while also producing a range of other economic, environmental, and social benefits. NNBF can be incorporated into riverine/fluvial and coastal systems and includes such features as beaches and dunes, islands, forests, wetlands, and reefs, all of which can

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[5] "U.S. Billion-Dollar Weather and Climate Disasters," National Oceanic and Atmospheric Administration, National Centers for Environmental Information, (Asheville, NC: National Oceanic and Atmospheric Administration, National Centers for Environmental Information, 2021), https://www.ncdc.noaa.gov/billions/.

[6] World Economic Forum, *The Green Investment Report: The Ways and Means to Unlock Private Finance for Green Growth* (Geneva, Switzerland World Economic Forum, 2013).

occur naturally or be constructed as nature-based features through human engineering. The EWN Initiative and other programs worldwide have invested in NNBF application by supporting research and development, technology transfer, stakeholder engagement, and full-scale project implementation. By way of example, the EWN Initiative has led a multiyear international effort to develop and publish (expected in 2021) technical guidelines for NNBF. This project brought together more than 180 people from 10 countries and 77 organizations across the public, private, nonprofit and academic sectors.

NNBF represents an opportunity to achieve both flood risk management and sustainability goals. Engineers, environmental scientists, conservationist, social scientists, government leaders, and the public at large have important roles to play in the process of innovating new, sustainable solutions for persistent and growing flood risk management problems. Projects in the *EWN Atlas, Volume 2* that were developed as NNBF projects are designated using the following symbol:

NNBF

Woody debris installed in Horsetail Creek provides cover for fish (project details on page 232). (Photo by Inter-Fluve)

With a View Toward the Future

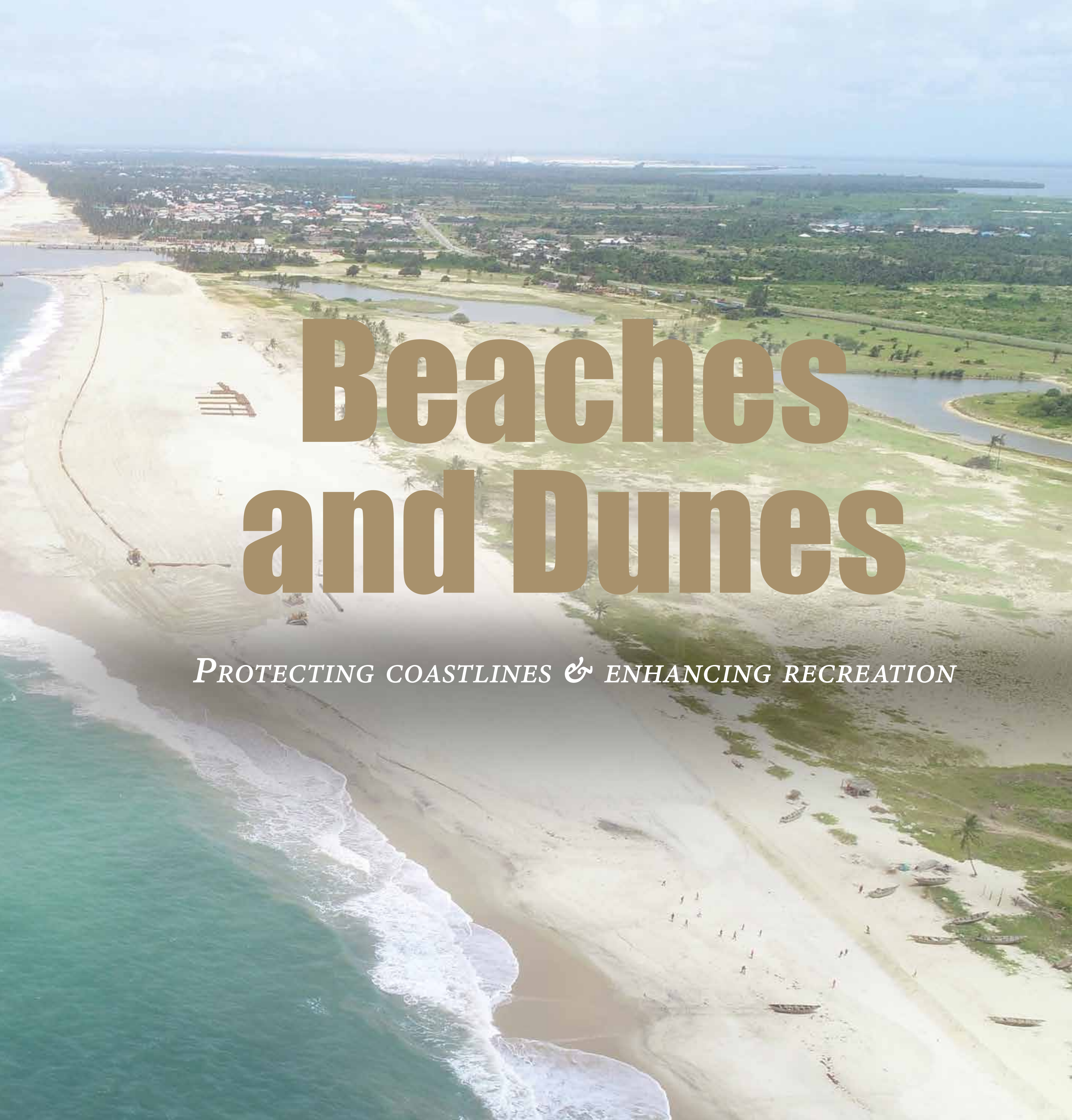
Listen to the voice of nature,
for it holds treasures for you.
—Wendat proverb

Before readers explore the EWN exemplars in this *Atlas*, there is benefit in creating a mindset that is fit for the purpose. The 62 projects described in the following pages represent only a sample of an ever-increasing number of interventions and projects that illustrate a partnership between engineering and nature. While exploring these example projects, we encourage readers to consider the following questions:

- What lessons do they teach?
- How could EWN support my community?
- What opportunities are there for creating new value through EWN in my sphere of activity?
- What obstacles exist for advancing the application of nature-based solutions?
- How can I contribute to the innovation needed to advance EWN and expand the value of infrastructure in the twenty-first century?

The future is shaped by understanding what others have done and then considering the potential for doing even more.

The sand engine downstream of the sandbar breakwater at Dangote's marine terminal during the construction phase (project details on page 28). (Photo by Boskalis and CDR)



Beaches and Dunes

Protecting coastlines & enhancing recreation

Beaches and Dunes

Introduction

Around the world, beaches and dunes projects are applying EWN principles. From the Great Lakes to the Gulf of Mexico, to busy ports in Nigeria and the Netherlands, these projects show that economic and environmental development are never exclusive. State-of-the-art modeling tools informed the construction of a breakwater from sand. This breakwater is more resilient and adaptable than conventional rock and uses nature's own wave energy in the form of a small sand engine to shape the structure over time. Dredged sand from a nearby navigation channel nourished a popular recreational beach, reducing coastal storm risk while enhancing habitat value and economic opportunities. Natural forces shaped sand-dune construction in the North Sea, enhancing habitat quality and mitigating the impact of a nearby port's expansion. Contaminated dredged sediment from a local navigation channel created habitat for a federally protected bird species while reducing reliance on scarce confined disposal facility space. And connecting all of these projects are the successful stakeholder collaborations that propelled them towards shared economic and environmental goals and, ultimately, project success.

Spanjaards Duin

’s-Gravenzande, South Holland, the Netherlands

Building a new dune area along the North Sea through beach nourishment. On the Delfland coastline along the North Sea near Rotterdam, three types of coastal dune habitats are common: white dunes, gray dunes, and dune slacks. However, the extension of the Port of Rotterdam (Maasvlakte 2) threatens these valuable dune habitats. Therefore, the Port of Rotterdam, the Dutch Ministry of Infrastructure and Water Management agency Rijkswaterstaat, and the nature management organization Zuid-Hollands Landschap worked together to construct and develop Spanjaards Duin, starting in 2008–2009. The project was to compensate for the anticipated increase of maritime and land-based traffic emissions and the resulting increase in atmospheric nitrogen deposition that would damage natural dune vegetation. Following the initial 6.0 million cubic meters of beach and dune nourishment, natural processes such as wind action, rainfall, groundwater dynamics, and vegetative development shaped the area further into new natural dune habitats. Careful management, monitoring, evaluation, and adjustments ensure that the calcareous, nutrient-poor dune marsh and dry dune grassland are developing successfully. The improved abiotic conditions allow for the settlement of dune slack pioneer species. The compensation habitats should be completely established by 2033 when Maasvlakte 2 is expected to be fully operational.

Producing Efficiencies

Spanjaards Duin is the first example in the Netherlands of constructing artificial dunes to create natural dune habitats as a compensation measure. The experience and data gained from the Spanjaards Duin project have already benefited other artificial dune construction projects in the Netherlands, such as the Sand Motor project and the Hondsbossche Dunes. By using Spanjaards Duin to test the scientific models as a case study of their applicability, the project team applied a practice-as-research approach—essentially, learning by doing.

Using Natural Processes

From the start, the project team knew they wanted to allow natural processes to shape the dunes. Crucial to this was ensuring proper grain size for aeolian dynamics and maintaining the groundwater level to support vegetation. In 2019, monitoring led the team to intervene. Excavating five gently sloping depressions in the dune valley brought the surface closer to the groundwater level. The new soil conditions now allow dune slack pioneer species, such as sand sedge (*Carex arenaria*), knotted pearlwort (*Sagina nodosa*), and goldmoss stonecrop (*Sedum acre*), to establish and start the vegetation succession towards a calcium-rich dune marsh.

Previous page: Shorebirds gather in the newly created dune valley. (Photo by Bert van der Valk)

*Top: Marram grass (*Ammophila arenaria*) planted on the foredune naturally limits sand transport into the dune valleys. Early in the project, too much sand was blowing into the valleys, creating an environment too harsh for target species. (Photo by Bert van der Valk)*

Bottom: Two dune rows are well established in 2019, 10 years after construction. (Photo by Marieke Eleveld)

Broadening Benefits

While the project team's aim was to provide local environmental benefits, the creation of Spanjaards Duin also provides social and economic benefits. By reclaiming part of the North Sea from historical erosion, the new dune and beach have created opportunities for nature-based recreation in this part of the Netherlands. The increased tourism will benefit the local economy and Spanjaards Duin compensation measures allow the expansion of the Rotterdam port to proceed. This further increases economic activity and growth in the region. Finally, the project provides a worldwide example of mitigating ecosystem damage on a large scale to compensate for engineering works.

Promoting Collaboration

Cooperation between business (Port of Rotterdam), national government (Rijkswaterstaat), regional government (Province Zuid-Holland), nature organizations (Zuid-Hollands Landschap), consultancy firms (RoyalHaskoningDHV), and knowledge institutes (Deltares) allowed for a successful integrative approach. All these actors discussed monitoring results, alternative interventions, and the details of the design. This resulted in a collaborative and shared decision, even under high pressure. The project team also made all of the modeling data freely available online, allowing easy monitoring by all stakeholders and promoting a wider understanding.

Top: A monitoring station was installed for sand and salt spray. (Photo by Stéphanie IJff)

Middle: The project team meeting with experts in the field. (Photo by Photo by Frank van der Meulen)

Bottom: Beachgoers enjoy sunny days on the beach of Spanjaards Duin. (Photo by Marieke Eleveld)

Piping Plover Habitat

Superior, Wisconsin, United States

Providing new nesting and foraging sites for an endangered species. Historically, the St. Louis River Estuary—the largest freshwater estuary in North America and the headwater of the Great Lakes—supported breeding populations of piping plover (*Charadrius melodus*). While these tiny shorebirds are occasionally still spotted during their spring migration, they have not nested in the estuary since 1985. Piping plover, federally listed as an endangered species in 1986, prefer large isolated beach and dune habitats for nesting, and loss of habitat leaves only a few critical locations across the Great Lakes. The complex issues at the project site have resulted from historical waste disposal and land use practices, such as those from logging and paper mills and from dredging and filling aquatic habitat. With funding from the Environmental Protection Agency's Great Lakes Restoration Initiative, the state of Wisconsin led the effort for the beneficial use of dredged sediment in a region that has an international legacy of sediment contamination. The robust application of science, engineering, and collaborative discussion resulted in piping plover nesting and foraging habitat while reducing maintenance dredging requirements in the estuary.

Producing Efficiencies

Piping plovers prefer nesting on coarse-grained sand beaches rather than the fine grains common in dredged sediment. So, the team built up the habitat by burying the fine dredged sediment beneath sandier dredged sediments. This allowed the team to leverage existing resources while providing the necessary habitat and preventing costly double handling of the dredged sediment. Further, the U.S. Army Corps of Engineers (USACE)–Detroit District and the Engineer and Research Development Center created and applied a model to ensure that the beach would provide the correct habitat even during high water levels.

Using Natural Processes

As piping plover like to nest in cobble and gravel areas, so the team constructed three cobble pans on the beach to make the site more desirable for nesting. They worked with species experts to determine the best stone characteristics to use to imitate nature. Additionally, to prevent vegetation from growing at the site, the team buried the existing seed bed under at least 15 centimeters of dredged sediment, naturally suppressing vegetative growth. Keeping the locally available dredged sediment in the same littoral system affected by severe erosion also mimics the Great Lakes system's native processes.

Previous page: Less than one year after construction, a piping plover was spotted on site. (Photo by Sam Hansen, St. Louis River Alliance)

Top: Piping plovers prefer coarse sand with cobble and gravel for their nests. (Photo by Sam Hansen, St. Louis River Alliance)

Bottom: A chain-link fence helps deter predators, protecting the plovers' nesting area. (Photo by USACE Detroit District)

Broadening Benefits

In addition to the nesting and foraging habitat created by the placement of the dredged sediment, this project increased habitat for the state-endangered hairy-necked tiger beetle (*Cicindela hirticollis*), increased fish-spawning habitat, and created new bird-watching opportunities. The project also removed the shoaling areas near the site, preventing future obstacles to navigation and commerce in the area, and kept available capacity in the harbor's confined disposal facility. Duluth-Superior Harbor is in the top 50 U.S. Water Ports in the nation when ranked by tonnage. Benefits to this system have a far-reaching cumulative effects across the region, the nation, and overseas.

Promoting Collaboration

The Wisconsin Department of Natural Resources partnered with the Environmental Protection Agency, the Fond du Lac Band of Lake Superior Chippewa, the Lac du Flambeau Tribe, and many other state and federal agencies to meet the overarching goal of increasing stopover and nesting habitat for the piping plover. The project team also sought feedback from local landowners and other stakeholders to gain support and show the beneficial impact to the region, and the two tribes contributed cultural experts to monitor ground disturbance. The importance of the piping plover helped to organize and focus stakeholders, leading to an effective collaboration and a successful project.

Top: Dredged sediment was hydraulically placed to create piping plover habitat. (Photo by USACE Detroit District)

Middle: Contractors mobilized to the site to continue placement of dredged sediment. (Photo by Duluth Area Office, USACE Detroit District)

Bottom: Completion of 5.7 hectares of beneficially placed dredged sediment and cobblestone nesting pans. (Photo by Duluth Area Office, USACE Detroit District)

King Fisher Beach

Port O'Connor, Texas, United States

Nourishing a beach and protecting a coastline. What locals call "the best kept secret in Texas," Port O'Connor houses the oldest marina in the state of Texas and is home to King Fisher Beach, a popular destination for swimming, boating, fishing, and birding. This beach is located near ecologically diverse habitat: large oyster reefs at Matagorda Bay; birding at Sundown Island, Texas's most diverse colonial nesting bird island; and critical habitat for endangered species, such as piping plover (*Charadrius melodus*) and whooping cranes (*Grus americana*), at Matagorda Island. However, the beach, which protects neighborhoods, restaurants, lodging, and schools from coastal storms, is susceptible to storm surge, rising sea levels, and erosion. Additionally, the beach provides habitat for colonial nesting birds and sea grasses. Therefore, the U.S. Army Corps of Engineers (USACE)–Galveston District saw an opportunity for beneficial use when performing maintenance dredging of a nearby federal navigation channel. In 2017, the Galveston District placed around 58,305 cubic meters of dredged sediment on King Fisher Beach by pipeline dredge from RLB Contracting Inc. The project was complete within just 125 days from the awarded contract, adding real estate value to surrounding neighborhoods, increasing tourism, building habitat, and providing storm protection and added protection against rising sea levels.

Producing Efficiencies

The project team started by using collected physical and chemical data from the federal channel, determining sand grain size and chemical composition. Beach placement was strategic, long-term engineering with nature because wave surges moved the material towards the shore and combated the rate of erosion. By using the maintenance dredging cycle and placing sufficient material on the beach, the team was able to reduce the cost to all parties involved while adding storm protection to surrounding communities.

Using Natural Processes

A major challenge in placing dredged sediment along coastlines is combating wave energy and the rising sea level's tendency to erode beaches. By using the composition of the material already on the beach, the project team worked with nature instead of against it to distribute the material in the littoral zone. Using similar material from the channel also created habitat that was already suitable for migrating and local shorebirds and the other species they depend on for sources of food.

Previous page: Sunset on the postconstruction beach. (Photo by David Paul Orr, USACE Galveston District)

Top: Shorebirds frequently gather on the renourished beach. (Photo by David Paul Orr, USACE Galveston District)

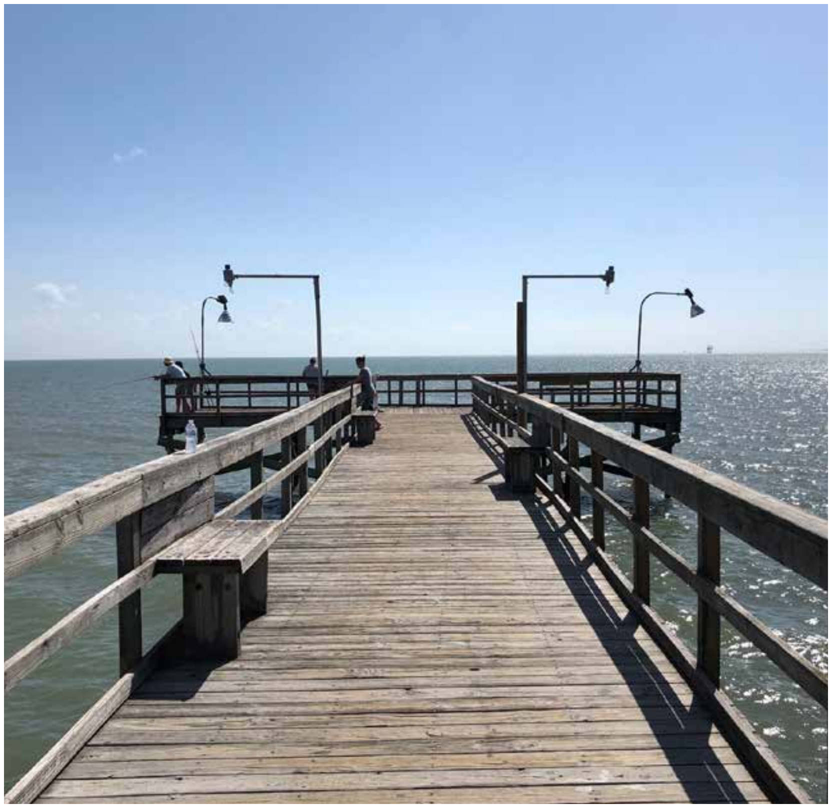
Bottom: The newly constructed beach is a popular spot for swimming, boating, and fishing. (Photo by David Paul Orr, USACE Galveston District)

Broadening Benefits

King Fisher Beach serves as a focal point for community celebrations such as the Fourth of July and Memorial Day. Restoring the beach protects this important local resource. Beach placement provides economic benefits as it reduces the cost of maintenance of federal placement areas, adds real estate value, and increases both recreation and tourism. Beach nourishment increases storm protection to surrounding communities and restores eroded habitat for coastal species. And the nearly 60,000 cubic meters of material dredged as a part of normal maintenance operations will now stay in the local ecosystem and reduce the rate of future erosion.

Promoting Collaboration

The Galveston District partnered with the U.S. Fish and Wildlife Service, the Port O'Connor Chamber of Commerce, and the Calhoun County Parks Board. The collaboration and the planning of this project ensured that placement would occur during periods less likely to impact both the economy and important nesting bird species. The result was a well-planned dredging project and a nourished, restored beach ready for tourists and local species alike.



Top: The restored King Fisher Beach positively impacted O'Connor businesses and residences. (Photo by David Paul Orr, USACE Galveston District)

Bottom: Locals and tourists enjoy recreational fishing on Park Street Pier off of King Fisher Beach. (Photo by David Paul Orr, USACE Galveston District)

Dangote Sandbar Breakwater

Lekki, Lagos State, Nigeria

Preventing erosion using nature-based solutions at Dangote's marine terminal. The coastal system of Nigeria is unique. Regular swells arriving at the coast at a relatively constant angle combined with a uniform steep and sandy coast result in a large and unidirectional longshore sediment transport. However, the coastal system of West Africa is highly affected by human interventions, such as maritime infrastructure, and is aggravated by climate change. Such infrastructure interrupts the steady eastward transport of sand, leading to coastal erosion and loss of habitat. The Dangote Oil Refining Company's new greenfield refinery, polypropylene, and fertilizer plant's own infrastructure required protection against the heavy wave energy. A conventional rubble-mound breakwater would cause a rapid advance of the coastline on the updrift side, ultimately burying the expensive armor rock. Instead, in 2016, CDR International and Svašek Hydraulics, both coastal engineering specialists, developed and designed a sandbar breakwater concept to be constructed mainly out of sand. The use of natural processes and the natural availability of construction materials made it a cost-effective design. In 2018 in less than five months, the dredging contractor Boskalis constructed the breakwater. Since, natural wave action has been shaping the sandbar breakwater and adjacent updrift coastline as designed.

Producing Efficiencies

Following a thorough investigation of the environmental systems and processes of the Lagos State coastline, the project team used state-of-the-art mathematical modeling tools to calculate the optimum placement, angle, and sand volume for the sandbar breakwater. This ensured that the structure will remain dynamically stable and that the steady eastward sand transport will continue to strengthen the breakwater. Additionally, the use of offshore sand eliminated the need to use rocks, stones, or concrete. This significantly reduced construction time, materials, and costs.

Using Natural Processes

Any obstruction of the alongshore sediment transport, whether a conventional breakwater, groyne, or a sandbar breakwater, will inherently lead to downdrift erosion and potentially significant loss of land. The most natural way to counteract this effect is by restoring the natural sand balance of the system. Therefore, a small-scale, nature-driven sand engine has been implemented in the design to mitigate the coastal retreat downdrift. As erosion continues, this sand engine will provide local distribution of the sand to stabilize the coastline over the coming decades.

Previous page: Aerial view of the completed breakwater and marine terminal entrance. (Photo by Boskalis and CDR)

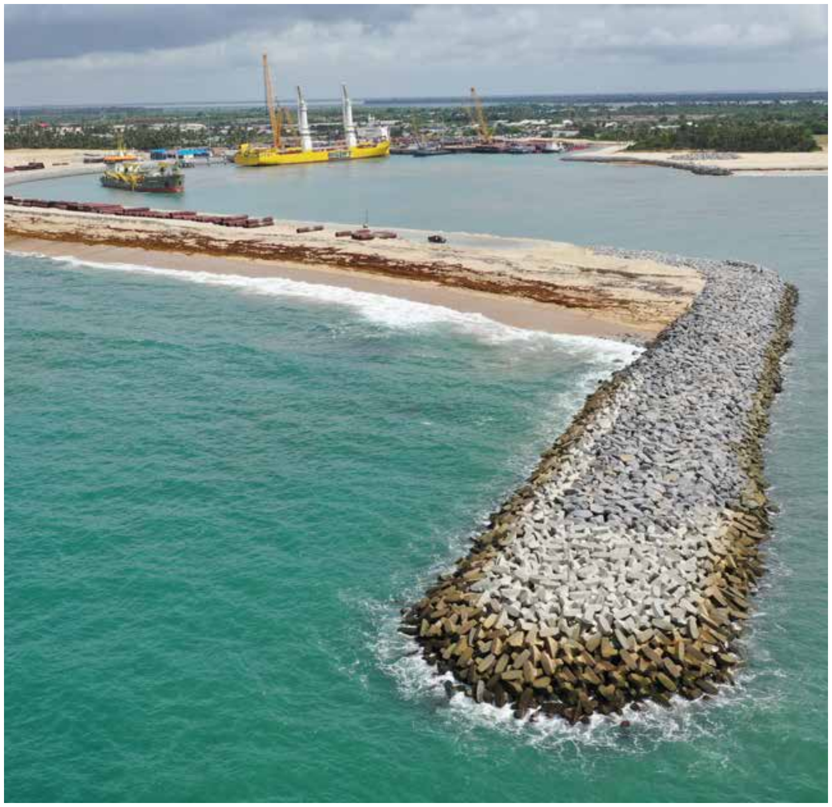
Right: Boskalis's trailing suction hopper dredger deposits sand during the breakwater's construction. (Photo by Boskalis and CDR)

Broadening Benefits

The natural shoreline growth at the west of the sandbar breakwater is already being used to enlarge the Dangote quay infrastructure. And, because sand can be moved and shaped more easily than traditional quarried rock, this new concept is flexible and allows for relatively easy future port expansion. Furthermore, the soft nature of the sandbar makes it more adaptable to climate change than conventional breakwaters are. All of these features work together so that the new breakwater keeps the Dangote loading facilities calm and safe.

Promoting Collaboration

The collaborative design efforts of the three Dutch companies, CDR International, Svašek, and Boskalis, optimized construction time, materials, and costs while retaining the natural characteristics of the coastline and design. This unique coastal zone benefits from resilient and sustainable maritime infrastructure solutions. By considering both the needs of the system and the function of the harbor, the team was able to maintain the natural aesthetics and habitats without hindering community access. The combined efforts resulted in an innovative and sustainable nature-based solution.



Top: Reclaimed sand was topped with 270,000 tonnes of rock and over 1,000 concrete Ekopodes. (Photo by Boskalis and CDR)

Bottom: A small-scale, nature-driven sand engine was implemented to stabilize the coastline. (Photo by Boskalis and CDR)

Prime Hook Wildlife Refuge

Milton, Delaware, United States

Implementing the largest ecosystem restoration project east of the Mississippi River. On Delaware Bay's western shore, Prime Hook National Wildlife Refuge has faced substantial challenges. Previously managed as coastal freshwater impoundments, its wetlands had become large areas of open water due to sea level rise and coastal storms. Since 2006, overwashes and saltwater intrusion fundamentally altered the profile of the refuge, with over 1,600 hectares of freshwater marsh and 240 hectares of riparian forest impacted or lost. The complex legacy of anthropogenic influences on the wetlands had created a coastal system out of sync with the evolving landscape—and susceptible to catastrophic failure. To remedy this vulnerability, the U.S. Fish and Wildlife Service, resource manager for the refuge, developed an extensive restoration plan to create an ecosystem resilient to climate change and rising sea levels. Over the course of two phases, the project team closed large breaches in the refuge using material dredged from a nearby offshore borrow area. To improve circulation and distribution of salinity and sediment, they then excavated 460,000 cubic meters of material to create a network of 37 kilometers of historic tidal channels. In total, the team moved over 1.08 million cubic meters of sand to recreate 2,700 meters of shoreline.

Producing Efficiencies

Several years of water level, water quality, sediment movement, and marsh accretion monitoring informed the team's robust hydrodynamic modeling, providing their restoration design with real-world data and conditions. Contrary to initial theories, the marsh's degradation was not because of an elevation problem but rather a hydrological problem—that is, water was not draining. With this knowledge, the team changed focus to lower water levels instead of raising sediment levels. This adaptive management through use of monitoring and modeling allowed the team to optimize project results to match the evolving conditions of the site.

Using Natural Processes

The team created a natural shoreline that encouraged overwashes. The design included a low-angle beach and berm, a low dune, and a 24-hectare back-barrier platform planted with back dune and wetland vegetation. This beach and barrier naturally preserve the refuge's numerous flood shoals, which serve as critically important bird breeding habitat. The team sprayed the dredged sediment directly into the unvegetated areas using a thin-layering approach, creating a microtopography. After seeding 400 hectares, the team allowed the remaining area to recolonize naturally over time.

Previous page: One of the many adult piping plovers spotted on the restored beach. (Photo by U.S. Fish and Wildlife Service)

Top: An aerial view of the completed project, with flooded refuge at left. (Photo by TI Coastal Services Inc., courtesy of Norfolk Dredging Company)

Bottom: Least tern chick seeking refuge among driftwood and a horseshoe crab carapace. (Photo by U.S. Fish and Wildlife Service)

Broadening Benefits

Ecotourism in the region has greatly increased as diverse migratory birds and waterfowl now flourish: snowy owl (*Bubo scandiacus*), snow bunting (*Plectrophenax nivalis*), the critically vulnerable saltmarsh sparrow (*Ammospiza caudacuta*), and many others. The newly restored beach has become a breeding hot spot for endangered piping plover (*Charadrius melodus*) and is experiencing some of the highest fledging success on the east coast. Additionally, the waterways have provided nursery grounds and refuge for native fish species, and flooding of the surrounding public roads and private lands is now nearly nonexistent.

Promoting Collaboration

Regulatory agencies, nongovernmental organizations, and other partner groups worked together throughout the process. A comprehensive data collection and restoration monitoring partnership has been in place with numerous state and academic partners since the wetland management challenges first arose and throughout restoration. It will continue into the future. The refuge now stands as a focal point for the public, government officials, and restoration practitioners to view the importance of restoring imperiled ecosystems.

Top: Bulldozers spreading sand after it is pumped onto the beach. (Photo by TI Coastal Services Inc., courtesy of Norfolk Dredging Company)

Middle: Preconstruction mudflats just after waters receded. (Photo by U.S. Fish and Wildlife Service)

Bottom: The same mudflats two years postconstruction. (Photo by U.S. Fish and Wildlife Service)

Bridges over the new wetlands will allow the public to enjoy the restored former mine site in Hot Springs, Arkansas (project details on page 68). (Photo by Dow)

Wetlands

Creating natural defenses & aquatic habitats

Wetlands

Introduction

Engineering With Nature principles are informing the creation and restoration of wetland ecosystems the world over. Projects using dredged sediments in beneficial ways have reduced coastal erosion, provided ecological habitats, and increased coastal resiliency. They are converting low-quality land into thriving wetland ecosystems. In Australia, tidal marsh and salt marsh restorations have achieved success on a grand scale. In coastal, riverine, and estuarine habitats, EWN principles have proven more cost effective and more ecologically beneficial than conventional alternatives. In Arkansas and Michigan, industry has taken the lead to implement more sustainable solutions and solve complex environmental challenges; and in England, natural flood management techniques have created lasting economic and environmental value. This chapter highlights tools developed specifically to identify nature-based solutions—solutions that are most cost effective and sustainable. These tools help managers balance costs with the multiple benefits associated with EWN principles put into practice (see the “Project Enablers” chapter for more information). Finally, a project just off the coast of the Florida Panhandle constructed using dredged sediment continues to provide high-quality habitat and erosion prevention of the adjacent navigation channel after over 40 years. In short, EWN projects stand the test of time.

Big Swamp

Coralville, New South Wales, Australia

Creating a new standard for large-scale intertidal restorations. *Big Swamp* is the local name for a series of drained agricultural floodplains located on the Manning River estuary on the mid-north coast of New South Wales, Australia. Historically a large, brackish backswamp known for its abundant bird populations, the Big Swamp floodplain has undergone major hydrologic changes over the past 120 years due to the construction of drainage networks, canals, levees, and floodgates. Unfortunately, the combination of extensive drainage and sulfidic subsoils has acidified the soil and adjacent waters. Following rainfall events, large plumes of acidic water spread through the lower estuary, lowering the pH and creating anoxic conditions toxic to aquatic life. To overcome these issues, the project team, led by MidCoast Council, undertook a detailed study followed by an extensive earthworks program to remediate the site. They filled in over 13 kilometers of canals in the drainage network, established a new tidal wetland ecosystem, enhanced the natural tidal flushing dynamics, and restored over 820 hectares of low-lying land. This nature-based approach has significantly improved water quality and has received multiple awards, including the prestigious Green Globe Award.

Producing Efficiencies

Before the project began, the team conducted a major scientific study to prioritize hot spots and inform proposed solutions. This included a novel study that traced the off-site impacts and determined how acidic discharges from the Big Swamp floodplain impacted other ecosystems, such as oyster reefs. The resulting data showed the team how to best optimize inundation on the floodplain. The final works included drain infilling, levee decommissioning, and the design of a new river channel to encourage tidal inundation and flushing, providing freshwater retention and flood mitigation.

Using Natural Processes

The Big Swamp Restoration Project restored the natural cycle of tidal flushing by constructing a new tidal river channel to encourage inundation of over 250 hectares. This innovative technique ensures that buffering agents inherent in seawater naturally spread across the acidic floodplain with every tide, neutralizing the acid and soil contaminants through regular chemical processes. This approach encourages the development of an organic soil horizon, fostering the growth of a salt marsh ecosystem—an endangered ecosystem type in Australia—and quickly improving the water quality.

Previous page: Big Swamp wetland has been created using Engineering With Nature principles and highlights the value of large scale projects. (Photo by MidCoast Council)

Top to bottom: The project has mapped the recovery of the site from a bare landscape lacking vegetation to an increasingly lush tidal wetland with high rates of blue carbon accumulation. (Photo by MidCoast Council)

Broadening Benefits

The Big Swamp restoration fits into a larger area of restored wetlands, serving as an educational case study in using natural processes to improve water quality and to mitigate floods. The project was also the first in Australia to include a detailed cost-benefit analysis of the social, environmental, and economic benefits of the current land uses versus alternatives, including wetland creation. This assessment provided a distributional analysis of the wetland restoration's benefits, ensuring an equitable sharing of the positive outcomes, and proving that large-scale intertidal restorations need not rely on a trial-and-error approach.

Promoting Collaboration

This restoration provides an excellent example of multidisciplinary collaboration. The project was led by local government (MidCoast Council) with funding support from state (New South Wales Fisheries) and federal agencies. Researchers at the University of New South Wales' Water Research Laboratory drove the technical components; and nonprofit groups, including Wetland International, supported community engagement. The project was ultimately successful due to the local stakeholders, landowners, and the oyster industry who invested resources into the project's implementation. Importantly, the local council, who has assumed ownership of the property, now serves as its steward and continues to adaptively manage the site.

Top and middle: Before and after images of major on-ground engineering works to create tidal infrastructure that uses natural inundation patterns to improve water quality. (Photo by MidCoast Council)

Bottom: Intertidal mangroves and salt marsh are thriving on-site post wetland creation. (Photo by MidCoast Council)

Dow Former Ash Pond

Midland, Michigan, United States

Creating a native wetland out of a postindustrial pond. This former ash pond was originally constructed in the late 1940s for an on-site coal-fired power plant, which closed in the 1980s. The 9-hectare site is bounded by a county drain to the north and the Tittabawssee River to the east and sits within the floodplain of the river. The ash pond held approximately 90,000 cubic meters of ash, and it was surrounded by an earthen berm of sand and silt. Because of the hydraulic connectivity to the river, Dow wanted to eliminate any pathways for compounds of concerns to end up in the larger ecosystem, but the project team did not want to use a traditional cap and long-term maintenance plan to solve the problem. Therefore, they engaged Dow's Nature Team and used the ESII Tool to define an alternative solution. From 2015 to 2016, the project team removed the ash and restored the area to a conservation wetland. Restoring this site improved important ecological functions in the area while improving natural habitat by reintroducing 25,000 native plants representing 65 different species—and saving $2 million over the traditional cap solution.

Producing Efficiencies

The project team used the Ecosystem Services Identification and Inventory (ESII) tool (see page 294 for more information) to establish the baseline ecological conditions of the project area and to compare alternative restoration scenarios. The ESII tool measured the impact of three different restoration plans by analyzing eight specific ecosystem parameters, such as water quality control, air quality control, and flood hazard mitigation, which allowed the team to compare the three design choices and ultimately show that the ash removal and native plant restoration would be the most effective.

Using Natural Processes

Water quantity control has, to date, been the most evident and obvious ecosystem service that Dow's Riverside Wetlands provide. Initially, the project team thought that the site would be fully functional and retain floodwater only when all of the plants were mature. Yet, twice in the first year, the project site flooded and reduced flooding impacts downstream. Furthermore, the native wildflowers such as swamp milkweed (*Ascelpias incarnata*) provide host plants for important pollinator species like the monarch (*Danaus plexeppus*).

Previous page: Native milkweeds were planted strategically to attract the monarch butterfly. (Photo by Dow)

Right: The restoration plan included both submergent wetland and seasonal vernal pools to maximize the ecosystem services. (Photo by Dow)

Broadening Benefits

The city of Midland has its own plan for beautification along the river and for improving community entryways. The Dow restoration project addresses components of this, improving 1.6 kilometers of riverfront directly across from downtown Midland and adding recreational spaces for members of the local community. Therefore, the site now benefits the community not only by retaining and storing floodwaters, reducing downstream flooding, but also by forming an important connection to a vast network of parks, open spaces, and trails.

Promoting Collaboration

The team used this project to beta test and refine the ESII tool. By using ESII to provide ecosystem service data in engineering terms, the team was able to demonstrate to all the local stakeholders the benefits of the ecological restoration alternative—the ash removal and replanting plan. Dow's resulting collaboration with The Nature Conservancy; the Michigan Department of Environment, Great Lakes, and Energy; and the city of Midland created a functional, ecologically diverse wetland.

Top: Installing 25,000 native plants in the wetland. (Photo by Dow)

Middle: The native wildflowers are now thriving and teaming with wildlife. (Photo by Dow)

Bottom: The vernal pools provide habitat to various plants and animals. (Photo by Dow)

Pierce Marsh

Hitchcock, Texas, United States

Restoring eroded marsh in the Gulf Intracoastal Waterway. The entire Pierce Marsh complex covers approximately 971 hectares and includes low marsh, shallow open water, and salt prairie. The marsh has a diverse ecosystem of marine invertebrates, fish, and numerous species of migratory and local birds, providing multiple ecological niches for coastal species. However, subsidence, freshwater intrusion, and erosion have led to habitat degradation of coastal prairie into intertidal marsh or open water. The Galveston Bay Foundation and other organizations have led intertidal wetland restoration efforts within Pierce Marsh since 1999 to address this. In 2016, the U.S. Army Corps of Engineers (USACE)–Galveston District in conjunction with their partners restored 32 hectares of the selected 49-hectare marsh section. The project took 150,000 cubic meters of unconsolidated fine material from routine maintenance dredging of the Gulf Intracoastal Waterway and used it to reduce erosion and raise Pierce Marsh to its target elevation of 1 meter. The project team restored valuable habitat at the site and used airboats to reseed the area with native vegetation. Since 2016, the Galveston District and their partners have continued restoring Pierce Marsh's intertidal march complexes by beneficially using dredged sediment from nearby navigation projects while avoiding impacts to local wildlife.

Producing Efficiencies

Silts and soft clays, also known as *fines*, are the most common material excavated in maintenance dredging in this reach of the Gulf Intracoastal Waterway. The material is ideal for beneficial-use projects that restore eroded habitat. Therefore, the Pierce Marsh project took advantage of this plentiful resource to elevate the marsh and restore habitat for colonial nesting birds and native vegetation. By using engineered perimeter berms and grade control markers, the team contained the dredged sediment in target areas while avoiding previously restored sections of the marsh. Now the coastal marsh can provide its own natural engineering benefits, such as protection against storm surge.

Using Natural Processes

Raising the elevation of targeted sections of Pierce Marsh by using engineered berms and the sediment removed from the federal navigation channel via cutterhead dredge reduced marsh erosion without permanently altering the ecological conditions. The Natural Resources Conservation Service's seeding operation helped to reestablish vegetation impacted by the restoration effort and restored resources in the marsh, providing a habitat to encourage the growth and return of native birds, fish, and invertebrates. Further, the intertidal marsh vegetation planted will filter pollution and act as a natural buffer to reduce future erosion.

Previous page: Pierce Marsh after restoration. (Photo by USACE Galveston District)

*Right: Roseate spoonbills (*Platalea ajaja*) and laughing gulls (*Leucophaeus atricilla*) using the marsh. (Photo by Galveston Bay Foundation)*

Wetlands

Broadening Benefits

Coastal marshes provide a wide range of environmental and economic benefits, including improved water quality, a buffer from erosion and rising sea levels, and increased property values in surrounding communities. They safeguard against extreme weather and provide foraging sites for local and migrating birds. Additionally, the increased biodiversity leads to increased tourism and interest, providing an opportunity to educate people on the value of marsh restoration and preservation. For example, over the years, hundreds of community volunteers have participated in hands-on restoration of Pierce Marsh at events such as Marsh Mania.

Promoting Collaboration

The Galveston District worked closely with its partners—the National Oceanic and Atmospheric Administration, the Department of the Interior's Natural Resource Damage Assessment and Restoration Program, the Natural Resources Conservation Service, the U.S. Fish and Wildlife Service, the Texas Parks and Wildlife Department, the Texas General Land Office, the Texas Commission on Environmental Quality, Ducks Unlimited, and the Galveston Bay Foundation—to coordinate the dredging and transport of dredged sediment to restore sections of Pierce Marsh. This partnership will continue as the team replenishes Pierce Marsh and restores other sections in future projects.

Top: Dredged sediment being pumped into the marsh. (Photo by Galveston Bay Foundation)

*Bottom: American avocet (*Recurvirostra americana*) using the restored Pierce Marsh. (Photo by Galveston Bay Foundation)*

Ellis Meadows

Leicester, England, United Kingdom

Building a multifunctional green space for people and wildlife. The River Soar runs through the center of the city of Leicester, located in England's East Midlands; and a major flood event would cause serious economic losses to the city. To combat this threat, the Environment Agency in partnership with Leicester City Council converted a former school playing field into a wetland and wildflower park complete with cycleway and boardwalk and reconnected the River Soar with its floodplain. Consisting of grass and decommissioned allotments, the public rarely used the site before this project; and ecologically it contributed very little. Funded in 2013 and completed in 2016, the 7.4 hectares restored at Ellis Meadows formed the second phase of a larger natural flood management project for the city. Taking a blue-green infrastructure approach to managing flood risk through a combination of land lowering and reshaping, wetland creation, and vegetation management has reduced the flood risk for over 2000 homes and businesses in Leicester. When river levels are high, it provides space for water-lowering levels upstream within the city center. The natural flood management technique worked straight away: a flash flood filled the Ellis Meadows wetland, preventing costly flood damage and demonstrating the project's success.

Producing Efficiencies

While most flood schemes in the United Kingdom use engineered defenses requiring environmental mitigation, Ellis Meadows' focus on blue-green infrastructure improvements and use of local materials cost a quarter of the price of the original proposal. Even the on-going maintenance costs of the habitats created, including a wildflower meadow, are lower than the previous costs of regularly mowing the grass. The support of the city mayor has been a crucial factor in delivering the scheme in an unusually short timescale for a major flood alleviation project.

Using Natural Processes

By planting native species that can tolerate a range of water levels, retaining mature trees and scrub, and adding a species-rich native wildflower meadow and new woodland, the project team created a diverse set of habitats. Grey heron (*Ardea cinera*) and little egret (*Egretta garzetta*) sightings have already become common, as are badger foraging and commuting paths. Additionally, the site encourages soil carbon sequestration and reduces greenhouse gases. As it is on the edge of a highly urbanized area, it will help to alleviate the urban heat island effect.

Previous page: Thistles, daisies, grasses, and other native wildflowers now grow in the meadow. (Photo by Leicester City Council)

Right: Funded by the Leicester and Leicestershire Enterprise Partnership, a new cycleway with solar-powered lighting provides a path through the park. (Photo by Environment Agency)

Broadening Benefits

In addition to protecting Leicester and the surrounding areas in the event of a flood, the wetland also functions as a fish refuge when levels in the main River Soar are high. Ongoing monitoring shows a range of birds, bats, amphibians, and dragon- and damselflies occupy the wetland, which together with the wildflowers, cycling path, and boardwalk create a rich, biodiverse tapestry for local residents. This abandoned school field has become a popular spot for cycling, walking, barbecues, and picnics.

Promoting Collaboration

Leicester City Council, as the landowner, played an important role in helping the Environment Agency restore the site, working closely with flood, parks, education, regeneration, and highways specialists to get overall agreement on the project. Drawing on the partners' expertise, it has been possible to engage with Leicester's diverse population at locations and in activities that go beyond normal audiences. Influencing communities and organizations in their everyday environment has again linked local people and the waterway.

Top: One year after planting, native species now grow along the edges of the wetland. (Photo by Environment Agency)

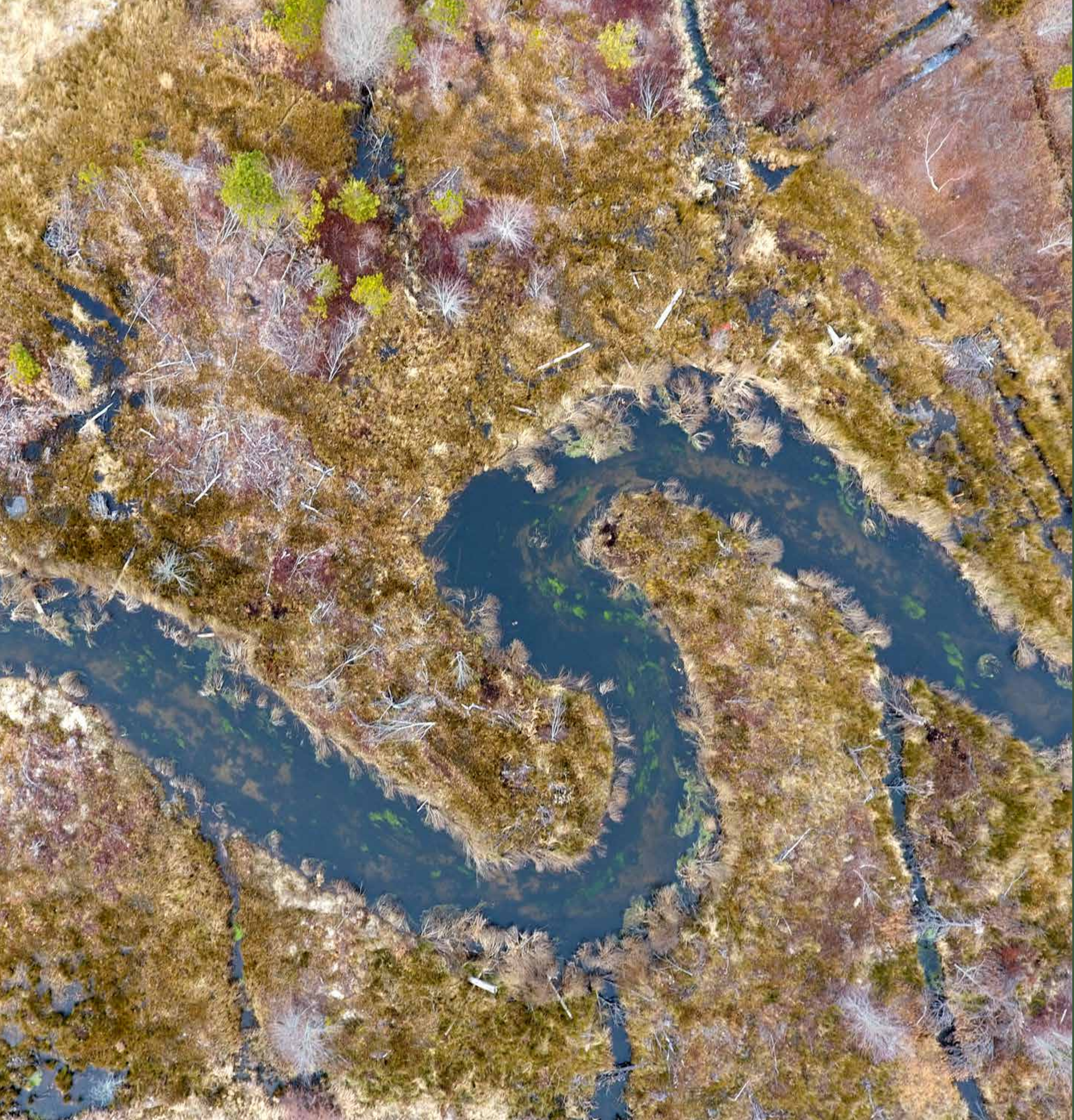
Middle: Two years after planting, juvenile fish and freshwater mussels occupy the water. (Photo by Environment Agency)

Bottom: The accessible boardwalk made of recycled plastic allows everyone to enjoy Ellis Meadows. (Photo by Environment Agency)

Tidmarsh Farms Cranberry Bog

Plymouth, Massachusetts, United States

Carrying out the largest freshwater restoration in Massachusetts. In 2009, the owners of Tidmarsh Farms entered an agreement with the U.S. Department of Agriculture's Wetlands Reserve Program to place nearly 80 hectares of cranberry bogs and degraded wetlands near the headwaters of Beaver Dam Brook into a conservation easement. The region had suffered from the effects of deforestation and draining since the seventeenth century, and cranberry farming practices had further impacted biodiversity, aquatic life, and local hydrology. The restoration process began by documenting the existing habitat and geomorphic conditions, then examining the possible wetland and stream restoration opportunities, and finally identifying the constraints and opportunities at the site. That analysis resulted in a concept design describing various restoration options for the bog complex, downstream channel, dam, and impoundment. In 2014, the project team decided on the final design: channel restoration, reestablishing hydrologic control, and native plant revegetation for the entire 80 hectares. Construction began in 2015 on 6000 meters of new stream channels, 100 hectares of fen and Atlantic white cedar bog restoration, sphagnum reintroduction, fish passage improvements, and the removal of the headwater dam. The final result is a thriving habitat, increased biodiversity, and a haven for birds, butterflies, and native wildflowers.



Producing Efficiencies

Economic shifts, climate change, and new farming techniques have resulted in farmers letting their cranberry farms go fallow around Massachusetts. This project models transforming abandoned cranberry farms to native stream and wetland ecosystems, restoring nonproductive land into valuable native habitat. There exist only a few known wetlands in the region not affected by the last 400 years of use, so the team had few real-world examples to draw on. The success of the Tidmarsh restoration will serve as a model for future projects and provide additional opportunities for scientific and academic research, design engineering, and permitting and monitoring.

Using Natural Processes

Constructing riffles in new stream channels and filling in and plugging perimeter and lateral ditches raised the water's surface elevation in the retired cranberry bog, converting them to native stream and wetland ecosystems. The project team used thousands of pieces of large wood and tree stumps, many from adjacent forestland or from local entities looking to dispose of downed trees, to provide complexity in habitat conditions for fish and other aquatic organisms. By engineering microtopography into the landscape through a pit-and-mound design, the team naturally encouraged diversification in flora and fauna and made the habitat more resilient to climate change.

Previous page: The new meandering stream intersecting some of the former drainage ditches. (Photo by Inter-Fluve)

*Right: Monarch (*Danaus plexippus*) larva using milkweed, its host plant. (Photo by Mass Audubon)*

Broadening Benefits

The Massachusetts Audubon's Nature Sanctuary and the Living Observatory demonstrate Plymouth's emergence as a center for ecotourism and scientific inquiry and provide the same level of employment—perhaps even more—as when Tidmarsh was a working farm. The sanctuary and observatory engage the public and provide educational and academic inquiry opportunities while also providing a space for recreation and wildlife observation. The restored wetland also makes the region more resilient to climate change as the design will adjust with sea level rise.

Promoting Collaboration

The team collaborated with the Department of Agriculture's Wetlands Reserve Program, the Massachusetts Division of Ecological Restoration, and with scientists from nearly a dozen academic institutions, including the University Massachusetts–Amherst's Geosciences Department for their expertise in spring flows and stream temperatures and the Massachusetts Institute of Technology's Media Lab for their expertise in remote-sensing operations. The Massachusetts Audubon purchased the site as a wildlife sanctuary and now provides trails, educational signs, and an educational center to encourage long-term research and monitoring.

Top: Large wood logs and root wads placed along the river and on the wetland surface provide valuable habitat for aquatic and terrestrial species. (Photo by Inter-Fluve)

Middle: The restoration actions have made the project site more suitable for a wide range of wetland plant species. (Photo by Mass Audubon)

Bottom: During the fall migration season, birds like this palm warbler rely on wetland and bog areas for foraging opportunities. (Photo by Mass Audubon)

Drake Wilson Island

Apalachicola, Florida, United States

Pioneering the beneficial use of dredged sediment for more than 40 years. In 1976, the U.S. Army Corps of Engineers–Mobile District established a 5-hectare marsh on Drake Wilson Island off the coast of Florida in the Gulf of Mexico, one of the earliest dredged sediment habitat improvement projects in the U.S. The created marsh provided a valuable habitat and prevented erosion into the adjacent navigation channel in an area subject to long wind fetches and strong currents. Previously an unmanaged, low-habitat-value, dredged sediment placement site composed of sandy dredged sediment deposits, the island has since become a thriving marsh habitat for native wildlife. The project team constructed the marsh in two phases using hydraulically pumped material derived from the adjacent navigation channel; and by 1982, the native plantings placed during construction completely covered the island. Meanwhile, as planned, natural events breached the dike in several places, providing intertidal flow. The most recent series of observations, in 2019, documented several diverse habitats on the island: natural sand deposits, pine woodlands, and high-quality marsh habitat. The island now provides forage and nesting sites for a variety of species, including least terns, clapper rail, willet, great blue heron, marsh wren, boat-tailed grackle, bald eagles, brown-headed nuthatches, and osprey.

Producing Efficiencies

In 1976, little information was available regarding appropriate techniques to design and construct wetlands. Though starting with engineered features, including a dike to contain the dredged sediment during marsh establishment and a weir system to maintain tidal exchange, the project team then allowed natural processes to take over. The successful weir, experimental planting techniques, and the development of appropriate elevation gradients all helped guide future efforts. Monitoring data from the 1970s and 1980s and again in 2019 provides a unique opportunity to evaluate project success and ecological trajectory over extended time scales.

Using Natural Processes

Once established, the created marsh was subject to natural processes, which degraded the dike and weir system, allowing for natural patterns of tidal exchange. Storm events introduced additional sediments, and recruitment of 17 native plant species has led to widespread vegetation. The site now exhibits low marsh habitat dominated by sturdy bulrush (*Bolbochoenus robustus*) and smooth cordgrass (*Sporobolus alternifolus*), high marsh dominated by black needlerush (*Juncus roemerianus*), and xeric slash pine (*Pinus elliottii*) hammock communities across an elevation gradient established during construction.

Previous page: Great blue heron surveying the marsh. (Photo by Nathan Beane, U.S. Army Engineer Research and Development Center [ERDC])

Right: Researchers monitoring conditions 43 years after construction. (Photo by Nathan Beane, ERDC)

Broadening Benefits

More than 40 years after its creation, the marsh at Drake Wilson Island is a valuable habitat and is now home to more than thirty species of birds, such as the great blue heron (*Ardea herodias*). While supporting habitat growth, the marsh and nearby areas provide recreational opportunities, such as camping, wildlife watching, and recreational fishing. Additionally, the location of the marsh, adjacent to Two-Mile Channel, decreases erosive forces in the area, improving navigation and decreasing dredging maintenance requirements.

Promoting Collaboration

The Mobile District partnered with the Dredged Material Research Program for the initial construction and implementation of Drake Wilson Island. The long-term monitoring continued through the Dredged Material Research Program as well as the Environmental Effects of Dredging Program, the Dredging Operations Technical Support Program, the Dredging Operations and Environmental Research Program, and the Engineering With Nature Initiative. The projects' decades-long span highlights the need to adequately document the design, construction, and monitoring aspects. This allows future studies to build on previous research and to capture the true life-cycle benefits of the restoration.

Top: Organic matter accumulating in the soil of the created marsh. (Photo by Nathan Beane, ERDC)

Middle: Intertidal exchange with Apalachicola Bay after the planned erosion of the earthen dike. (Photo by Nathan Beane, ERDC)

Bottom: Dense low and high marsh precedes pine forests at higher elevations. (Photo by Nathan Beane, ERDC)

Jekyll Creek

Jekyll Island, Georgia, United States

Piloting a new thin-layer placement technique in coastal Georgia. More than half of all dredged sediment from U.S. Army Corps of Engineers (USACE) projects is placed in upland facilities, which are expensive to manage, or offshore, resulting in the loss of valuable material. At the same time, coastal marshes are slowly drowning through sea level rise, subsidence, and groundwater withdrawals and need sediment to keep up vertically with these threats. Jekyll Creek, a long-standing navigational concern, provided an ideal opportunity to promote beneficial use of dredged sediment to build coastal marsh resiliency. In 2017, the USACE Savannah District partnered with the Jacksonville District, the Georgia Department of Nature Resources, the Jekyll Island Authority, and The Nature Conservancy to develop a 2-hectare thin-layer placement (TLP) project on Jekyll Island to understand the potential benefits of this placement strategy in the region. Completed in April 2019, the project is the first TLP project in the State of Georgia and the first constructed by the USACE South Atlantic Division. It has been a success in partnership building and use of an innovative disposal technique that has both economic and environmental benefits.

Producing Efficiencies

TLP is an emerging dredged sediment placement technique, and the Jekyll Island project provided the perfect case study for applying lessons from comparable projects in the North Atlantic and Gulf of Mexico. Coastal Georgia experiences the largest tidal range in the South Atlantic (1.8–2.7 meters) and presented numerous project design and construction challenges. To address this, the team placed coconut coir logs to contain material and limit turbidity outside the placement area. Monitoring by unmanned aerial vehicles documents vegetation changes, while use of the Marsh Equilibrium Model aims to quantify the marsh's response to sea level rise.

Using Natural Processes

Natural deposition of fine material on marsh surfaces occurs during high tide and storm events and through natural growth and decay of organic material. However, traditional dredging practices often remove sediment from active sediment systems, resulting in the loss of sediment from estuarine and coastal systems. The Jekyll Island project took advantage of material dredged during routine navigation channel maintenance and maximized coastal resiliency by keeping valuable sediments in the system, mimicking natural processes by hydraulically placing the material on the marsh surface.

Previous page: Georgia Southern University and University of South Carolina students collecting data to determine the effectiveness of the TLP pilot. (Photo by Christine Hladik, Georgia Southern University)

Top: Jekyll Creek site after placement. (Photo by The Nature Conservancy and the Jekyll Island Authority)

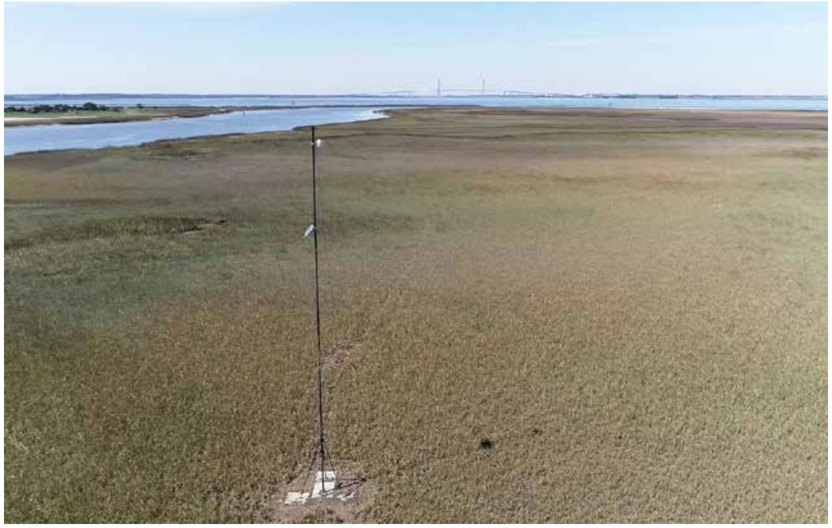
Bottom: A dredging project manager monitoring dredged sediment placement in April 2019. (Photo by Clay McCoy, USACE Jacksonville District)

Broadening Benefits

The Jekyll Island TLP project developed and evaluated alternative placement strategies for dredged sediments while enabling unimpeded navigation by commercial and recreational vessels. However, these methods also benefit the tidal system. Allowing valuable sediments to remain in the region strengthens coastal marshes as they face increasing sea level and supports invertebrates, shorebirds, and marsh grasses. The result is a more resilient marsh system that helps to protect upland residential communities in the event of storm surges and sea level rise. Continued monitoring is providing valuable opportunities to assess the long-term benefits and to engage the public.

Promoting Collaboration

The team wanted to strengthen the South Atlantic Division's relationship with regulatory agencies and stakeholders through collaboration and project execution. The partnership included local USACE districts, the Georgia Department of Natural Resources' Coastal Resources Division, the National Marine Fisheries Service, the U.S. Fish and Wildlife Service, The Nature Conservancy, the Jekyll Island Authority, Cottrell Dredging, and Georgia Southern University. Once monitoring is complete, the team hopes that Jekyll Island stands as a successful effort by multiple agencies and experts and demonstrates TLP as an effective tool to support coastal resiliency.



Top: USACE project manager on site on the first day of sediment pumping. (Photo by Georgia Department of Natural Resources' Coastal Resources Division)

Middle: Dredged sediment spreading across the containment area. (Photo by Clay McCoy, USACE Jacksonville District)

Bottom: Site monitoring camera installed prior to material placement. (Photo by Georgia Department of Natural Resources' Coastal Resources Division)

Umetco Former Mine Site

Hot Springs, Arkansas, United States

Creating a thriving aquatic habitat from an open-pit mine. From 1967 to 1985, Umetco conducted mining activities across 150 hectares of this 200-hectare property in the Ouachita Mountain ecoregion, resulting in low pH and mobilized zinc in the surface water. Acid rock drainage further degraded the water quality, and mine spoil areas and unimproved roads increased sedimentation in headwater streams. From 2015 to 2019, Umetco installed permanent, natural treatment systems to restore water quality and improved existing stormwater drainage to promote overland flow into lined, limestone riprap channels. This change limited water infiltrating into buried mine spoils and promoted conveyance of clean water to nearby streams, one such restored by adding cobble substrate and strategically placing downed trees to stabilize the banks and to create riffles and pools. The project team also engineered a unique, three-layer sediment cover in a 52-meter deep former mine pit lake, encapsulating sludge containing metal hydroxides and neutralizing pH in sediments and overlying water. Upland habitats restored with native wildflowers and grasses now provide food for a variety of pollinators and support ground-nesting songbirds. This project emphasized passive engineering solutions to improve water and habitat quality and to minimize maintenance. In response, terrestrial and aquatic biological communities are thriving.

Producing Efficiencies

Using a georeferenced barge attached to cables anchored at the sides of the 6.5-hectare former mine pit lake, the team applied three layers of sediment cover along the bottom of the lake. The placement of an engineered cover this deep in a mine pit lake had not been successfully attempted previously, but quality assurance monitoring has demonstrated that the cover is working. The resulting water quality has been outstanding, and the population of native fish species is thriving, also in part due to the habitat enhancements using on-site downed trees to promote pool-and-riffle features.

Using Natural Processes

The project team created approximately 0.8 hectare of wetlands at the outflow from a former mine pit lake to create habitat and to reduce metals concentrations in the water prior to its entering an adjacent stream. Additionally, the team planted native wetland and upland plants with an emphasis on plants used by pollinator species. In the year since the wetland creation, the water quality entering the stream has dramatically improved. Fish species have returned; and pollinator species, such as the tall poppy mallow (*Callirhoe leiocarpa*) and plains coreopsis (*Coreopsis tinctoria*), have emerged.

Previous page: Pedestrian access bridge overlooking the capped former mine pit lake. (Photo by Dow)

*Top: Plains coreopsis (*Coreopsis tinctoria*) growing at the edge of the constructed habitat wetlands. (Photo by Dow)*

*Bottom: Black-eyed Susans (*Rudbeckia hirta*) growing in the seeded area. (Photo by Dow)*

Broadening Benefits

The Umetco team created over 80 hectares of improved habitat and prepared the site for long-term biological productivity. With the restoration complete and water quality improving throughout the 200-hectare site, the project team is now developing a plan to return the site to beneficial community use. The system of trails, used in the past to monitor fence lines, and installed wooden and steel pedestrian bridges could allow the public to enjoy the site; and the team hopes to demonstrate to the public that a properly restored former mine site can become an amenity for the community at large.

Promoting Collaboration

The project team developed three-dimensional conceptual site models to help clearly explain to regulatory partners the project challenges and their plans to address them effectively. Although public access to the site was denied for safety reasons during construction activities, the team posted informational signs at the site entrance to inform the public of the transformation taking place. Currently, they are working with the local community and conservation groups to transfer ownership and management of the property to provide this natural space to the public for decades to come.

Top: Vegetated cover over the mine spoils repository. (Photo by Dow)

Middle: The constructed wetland downstream of the vegetated cover. (Photo by Dow)

*Bottom: Indian blanket (*Gaillardia pulchella*) growing in the seeded area. (Photo by Dow)*

Clinton River Mouth Wetland

Harrison Township, Michigan, United States

Innovating a new approach to wave breaks at the edge of an open lake. Since the 1987 Great Lakes Water Quality Agreement between Canada and the United States, restoring Lake St. Clair has been an international priority. Converted to a dredged sediment disposal facility in the 1960s, the site had become covered with invasive phragmites (*Phragmites australis*), creating a low-quality habitat; and the construction of the facility itself had destroyed a large portion of the wetland complex. Starting in 2015, the project team began the process of improving the quality and resiliency of coastal wetland for fish and wildlife species in an area that experiences extreme lake level fluctuations and ice scour. Continuing through 2021, the team has used traditional measures such as removing invasive species and planting native ones as well as nontraditional measures like installing root-wad wave breaks and using dredged sediment to create emergent wetland habitat. The eventual goal—delisting the Clinton River as an Area of Concern—will promote significant new real estate and commercial development interest, allow for increased use of the area for recreational activities, improve the quality of life for the local community, and serve as a recruiting tool for local businesses.

Producing Efficiencies

The root wads used as wave breaks for the project were secured to the lake bottom with earth anchors and then, for further stability, buried with dredged sediment from the nearby channel. Designs including permanent features, in contrast, would have increased the initial project cost and, over time, required more long-term maintenance than the nature-based features used. This beneficial use of dredged sediment increases project efficiency by using existing operations and maintenance funding for multiple benefits.

Using Natural Processes

Fluctuating lake levels in Lake St. Clair, and across the Great Lakes in general, makes sustainable wetland restoration benefits difficult to consistently maintain through time. Using the root wads, which will degrade naturally, gives native wetland vegetation time to establish, providing long-term stabilization. The project team intentionally placed the wetland on the south side of the site to provide additional protection from wind and waves and therefore encourage its successful establishment. They also constructed the wetlands at two different elevations, increasing long-term resiliency to fluctuating lake levels.

Previous page: Root wads for anchoring to the lake bottom as a wave break. (Photo by Keith Kropfreiter, U.S. Army Corps of Engineers (USACE)–Detroit District)

Right: Placing dredged sediment from the navigation channel in the wetland. (Photo by Keith Kropfreiter, USACE Detroit District)

Broadening Benefits

Transformed from a monoculture of phragmites with very little ecological value to a diverse landscape, the site now includes a variety of coastal and wetland species, such as pickerelweed (*Pontederia cordata*) and swamp milkweed (*Asclepias incarnata*). These wetlands provide nursery habitat for juvenile fish and valuable resting habitat along the globally significant Mississippi Flyway. Clinton River Mouth Wetland Restoration Project is also adjacent to one of the busiest boat launches in southeast Michigan, improving local housing values and bringing in additional tourism revenue to the region.

Promoting Collaboration

In addition to the Environmental Protection Agency providing guidance and Great Lakes Restoration Initiative funding, the state of Michigan, Clinton River Watershed Council, and the Clinton River Public Advisory Council made major contributions to the project's success. Additionally, the local sheriff's office provided invaluable assistance, keeping boaters away from the discharge pipeline and pump. The beneficial use of dredged sediment to create nearshore wetland habitat was a first for Michigan and has led to the development of best management practices that can be used for future projects.

Top: Vegetation stabilizing the beneficially placed dredged sediment. (Photo by Keith Kropfreiter, USACE Detroit District)

Middle: Earth anchors securing the root wads to the lake bottom. (Photo by Keith Kropfreiter, USACE Detroit District)

Bottom: Seeding the site with native plants after removing invasive species. (Photo by Keith Kropfreiter, USACE Detroit District)

Tomago Wetlands

Tomago, New South Wales, Australia

Restoring a salt marsh's hydrology regime with large-scale engineering. Hunter Wetlands National Park lies along the Hunter River estuary in southeastern New South Wales. Because it provides foraging habitat for migratory wading birds along the East Asian–Australasian Flyway, it is a designated wetland of international importance. However, due to sea level rise and an enhanced tidal range, the salt marsh ecosystem in the park has been under threat, experiencing ecosystem loss. To combat this loss and provide a nature-based solution, New South Wales National Parks and Wildlife Service, working with researchers from the University of New South Wales Sydney, restored a 450-hectare area of low-lying and drained land called the Tomago Wetlands. In 2007, the restoration began by installing novel tidal control gates and reintroducing tidal inundation to 250 hectares. In 2012, the project restored an additional 62 hectares; and in 2015, the team restored the final 138 hectares. This project, one of the first large-scale intertidal restoration projects in Australia, has successfully expanded the park's salt marsh habitat and established significant foraging grounds for migratory avifauna—including over 5,000 birds in a single month. Additionally, the site remains an important test case for ongoing research linking hydrodynamics, geomorphology, and ecology in Australia.

Producing Efficiencies

Examining hydroperiods of salt marsh and mangrove systems across the estuary determined the optimal operational design to promote ecosystem recovery. The project team incorporated these variables into a detailed ecohydrodynamic model to provide on-the-ground site management options. To maximize salt marsh growth while also ensuring that adjoining landholders were not negatively affected, the team implemented an innovative SmartGate system at Tomago. The gates permit adaptive tidal inundation control across the large intertidal flats, protecting both the restored areas and the adjoining commercial properties from river-based floods.

Using Natural Processes

At Tomago, unlike at other shorelines, the project team wanted to limit mangrove expansion because the natural predators of migratory wading birds are often found in mangrove ecosystems. But the team also wanted to maximize the benefits of the local natural processes. The team achieved both by promoting the preferred hydrodynamic regime for salt marsh ecosystems while also installing sufficient water-level control to limit mangrove expansion. This hydrologic regime naturally optimizes carbon accumulation processes, enhancing the accretion rate of the wetland.

Previous page: Tomago Wetlands is a thriving tidal wetland and part of the Ramsar-listed Hunter Wetlands National Park. (Photo by Will Glamore, PIANC)

Top: In contrast to its former drained state, the site now stores blue carbon at a high rate. (Photo by Will Glamore, PIANC)

Bottom: Multiple species within the salt marsh are flourishing on-site because of carefully controlled inundation patterns. (Photo by Will Glamore, PIANC)

Broadening Benefits

The site is part of the lower Hunter River flood mitigation scheme, which ensures flood storage and retention for the nearby city of Newcastle. Open to the public and managed according to the local community's needs, the restored wetlands now are not only an important habitat but also provide flood control to adjoining properties. By integrating a community approach and completing the project in stages, the New South Wales National Parks and Wildlife Service has made sure the restoration provides ecological, economic, and social benefits to the entire region.

Promoting Collaboration

The various collaborative partners on the Tomago project are still working to ensure the continued success of the plan. Researchers working on site have established long-term monitoring to assist with adaptive management plans, and the community has access to a live-streaming camera of the site—with over 15,000 images available since 2007—to ensure the site evolves as planned. Finally, the local bird watching club provides monthly monitoring of bird populations to track the project's success. Together, these groups help to maintain the ongoing adaptive management of the site.

Top: Hydrologic controls are aimed at creating salt marsh growth for a range of ecosystem services, including migratory bird species. (Photo by Will Glamore, PIANC)

Bottom: Ecosystem restoration has promoted foraging and roosting for birds such as the Eastern Great Egret (Ardea alba) *(Photo by Will Glamore, PIANC)*

Sabine National Wildlife Refuge

Cameron, Louisiana, United States

Constructing a permanent dredged sediment pipeline for marsh creation. Located in the Chenier Plain ecosystem, the Sabine National Wildlife Refuge (NWR) is the largest coastal marsh refuge on the Gulf. However, saltwater intrusion during tropical storms and from the Calcasieu River Ship Channel has converted significant areas within the Sabine NWR from vegetated intermediate marsh into large areas of shallow brackish water. Wind-driven waves further erode the surrounding marshes. Therefore, through the beneficial placement of material from maintenance dredging of the Calcasieu River Ship Channel, the Sabine NWR Marsh Creation Project strategically re-creates brackish marsh habitat in large, open-water areas of the interior marsh to prevent wind-induced saltwater introduction and freshwater loss. In addition, the placement of dredged sediment nourishes adjacent marshes while reducing open-water fetch (the distance a wave can travel) and further erosion. This multiyear, multiphased project is a partnership between the U.S. Army Corps of Engineers (USACE), the Coastal Protection and Restoration Authority of Louisiana, and the U.S. Fish and Wildlife Service through the Coastal Wetlands Planning, Protection, and Restoration Act of 1990 (CWPPRA). The many cycles of the project allowed land to be built quickly, creating critical wetland habitat in degraded areas.

Producing Efficiencies

The team determined that a permanent pipeline from the river to the northeastern corner of the reserve would eliminate the costs and impacts associated with installing a temporary pipeline for each dredge cycle, saving approximately $2 million for each. To give estuarine organisms access to the marsh, the team built some small artificial bayous, known as *trenasses*. They revised this method after subsequent experience showed that driving a track hoe or marsh buggy over the marsh-creation site one year after construction allowed tidal ingress and egress more effectively and economically than constructing the trenasses.

Using Natural Processes

The project reduces the environmental footprint of the Calcasieu River navigation channel by using dredged sediment to re-create marsh instead of placing the material in limited-capacity upland disposal sites. This dredged sediment nourishes adjacent marsh habitat and improves water quality by filtering pollutants and sediment naturally. It also absorbs water during periods of heavy rainfall. The marsh then releases the excess water more slowly into waterways, reducing the magnitude of any flooding. Smooth cordgrass (*Spartina alterniflora*) at the marsh perimeter naturally encouraged revegetation throughout the interior of the newly created site.

Previous page: Distichlis spicata *(L.) Greene (saltgrass) is the dominant plant species in the area providing nesting grounds for birds and protection from natural erosion along open water areas. (Photo by USACE New Orleans District)*

Top: Mature vegetation at project site and the levee in background. (Photo by USACE New Orleans District)

Bottom: Lush vegetation throughout the marsh and containment site. (Photo by USACE New Orleans District)

Broadening Benefits

The channel requires dredging every two years, and by piping it to the refuge, this project re-created approximately 453 hectares of marsh over 5 dredging cycles. It will prevent the loss of existing adjacent marshes and help restore the area's hydrology. This intertidal marsh habitat, located in a designated Internationally Important Bird Area, benefits a number of rare species, species of concern, and threatened and endangered species, such as least bittern (*Ixobrychus exilis*), Black Rail (*Laterallus jamaicensis*), king rail (*Rallus elegans*), Louisiana Eyed Silkmoth (*Automeris Louisiana*), and saltwater topminnow (*Fundulus notti*).

Promoting Collaboration

The collaboration between USACE's navigation program and the CWPPRA's ecosystem restoration program was highly beneficial. As USACE already funds the dredging of the Calcasieu River, CWPPRA had to fund only the incremental cost of transporting and placing the dredged sediment in the marsh creation site. By working with the Louisiana Department of Natural Resources, the Coastal Protection and Restoration Authority of Louisiana, the U.S. Fish and Wildlife Service, the Environmental Protection Agency, the Department of Agriculture, and the National Oceanic and Atmospheric Administration, the team received support to construct the permanent pipeline to be used for future marsh creation projects.

Top: Constructed in 2002, Sabine Marsh Creation Cycle 1 includes trenasses for fisheries and water movement. (Photo by USACE New Orleans District)

Middle: Construction of containment dikes at placement site. (Photo by USACE New Orleans District)

Bottom: Placing the dredged sediment with a temporary pipeline. (Photo by USACE New Orleans District)

Aerial view of West Ship Island taken in the aftermath of Hurricane Nate (10 October 2017) after Phase I of construction (project details on page 96). (Photo by U.S. Army Corps of Engineers–Mobile District)

Islands

Discovering placement solutions with multiple benefits

Introduction

A central theme running through the efforts to restore natural island process is how the application of EWN principles continues to meet project objectives. As a natural feature, islands play an important environmental and engineering role yet multiple environmental and anthropogenic forces have combined to degrade this role over time. The projects presented in this chapter showcase the range of outcomes possible using EWN principles. Whether coastal islands or inland features in lakes and rivers, these projects are exemplary for their overwhelming success. In Minnesota, islands in the Missouri River have become havens for native flora and fauna; and from Chicago to the Netherlands, a new kind of recreational refuge proves that humans and wildlife mutually benefit when engineering with nature. Sediment beneficial use plays a key role in nature-based features in both the Chesapeake Bay and the Gulf of Mexico, taken from navigation channels and increasing commercial and habitat value at the same time. Coastal islands specifically have an important function: reducing the effects of coastal storms. So their restoration through EWN applications improves not only their habitat value (migratory birds and fish, submergent and emergent aquatic vegetation) but also the resiliency of the communities behind them. But what all of these islands have in common is their ability to serve as habitat for a variety of species while building connections between people and communities, creating an abundance of recreational and educational opportunities.

Northerly Island

CHICAGO, ILLINOIS, UNITED STATES

Converting a private airport into a haven for wildlife. In 1909, Daniel Burnham envisioned Northerly Island as a lakefront haven for the public on the shores of Lake Michigan in downtown Chicago. The 37-hectare peninsula was constructed in 1920 but spent 57 years of its history as a concrete desert until 2003 when its stint as a private airport ended. The island had no aquatic connection to Lake Michigan and consisted mostly of turf grass, resulting in no habitat diversity and little overall ecological value. So in 2012, the U.S. Army Corps of Engineers (USACE)–Chicago District proposed transforming 16 hectares of the island into re-creations of the six habitats native to the Chicago region: lacustrine, dunal pond–lacustuary lagoon, emergent marsh, wet prairie, mesic prairie, and savanna. They moved 160,000 cubic meters of material, excavating a pond and connecting it to Lake Michigan, building up savannas, and planting a range of native vegetation—275,000 plugs, 11,800 shrubs, 400 trees, and 150 kilograms of seed. USACE completed construction in 2020; and now Northerly Island is a thriving, natural oasis for people and wildlife alike, all amid the Chicago skyline.

Producing Efficiencies

The team removed no materials from Northerly Island, instead reusing them across the restoration. They preserved a historical timber fish crib, discovered during the pond's excavation, as additional fish habitat and used the asphalt remains of the airport to contour the rolling hills of the oak savanna. They then topped the hills with sand and soil excavated from the pond. The tallest of the hills sits at over 10 meters above the lake, providing striking views of the downtown Chicago skyline while protecting the island from both the winds coming off Lake Michigan and the noise pollution from the city.

Using Natural Processes

Chicago historically was rich in biodiversity, with different habitat types found in close geographic proximity. The project team aimed to replicate this by building a diverse range of habitats to meet the needs of a diverse range of species—over 300 species of birds alone nest in, migrate through, or overwinter in the Chicago region, which sits in the Mississippi Flyway. Already, the new pond and lacustrine littoral habitats provide refuge and more habitat diversity than the bottom of Lake Michigan. Furthermore, the team planted 350 native plant species, including several state-listed plants, to prevent erosion at the site.

Previous page: Looking north over the newly restored pond and prairie with the Chicago skyline in the background. (Photo by USACE Chicago District)

*Top: Native foxglove beardtongue (*Penstemon digitalis*) attracts pollinators. (Photo by USACE Chicago District)*

Bottom: The restored habitat is used by various bird, as evidenced by this clutch of killdeer eggs found on the island in 2017. (Photo by USACE Chicago District)

Broadening Benefits

Residents and visitors now use the island for biking, hiking, bird watching, and fishing; and the Chicago Parks District offers various programs at the park, including educational opportunities at the outdoor laboratory. The numerous habitats, especially the rarer emergent marsh habitat, are thriving. In 2015, the project team discovered 20 black buffalo (*Ictiobus niger*) in the new lagoon, which is only the fourth recorded occurrence in southern Lake Michigan. One of these now resides in Chicago's Shedd Aquarium. Additionally, the lagoon is home to the state-threatened banded killifish (*Fundulus diaphanus*) and several other uncommon native lake fishes.

Promoting Collaboration

The Chicago Park District partnered with USACE to implement the restoration piece of their Northerly Island 2010 Framework Plan under the Great Lakes Fishery and Ecosystem Restoration (GLFER) program. They worked with experts from the National Audubon Society, Field Museum, Openlands, the Forest Preserve of Cook County, and the Shedd Aquarium to design the rolling hills, dunal pond, and other habitats and to select the most suitable native plant species for each. This successful collaboration and the resulting wildlife oasis and living laboratory it will produce led the team to win the 2012 Model Project Award from the Illinois Department of Natural Resources.

Top: Dunal pond and emergent marsh habitats under construction in 2013, facing eastward toward Lake Michigan. (Photo by USACE Chicago District)

Middle: Mesic prairie restoration immediately after planting seed in 2013, facing northwest into downtown Chicago. (Photo by USACE Chicago District)

*Bottom: Illinois's only native prickly pear (*Opuntia humifusa*) grows on a sandy hillside in the project area in 2018. (Photo by USACE Chicago District)*

Marker Wadden

Lake Marken, Flevoland, the Netherlands

Inventing a new engineering technique to bring a dead lake back to life. Lake Marken, or *Markermeer*, lies in the center of the Netherlands. The conditions of this lake became ecologically very poor because of plans to turn the lake into a polder. Though these plans were suspended in the 1990s, many dams and dikes were already built by then. So, the lake lacked natural shores. As a result a 30-centimeter layer of sediment on the lake bed turned the water increasingly murky, making life difficult for many aquatic species. As fish populations dropped, the birds also disappeared, leaving an area devoid of wildlife. In March 2016, Natuurmonumenten (a Dutch nongovernmental organization for nature conservation) and Rijkswaterstaat, with input from dredging experts, nature conservationists, engineering firms, universities, and landscape architects, began restoring an area in the northeastern portion of the lake. The project team added 1,000 hectares of new habitat, including islands constructed from sand, clay, and silt—an engineering first at this scale. The islands' harbor opened in 2018; but from the start, the team has provided visitors and researchers many opportunities to visit these new islands. Remarkably, wildlife began returning to the site as soon as construction started; biodiversity has exploded.

Producing Efficiencies

The same fine sediment that caused the ecological problems in the lake has become the solution as the team constructed the islands by using dredged clay and fine sediment. Building with sediment on the soft lake surface had never been done before. Therefore, to address this new challenge, several universities and institutes, in addition to researchers from the dredging company, have monitored every step of the process. The innovative hydraulic engineering techniques used for this maritime construction will lead to an increased understanding of sediment processing.

Using Natural Processes

The Marker Wadden archipelago allows the lake and new marshland ecosystem to interact more fully. The islands are a mosaic of mudflats, marshland vegetation, creeks, and shallow isolated pools, surrounded by wide channels that provide additional sheltered shallow water. Further, gradual transitions from land to water, ideal for marsh and water vegetation, create areas that trap sediment and trigger biochemical processes, capturing phosphorus and stimulating nitrification and denitrification. Wind causes waves to enter the area and leave more sediment between the marshes, and specially created washovers stimulate these natural processes.

Previous page: The new footpath through the marshes was created for recreational and educational use. (Photo by Peter Leenen, Straystonephoto)

Right: This large screen allows visitors the perfect view for birdwatching. (Photo by Peter Leenen, Straystonephoto)

Broadening Benefits

With the creation of the islands and the improved water quality, many species, such as common terns (*Sterna hirundo*), avocets (*Recurvirostra* spp.), and black-headed gulls (*Chroicocephalus ridibundus*), have returned. The islands function as a living laboratory for both citizen-scientists and academic researchers. Many tourist companies have started offering special nature trips to the islands, and water recreation from the harbor island has become popular. The next phase's visitor center will further foster the growth of this community hub for recreation, nature, and science.

Promoting Collaboration

With a goal of restoring 100 square kilometers, Marker Wadden represents one of the largest nature-based engineering projects in Europe. To succeed, the project brought together a broad range of complementary expertise and enabled mutual learning. Working together since 2013, Rijkswaterstaat and Natuurmonumenten have combined their nature restoration and public work experience. To this they added Boskalis's innovative technology and the support of many partners and stakeholders. Because of this, Marker Wadden now serves as a testament to Dutch marine engineering.

Top: The islands offer a suite of recreational opportunities for visitors. (Photo by John Gundlach, Boskalis)

Middle: The range of habitats attracts a variety of wildlife for observation and study. (Photo by John Gundlach, Boskalis)

Bottom: This tower overlooking the marshes gives visitors and citizen-scientists alike the opportunity to watch nature at work. (Photo by Peter Leenen, Straystonephoto)

Cat Island and Ship Island

Cat Island and Ship Island, Mississippi, United States

Creating valuable habitats while protecting the mainland coast and Mississippi Sound. Hurricane Camille cut Ship Island in half when it raged through the Gulf Coast in 1969. The 5.6-kilometer breach between East and West Ship Islands, known as Camille Cut, had almost naturally healed when Hurricane Katrina carved it open again in 2005. Meanwhile, Cat Island, another barrier island off the coast of Mississippi, had lost hundreds of acres of land to erosion. The two islands represented a critical opportunity to restore the Mississippi coastlines' first line of defense against coastal storms. The U.S. Army Corps of Engineers (USACE)–Mobile District partnered with Mississippi's Secretary of State's Office and the Mississippi Department of Marine Resources to restore Cat Island and the National Park Service to restore Ship Island, the latter of which is the second largest restoration project in the history of the National Park Service. Using millions of cubic meters of sand and reused dredged sediment, the project teams restored areas of both islands, creating valuable beach and dune habitats and enhancing their ability to absorb wave energy, sheltering the mainland Mississippi coastline.

Producing Efficiencies

For Ship Island, the riskiest part of the project was closing Camille Cut without significant sediment losses, and the most challenging for Cat Island was matching sand grain size and color to the native beach. In both cases, extensive scientific research and on-site investigations ensured the technical precision required to succeed. For Cat Island, researchers identified a borrow site through a partnership with the U.S. Geological Survey. The Ship Island project team took advantage of hydrodynamic and morphological modeling to choose the most effective method of closure. For both, scientific and engineering expertise translated to cost savings and successful outcomes.

Using Natural Processes

Both islands have specific erosion patterns, so the project teams worked with these natural tendencies to minimize sediment losses during construction. Plantings of native plant species, such as Gulf bluestem (*Schizachyrium maritimum*), sea oats (*Uniola paniculate*), and bitter panic (*Panicum amarum*), further maximized sand retention and natural revegetation. On Ship Island, many plantings were from cuttings and seeds from the island itself, taking advantage of an already-available natural resource. The two projects planted a combined 415,000 plants, which established healthy stands within months of installation.

Previous page: Cat Island postrestoration in 2017. (Photo by USACE Mobile District)

Top: Ship Island construction in 2018. (Photo by USACE Mobile District)

Bottom: Path traveled by sea turtle hatchlings on Cat Island in 2017. (Photo by USACE Mobile District)

Broadening Benefits

Restoration of both Cat Island and Ship Island provide a wealth of societal benefits. They provide additional areas for fishing, hiking, birdwatching, and other recreational activities; and they help guard the Mississippi coastline from wave action and storm surges. This will protect cultural sites, improve public safety, raise property values, increase local tax revenue, and shield fishery habitat and limit saltwater intrusion in Mississippi Sound. Furthermore, the restored islands provide critical habitat for sea turtles; commercially valuable shellfish; native and essential fish; and coastal, marine, and migratory bird species.

Promoting Collaboration

A combined 16 different organizations, including state and federal agencies, universities, and private companies were critical in the planning, design, and implementation of these restoration projects. Although the numerous stakeholders and agencies involved had differing perspectives and governing missions, they ultimately strongly supported the effort, making the projects successful. That the native habitats on each island are thriving is a testament to the positive outcomes possible when people are willing to work hard, be honest with each other, and listen to the perspectives of others.

Top: Construction pad at the center of the Camille Cut at Ship Island during construction. (Photo by USACE Mobile District)

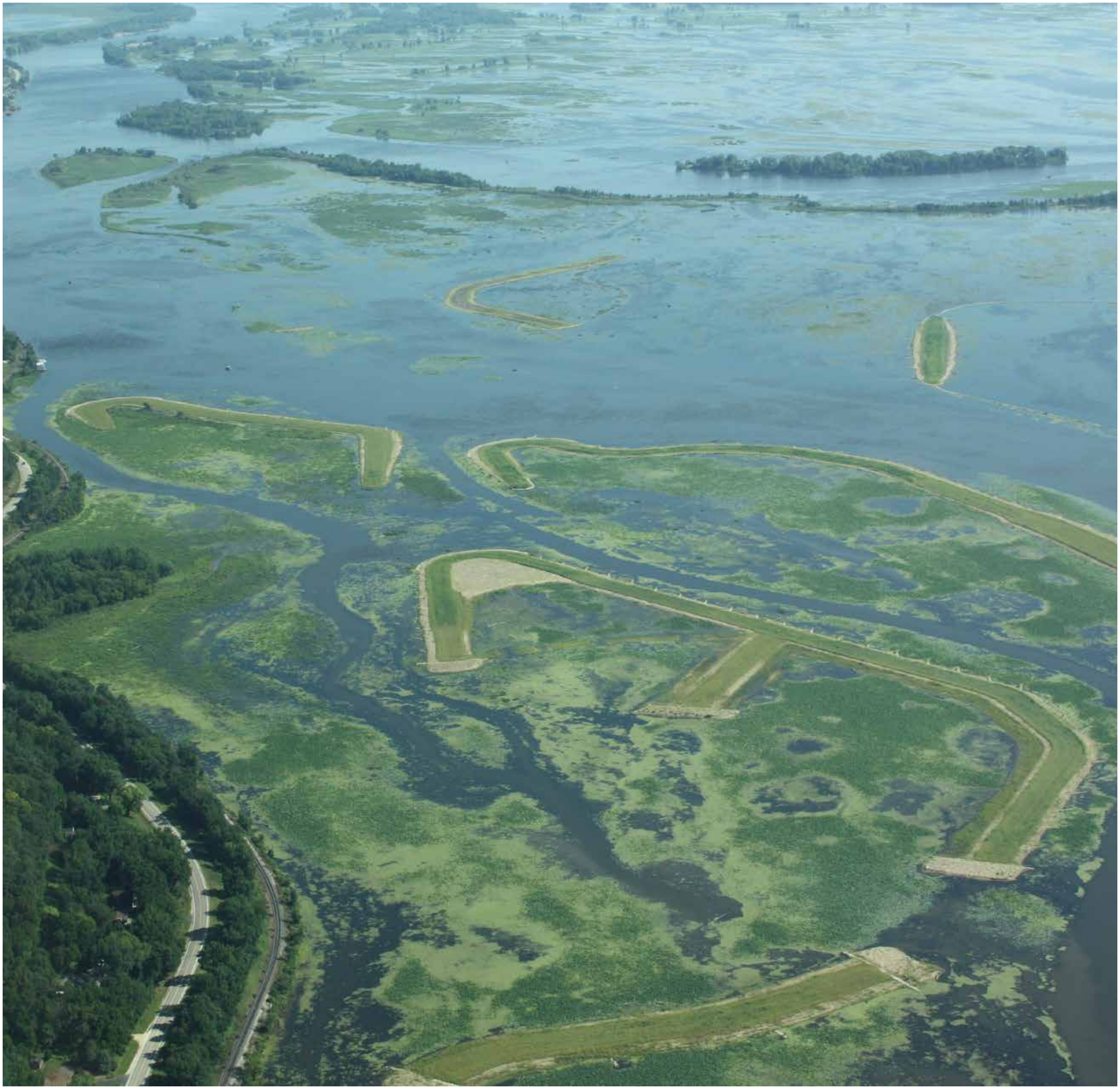
Middle: Plantings on the landward side of sand fencing at Cat Island in 2017. (Photo by USACE Mobile District)

Bottom: Ongoing beach restoration at Cat Island in 2017. (Photo by USACE Mobile District)

Pool 8

Brownsville, Minnesota, United States

An interagency effort combining hydraulic, geotechnical, and biotechnical expertise. Pool 8 is part of the Upper Mississippi River System, a nationally significant ecosystem and a crucial part of the Mississippi River's commercial navigation network. Conditions across the 15,400-hectare pool deteriorated in the decades following completion of Lock and Dam 8 around 1939. This created an environment for amplified wave action, inundation of the floodplain, altered hydraulics, and intensified ice action that degraded aquatic and terrestrial habitat across the pool. To combat these effects, the U.S. Army Corps of Engineers (USACE)–St. Paul District used dredged sediment to reconstruct a series of islands in Pool 8. Construction first began in 1989 as part of the Upper Mississippi River Restoration Program; and over the course of three phases, the district and its project partners restored more than 182 hectares of habitat. The team designed the new islands to reduce the factors that had previously caused the erosion, resulting in improved water clarity and increased growth of aquatic vegetation. The new islands benefit fish, waterfowl, and other wildlife and create a beautiful new location for ecofriendly recreation.



Producing Efficiencies

The project team modeled the islands after historic conditions. A two-dimensional hydraulic model of measured flow rates and water-surface elevations along with historic information on island configuration helped to maximize habitat in the Lower Pool 8 design. To divert the flow of wind and water, the team built the islands with a sand base, rock features to provide erosion resistance, and fine sediment to act as topsoil. Sand berms provide substrate for willow trees, rock groins stabilize the sand berms, and other vegetation provides further island stabilization. The team used these techniques to stabilize nearly 16 kilometers of shoreline.

Using Natural Processes

The new islands restored the river to a more natural hydrologic regime, creating physical conditions that sustain aquatic ecosystems and benefit fish, mussels, and other aquatic and wetland taxa. Dredging in backwater areas provided fine sediments for topsoil and also created deep waters for overwintering fish. Berms captured this hydraulically dredged sediment without violating water quality standards, and these containment areas were transformed into wetlands. The use of grasses, shrubs, trees, and legumes stabilized the islands, and the creation of seed islands allows growth through natural deposition processes. The combination of these processes provided valuable habitat for migratory birds and other terrestrial species.

Previous page: A 2010 aerial image shows the series of islands reconstructed from dredged sediments. (Photo by Wisconsin Department of Natural Resources)

Top: A well-established seed island has formed due to sediment accumulation in the deposition zone behind a wildlife loafing structure, or large woody debris, in 2010. (Photo by USACE St. Paul District, Eastern Area Office)

Bottom: A rock vane and loafing structure integrated into a newly constructed island in 2011. (Photo by USACE St. Paul District, Eastern Area Office)

Broadening Benefits

The Upper Mississippi River Restoration Program agency partners conducted surveys to quantify the benefits of the project, demonstrating the improved environment and more sustainable ecosystem that resulted. New fish populations are developing in the project areas, which support recreational opportunities such as local fishing tournaments. Dabbling and diving ducks, such as the canvasback (*Aythya valisineria*), among other migratory waterfowl, have benefited from the new growth of rooted floating and submerged aquatic vegetation as a food source. Also, beneficial use of dredged sediment helped manage material and ease overcapacity at existing placement areas.

Promoting Collaboration

The Upper Mississippi River Restoration Program is a unique, long-term partnership that has fostered collaboration among five states and seven Federal agencies since 1986, and the Pool 8 islands project is one of over 70 ecosystem restoration projects built under this collaboration during that time. The St. Paul District worked with a number of partners to complete this major restoration, including the U.S. Fish and Wildlife Service, the Wisconsin Department of Natural Resources, the Minnesota Department of Natural Resources, the U.S. Geological Survey, and the public.

Top: Pelicans seeking refuge provided by a seed island. (Photo by USACE St. Paul District, Eastern Area Office)

Middle: A rock and log sill installed in the river to increase the flow in the area during flood events. (Photo by USACE St. Paul District, Eastern Area Office)

Bottom: A rock sill redirects water during high-flow events. (Photo by USACE St. Paul District, Eastern Area Office)

Unity Island

Buffalo, New York, United States

A first-of-its-kind project using dredged sediment from the Buffalo River. Unity Island is located in the Upper Niagara River, which connects Lake Erie to Lake Ontario, and falls within the Niagara River Area of Concern (AOC). Here, industrial development in the twentieth century, combined with the development of marinas, private docks, and water-control structures, led to the loss of thousands of hectares of coastal wetlands, disconnected bodies of water, and ponds too deep to support wetland vegetation. In 2018, the U.S. Army Corps of Engineers (USACE)–Buffalo District partnered with the city of Buffalo to reuse 43,000 cubic meters of dredged sediment from the Buffalo River navigation channel to create 2 hectares of emergent and submerged wetland habitat and reconnect 4 hectares of backwater habitat to the main stem of the Niagara River. The project was one of a suite of sediment remediation and habitat restoration projects that were identified through a robust Great Lakes Restoration Initiative–funded, state led, and locally influenced process. Today, at Unity Island, native emergent and submerged aquatic vegetation flourishes on the placed dredged sediment, and the natural recruitment of plants from the river via the new connection has established a diverse native plant community.

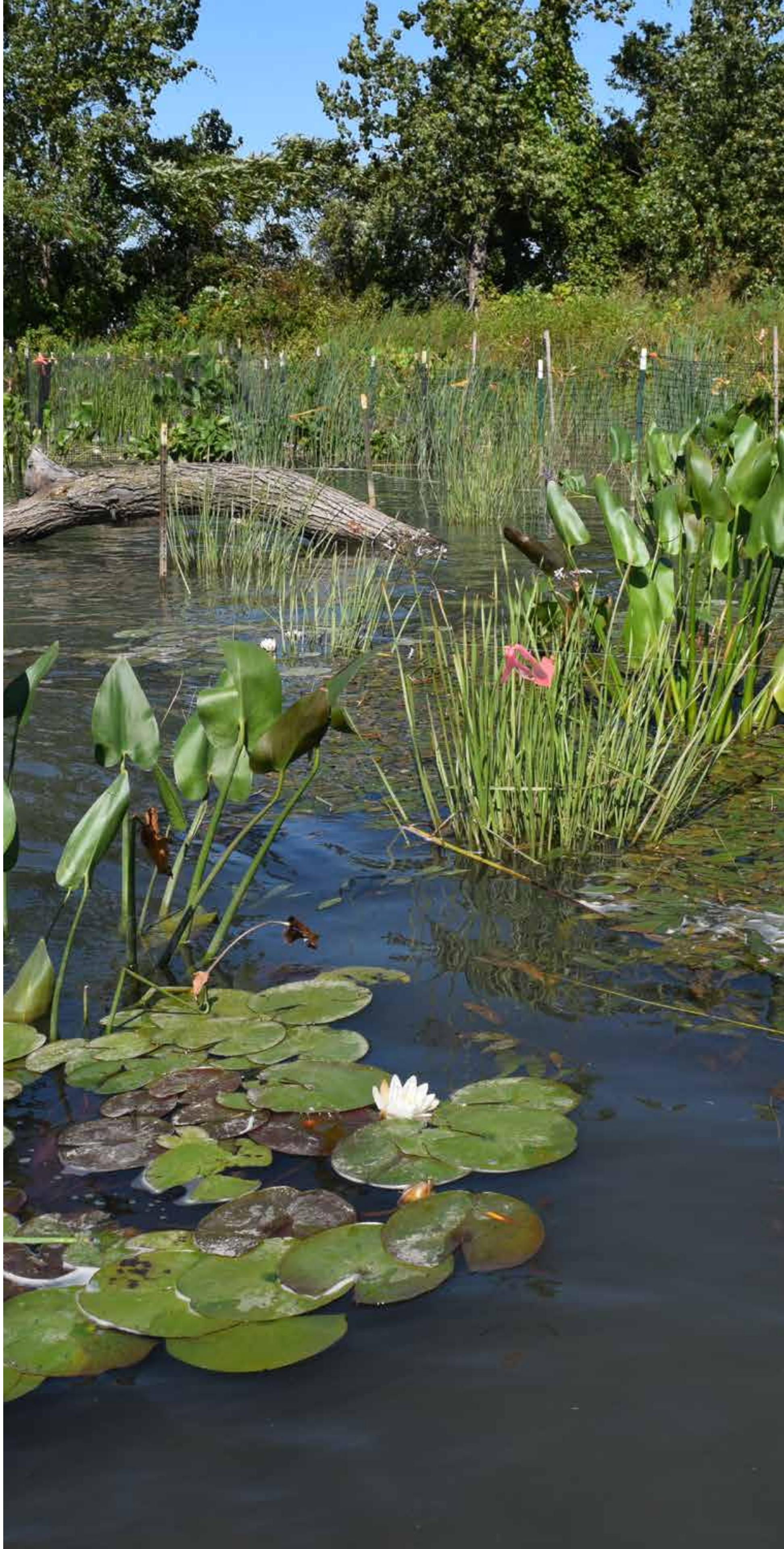
Producing Efficiencies

As the Unity Island project was the first of its kind within the Great Lakes, the project team conducted a thorough feasibility study under the Continuing Authorities Program, Section 204 authority. The study examined the characteristics of dredged sediment in the Buffalo River and is now an example for other projects. This knowledge applies to at least three other projects in the Buffalo District Civil Works Program, allowing them to undergo an abbreviated feasibility phase. Also, the beneficial use of dredged sediment reduced the need for a confined disposal facility and provided a native seed bed, both leading to significant cost savings.

Using Natural Processes

By simply creating an opening in an existing rubble-mound structure, this project has provided habitat connectivity between the Niagara River and four hectares of slack water, creating coastal wetland habitat directly adjacent to the main stem of the Upper Niagara River. Natural recruitment of native plants floating in from the river greatly enhanced the establishment of the wetland plant community, which benefits local wildlife such as the northern pike (*Esox lucius*) and the state-threatened common tern (*Sterna hirundo*).

Previous page: Aerial view of the wetland at Unity Island two years after placement of dredged sediment. (Photo by Kevin Lesika, USACE Buffalo District)



Right: Native wetland vegetation has flourished on the placed dredge sediment. Habitat logs and a submerged reef were created by reusing materials from construction. (Photo by Andrew Hannes, USACE Buffalo District)

Broadening Benefits

With many of the coastal wetlands in the Niagara area destroyed due to urban development, restoring even a small amount of wetland habitat can make a big difference for the survival of native plant, fish, reptile, amphibian, and migratory and local bird species. The additional tourism activity generated by the Great Lakes restoration project has boosted the local economy. Furthermore, the project has boosted local housing prices, demonstrating the value of these amenities to local residents.

Promoting Collaboration

This project required a wide variety of engagement strategies and included a broad group of stakeholders: the USACE Buffalo District, the Niagara River Greenway Habitat Enhancement Restoration Fund, the city of Buffalo, the New York State Department of Environmental Conservation, and the Niagara River Area of Concern Remedial Action Committee. Funding from the Great Lakes Restoration Initiative and lessons from a comprehensive portfolio of previous projects on the Buffalo River made this project possible.

Top: Buffalo District biologists conduct a fish population survey while teaching local students about the importance of wetlands. There has been a substantial increase in abundance and diversity of native fish species since project completion. (Photo by Adam Sanders, USACE Buffalo District)

Bottom: Buffalo District biologist inspects new plantings at Unity Island. The planting plan is three years in duration to account for water-level fluctuations, which have proven vital for establishing a resilient wetland ecosystem at Unity Island. (Photo by Jess Levenson, USACE Buffalo District)

Swan Island

Chesapeake Bay, Maryland, United States

Providing resilience for coastal communities. The coastal islands and marshes of the Chesapeake Bay are disappearing, along with their ecosystems and the shoreline protection they provide. Within the last half century, the cumulative effects of shoreline erosion, subsidence, inadequate sediment supply, and sea level rise have accelerated the rate of island submergence. For example, the Smith Island complex, of which Swan Island is a part, has eroded at rates of up to 2 meters per year over the past 75 years. To counter these losses, the U.S. Army Corps of Engineers (USACE)–Baltimore District is restoring historic island footprints using clean dredged sediments. This project to restore and monitor the 11-hectare Swan Island is in partnership with the U.S. Army Engineer Research and Development Center (ERDC), the National Oceanic and Atmospheric Administration, the Maryland Department of Natural Resources, and the U.S. Fish and Wildlife Service. The sediment placement resulted in elevation gains from 0.15 to 0.5 meters, which transformed Swan Island from a low-elevation fragmented and sinking marsh to a higher elevation gradient. The restoration will significantly benefit the larger ecosystem, increasing resilience to future sea level rise, reducing erosion in the adjacent coastal community, and providing new habitat to local wildlife.

Producing Efficiencies

To quantify and assess restoration outcomes for Swan Island, the project team is using data from pre- and postrestoration monitoring to develop an integrated hydrodynamic and ecological model. The simulation model will help to evaluate island performance under a range of future sea level rise scenarios and to plan future sediment additions. The general approach and results of model outcomes will be applied to other island systems and regions, facilitating island restoration approaches in the future.

Using Natural Processes

Swan Island functions as a natural wave break for the town of Ewell on nearby Smith Island. Restoring the elevation, combined with planting and rapid recolonization with native vegetation, helps to stabilize the placed sediments, minimize erosion, and facilitate the trapping of new sediments, thus rendering the island more resilient to storms and sea level rise. It also has ecological benefits for a multitude of species as this effort will recapture much-needed migratory bird habitat previously lost in the Chesapeake Bay.

Previous page: Swan Island in 2019 after placement of dredged sediments. (Photo by NOAA)

Right: Real-time kinematic GPS determines locations and elevations of vegetation on the island. (Photo by NOAA)

Broadening Benefits

The restored island will support migratory birds, fish, and invertebrates. Only four months postplacement, fish were observed in the newly formed channels, and migratory birds were abundant. As the vegetative community matures, bird and aquatic life usage is expected to increase. Adjacent island communities also benefit economically through the routine maintenance of navigation channels, which support local tourism and provide access to fishing grounds, transportation, and commerce. Finally, keeping clean sediment within this sediment-starved ecosystem enhances the ability of marsh communities to trap those sediments, increasing island resilience.

Promoting Collaboration

The Swan Island restoration project is a collaborative partnership of five federal and state agencies and USACE's Engineering With Nature Initiative. It leverages the resources, expertise, and mandates of the agencies involved to meet project objectives, pooling their knowledge of hydrodynamics, sediment transport, subtidal and intertidal habitats, and the Martin National Wildlife Refuge itself. Also, ERDC scientists are training project partners in developing an integrated hydrodynamic and ecological model to better quantify the resilience and ecological benefits of the project. This collaborative partnership is filling critical knowledge gaps relative to the resilience and ecological benefits of island restoration projects.

Top: Placing feldspar clay on sediment to determine the amount of sediment accretion. (Photo by NOAA)

Bottom: An aerial view of Swan Island in 2017 showing the severe island submergence before restoration. (Image from Google Earth)

Reefmaker structures along the Cape Fear River diffuse wave energy, providing a long-term solution to severe shoreline erosion (project details on page 120). (Photo by Phillip Todd, Atlantic Reefmaker)

Reefs

Stabilizing shorelines and creating habitat

Reefs

Introduction

The projects in this chapter present novel ways to stabilize shorelines and protect economic, engineering, and ecological assets by using nature-based reef structures, creating valuable habitat and restoring complex ecosystems. The following projects have all implemented nature-based features designed and constructed to serve as a base for aquatic species—while still serving key engineering functions. Nature-based reefs from a variety of materials and designs protect not only shorelines vulnerable to erosion but also land-based features and functions compromised by coastal storms and wave action. In short, these reefs improve coastal resiliency. Key environmental enhancements include creating substrates for oyster colonization and restoring habitat for a variety of coastal species. On the landward side of these structures, the accretion of sediments creates additional shore protection and habitat, and when space precludes traditional living shoreline designs, innovative seawalls mimic coastal habitat features instead. Nature-based reefs also reintroduced a nearly extinct species while providing scour protection to offshore wind farms. Taken as a whole, these reefs show that coastal engineering projects provide ample opportunities to enhance habitat, restore biodiversity, and protect local communities.

Goldbug Living Shoreline

Sullivan's Island, South Carolina, United States

Reefs

Protecting salt marshes with a living oyster reef. Goldbug Island sits on the eastern side of the Charleston Harbor, along the Atlantic Intracoastal Waterway. Wave energy from recreational boat traffic had exacerbated erosion of the local salt marsh, already affected by coastal development and sea level rise. So in 2016, The Nature Conservancy in South Carolina installed an Oyster Castle reef, the longest reef the group had established in the state. The 67-meter-long reef reduces wave energy, promotes oyster growth, and advances the front edge of the *Spartina alterniflora* marsh grass. The installation was one part of a larger, multiyear project funded by the Wildlife Conservation Society's Climate Adaptation Fund to install demonstration projects that serve as a learning platform while the state develops a living shoreline permitting process for private property owners. The Conservancy organized three different volunteer days to prepare and install the materials, receiving assistance from South Carolina Department of Natural Resources staff and over 200 volunteers from the community. Volunteers continue to monitor its progress, reporting sitings of numerous species using the reef, including commercially important fish species.

Producing Efficiencies

CH2M designed the living shoreline reef for The Nature Conservancy. The reef structure reduces wave energy from boat wakes and promotes sediment accretion on the landward side of the reef. The presence of soft, watery mud might have made for a difficult and expensive installation, but the team used pallets as a base layer and wrapped them in geotextile fabric to "float" in the mud. These pallets, combined with Oyster Castles and dried, bagged oyster shells, will stay within the water column and remain available for future spat to settle.

Using Natural Processes

Besides preventing erosion and promoting sediment accretion, oyster reefs support over 130 aquatic species. They provide interstitial spaces for juvenile and small species to find protection; feeding grounds for larger species; and plentiful surfaces for oysters, which then support future populations of oysters in the local waterways by producing seed. Oysters are filter feeders, filtering up to 190 liters of water per day, so this reef will also provide cleaner water and reduced turbidity, while the growing marsh behind it will provide new habitat for local and migratory birds.

Previous page: Nearly 200 volunteers helped install the shoreline in April 2016. (Photo by South Carolina The Nature Conservancy [SCTNC])

Top: Volunteers from The Citadel and the local community line up walking boards (Photo by SCTNC)

Bottom: Monitoring oysters showed 7.6 centimeters of growth after the first year. (Photo by SCTNC)

Broadening Benefits

South Carolina still has one of the largest wild oyster harvest industries in the region, so protecting current populations and seeding new ones directly benefits the South Carolina economy. But oyster reefs also save $750 per meter on coastline protection, diffusing wave energy from storm surges and reducing the risk of flooding from coastal storms. Oyster reefs play an important role in filtering water and sequestering greenhouse gases, and they support a resilient coastal ecosystem. Additionally, this living shoreline project provides an educational opportunity and a highly visible example of the benefits of nature-based shoreline stabilization.

Promoting Collaboration

The Nature Conservancy worked with Lowcountry Land Trust, which holds a conservation easement on Goldbug Island, in hopes that the conservation easement would help prevent future coastal property development on the island, promoting the long-term stability of the project. The property owners, East Cooper Outboard Motor Club, agreed to allow property access to the Conservancy for five years to install and monitor the living shoreline project. CH2M and the South Carolina Department of Natural Resources were also partners on the project, bringing shoreline reef design experience and sediment accretion and analysis expertise.

Top: Preinstall site visit reveals erosion to the salt marsh, August 2014. (Photo by SCTNC)

Middle: The natural salt marsh vegetation is recovering due to shoreline stabilization, July 2019. (Photo by SCTNC)

Bottom: Post–Hurricane Dorian site check reveals resiliency of the project site, September 2019. (Photo by SCTNC)

Brunswick Town / Fort Anderson

Cape Fear River, North Carolina, United States

Protecting an important piece of American history. Brunswick Town–Fort Anderson, a historic colonial and Civil War site on the coast of North Carolina, was at risk. Constant tide forces and dynamic wave action were bombarding the colonial-era wharves and washing important historical artifacts into the Cape Fear River. Additionally, the erosion was destroying valuable coastal resources. So in 2012, the North Carolina Department of Natural and Cultural Resources tried unsuccessfully to stop the erosion and in 2017 turned to the Reefmaker concept as a way to mitigate the high wave energy causing it. The first phase of the project installed 67 meters of Reefmaker along the area with the highest erosion, and the second phase installed an additional 73 meters—just before Hurricane Florence hit the North Carolina coast. The Reefmakers proved effective; no structural damage occurred as a result of Hurricane Florence, and the shoreline is now stable. Further, the reef has encouraged a new marsh shoreline to form in front of the rock toe stabilization on the landward side of the phase-one Reefmaker structure, proving the Reefmaker's ability to disrupt wave energy and enable accretion.

Producing Efficiencies

The Department of Natural and Cultural Resources needed a long-term, cost-effective solution to the destructive wave action at Brunswick Town–Fort Anderson. With few maintenance costs, minimal impacts to the substrate, and the flexibility to adjust to any rise in sea level without additional permits, the Reefmaker met their needs. It now protects nearly 150 meters of vulnerable coastline, including the invaluable cultural resources at the historic site, and reduces current maintenance costs. This efficiency allows the department to focus on preserving other critical North Carolinian cultural heritage sites instead of maintaining the protective structure along the coast.

Using Natural Processes

Unlike traditional breakwaters, the artificial reefs allow sand to move from the open water to the shore, removing sediment from the water column and mimicking the natural accretion process of a coastal system. Without the destructive wave energy, the new material shores up the existing rocky revetment, adds to existing marsh, and allows the smooth cordgrass (*Sporobolus alterniflorus*) to regenerate naturally. The Reefmaker also provides a plethora of hiding spaces for local species such as eastern oyster (*Crassostrea virginica*) and blue crab (*Callinectes sapidus*), building up and maintaining the region's natural biodiversity.

Previous page: The installed Reefmakers protect the shore from excessive wave energy. (Photo by Christopher Dustin, Scenic Consulting Group, PLLC)

Right: The wave attenuator also provides substrate for oysters to grow. (Photo by Phillip Todd, Atlantic Reefmaker)

Broadening Benefits

The Brunswick Town–Fort Anderson State Historic Site attracts almost 35,000 visitors a year and hosts several programs for students in the county. Solving the erosion threatening the site reduced sedimentation and turbidity in the water column, created new habitat, and allowed the existing habitat to recover naturally over time. Further, the Reefmaker structure has withstood flooding and high-tide storm surges from hurricanes, proving its resilience. Overall, the project enhanced the environment while maintaining tourism income for the region and protecting a historically important site.

Promoting Collaboration

The North Carolina Department of Natural and Cultural Resources worked with the North Carolina Department of Transportation and the U.S. Army Corps of Engineers–Wilmington District to design a solution to the erosive forces acting on Brunswick Town–Fort Anderson without disrupting the local ecosystem or creating ongoing maintenance costs for state and local municipalities. This Reefmaker project is a first for North Carolina, and these collaborations and outreach to other agencies ensured success.

Top: The line of artificial reefs allows water to pass through while dissipating wave energy from passing boat traffic. (Photo by Phillip Todd, Atlantic Reefmaker)

Middle: Phase 1 of the installation; the three phases took place from 2017 to 2020. (Photo by Brandon Spaugh, North State Environmental Inc.)

Bottom: The new structure has stabilized the shoreline and allows for sediment accretion. (Photo by Christopher Dustin, Scenic Consulting Group LLC)

Bonner Bridge

Oregon Inlet, North Carolina, United States

Reducing wave energy for seagrass regeneration. Oregon Inlet is located in Pamlico Sound, the largest lagoon on the east coast and part of the Albemarle-Pamlico sound system, the second largest estuary in the United States. In this area, increased land use and development have in turn increased runoff, resulting in higher concentrations of nutrients, pollutants, and suspended solids in the sound. Overharvesting of oysters and the commercial removal of oyster reefs beginning in the late 1880s exacerbated the poor water quality in the sound, home to 90% of North Carolina's commercial fishing industry. Therefore, mitigating the ecological impacts of the construction of Bonner Bridge was essential. In 2017, the North Carolina Department of Transportation hired CSA Ocean Sciences to find a mitigation opportunity for 0.52 hectares of affected submerged aquatic vegetation (SAV), but no locations near the project met the traditional mitigation requirements. Instead, they proposed an alternative mitigation strategy. The team installed a 150-meter wave-attenuating Atlantic Reefmaker structure, providing a wave-energy shadow that allowed the vegetation to grow undisturbed. Now, a dense and vibrant bed of seagrass lies at the bottom of the sound, creating habitat for fish and other aquatic species.

Producing Efficiencies

CSA's extensive past research demonstrated that SAV habitat sheltered from wind waves developed continuous cover unlike those exposed. Therefore, the project team developed wave-forecasting models to precisely identify the size, location, and orientation of the wave attenuation system needed to aid SAV growth. The team installed the Atlantic Reefmaker system using pilings to support cast concrete disks at specified elevations above the seafloor. This design prevents the structure from settling into the seafloor over time and makes it readily adjustable to future sea level rise without requiring additional environmental permitting or compensatory mitigation.

Using Natural Processes

The reef installation method itself aimed to reduce environmental disturbances during placement, and the reef now acts as a natural impediment to waves. The wave shadow provided by the Reefmakers allows submerged vegetation to send runners along the seafloor, connecting existing patches and colonizing new ones. The result is a restored area of vegetation that will naturally increase habitat for other species. Furthermore, the Reefmaker's piling-based design minimizes the footprint of the structure, allowing SAV to colonize more local seafloor.

Previous page: Atop the reef structure facing the Bonner Bridge replacement. (Photo by CSA Ocean Sciences Inc.)

Top: The artificial reef protects the seafloor from destructive wave energy. The chevron points due north, the direction of the most destructive wave energy. (Photo by CSA Ocean Sciences Inc.)

Middle: Monitoring will continue through 2021. (Photo by CSA Ocean Sciences Inc.)

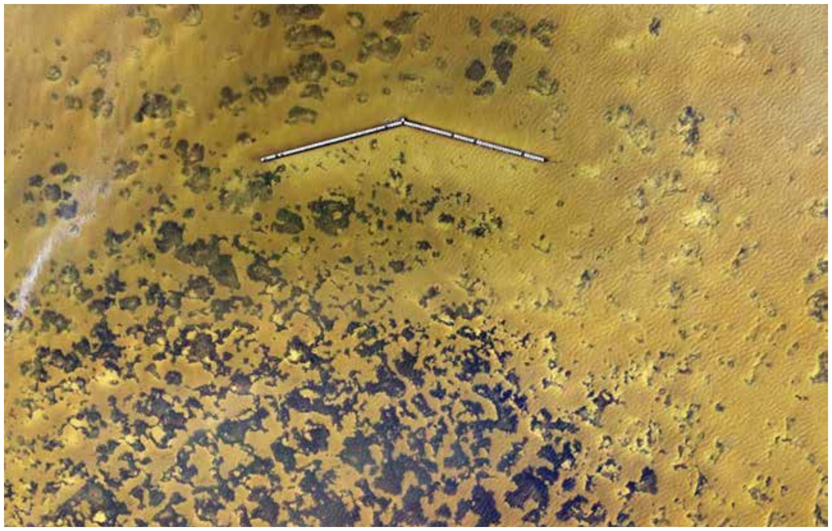
Bottom: A variety of small crustaceans use the Reefmaker for shelter, such as these hermit crabs. (Photo by CSA Ocean Sciences Inc.)

Broadening Benefits

Installing the Reefmaker minimized impacts of the bridge construction. As the abundance of fish, shrimp, and crabs is directly proportional to SAV acreage, preserving and encouraging native SAV growth have had a positive effect on local species. Oysters have already heavily colonized the Reefmaker structure itself; and fish inhabit the spaces in, around, and under the suspended Reefmaker, further contributing to the development of a stable, complex ecosystem. The solution has provided ecological, commercial, and recreational benefits while allowing in-kind mitigation, protecting valuable resources.

Promoting Collaboration

The North Carolina Department of Transportation and CSA Ocean Services collaborated to conceptualize, plan, and implement the solution. By leveraging peer-reviewed science, the team was able to create a defensible and compelling strategy to mitigate environmental impacts of the Bonner Bridge project. The collaborators fostered a spirit of innovation and project ownership, garnering the support of other stakeholders and government agencies, such as the U.S. Army Corps of Engineers, the North Carolina Department of Environment and Natural Resources, and the Federal Highway Administration.



Top: The abundance of hiding spaces for prey species attracts larger fish. (Photo by CSA Ocean Sciences Inc.)

Middle: Without the excessive wave energy, native seagrasses are free to proliferate. (Photo by CSA Ocean Sciences Inc.)

Bottom: Satellite imagery shows the accretion of vegetation on the seabed. Landward is to the bottom of the photo, and the dark areas represent new vegetative growth. (Photo by CSA Ocean Sciences Inc.)

Mangrove Reef Walls

Englewood and Fort Pierce, Florida, United States

Blending art and science to create a new type of seawall. Florida has more than 17,700 kilometers of waterways, much of which is lined with concrete seawalls installed in the mid-twentieth century and now undergoing replacement. Tidal ecosystems previously occupied these areas, rich in species that filtered water and formed nursery and hunting grounds for recreational and food-source species. Traditional seawalls have negatively affected these ecosystems. To counteract this, Mangrove Reef Walls are seawall-enhancing panels that create engineered-living tidal habitat along urbanized waterfronts, particularly in areas where conventional living shorelines are not feasible, such as in narrow canals or high energy zones. The panels, installed in two Florida locations—Englewood in 2016 and Fort Pierce in 2018—provide optimal conditions for a range of foundation species: oysters, tunicates, sponges, and other primary ecological producers that colonize the surface and enhance the constructed habitat. The reef walls provide a hierarchy of habitat niches to fill the void created by human development along these waterways. Although the panels will not recreate living mangrove trees, other foundation species perform many of the same services as mangrove shorelines and create habitat patches in developed areas that better connect the surrounding environment.

Producing Efficiencies

Mangrove Reef Wall panels ensure an ecologically responsive and viable approach to shoreline enhancement. No longer passive, the seawall articulates the exposed water side to improve the environment. The custom high-strength concrete is balanced with oyster flour, silica fume, and macrofiber reinforcement to attract oysters, resist saltwater deterioration, remove spalling risk, and double the material's lifespan. Restaurants' disposal of huge quantities of oyster shells creates a potential waste stream for producing these ecofriendly seawalls. Further, the design uses existing seawall production methods, creating a high-impact investment when replicating many panels.

Using Natural Processes

Mangrove Reef Walls create a scaffold for nature, enhancing ecosystems alongside human development. The walls' ability to dissipate wave energy in the same way that mangroves do improves water clarity by reducing suspended sediment and increases the walls' longevity by preventing sediment erosion. Oysters form bonds across seawalls and, in some cases, strengthen the walls with nacre—a material that exceeds concrete in strength. The small eddies produced by the uneven surface of the walls help attract drifting colonizers, diversifying the ecosystem and attracting grazing species, which in turn attract larger predators.

Previous page: Viewed from the water, Mangrove Reef Walls create a hierarchy of habitat relief and aerate tidal waters via wave and flow action across the panels. (Photo by Keith Van de Riet)

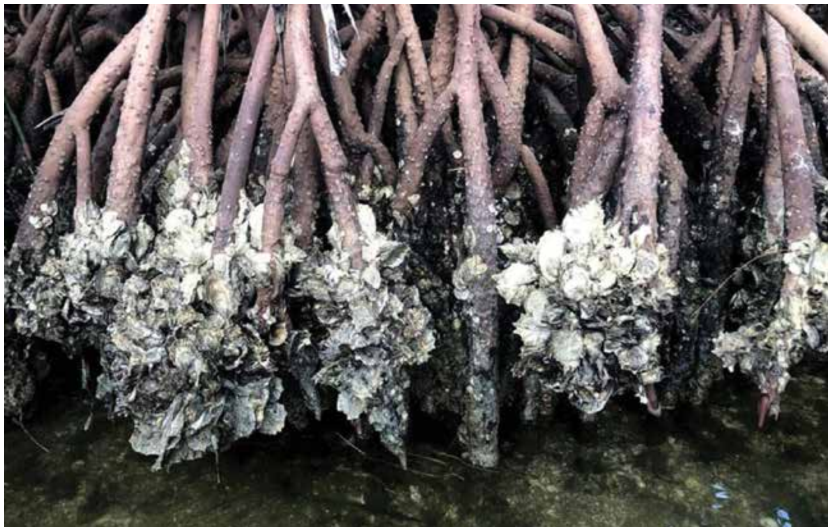
Right: Precast wall panels, developed by Keith Van de Riet, founder of Mangrove Reef Walls and associate professor at University of Kansas Architecture, awaiting installation. (Photo by Jose Beltran)

Broadening Benefits

The filtration capacity of tidal ecosystems directly affects water quality. Therefore, improving tidal environments can enhance Florida's multibillion-dollar tourism industry. Increasing filter-feeder populations may also mitigate harmful algal blooms (red tides), one of the most serious environmental and economic threats to Florida communities. In addition to improving the quality of waterways' ecosystems, the presence of this visually appealing infrastructure further enhances public awareness of shoreline issues and possible integrated solutions. The project promotes stewardship from waterfront property owners to create healthier nearshore environments that can be enjoyed by all.

Promoting Collaboration

Many individuals and organizations supported the development and design of the Mangrove Reef Walls, including Jessene Aquino-Thomas of Florida Atlantic University and Turrell, Hall, and Associates. CTS Cement Products, the WannaB Inn, and the Ocean Research and Conservation Association Inc. provided sponsorship. The interdisciplinary project team participates in many outreach events—critical for encouraging mainstream adoption of next-generation living shoreline technologies. Currently, a collaborative study with Florida state agencies is evaluating the design's potential positive impacts for the numerous canals and other waterways that cannot accommodate traditional living shorelines.



Top: Digital fabrication creates a complex surface for marine life to adhere to. (Photo by Jose Betran)

Middle: Oyster and other marine colonization of actual mangrove roots. (Photo by Keith Van de Riet)

Bottom: Flat seawall construction eliminates tidal habitat and enables invasive species to dominate waterways, challenges the Mangrove Reef Walls address. (Photo by Dr. Edith Widder, Ocean Research and Conservation Association)

Wind Farm Oyster Reefs

Borssele, Zeeland, the Netherlands

Analyzing oyster growth in an offshore environment. The European flat oyster (*Ostrea edulis*) used to cover about 20% of the Dutch part of the North Sea; but overharvesting, habitat destruction from bottom-trawling fisheries, and disease drove the species nearly to extinction. As bottom-trawling activities are not allowed at wind farms to protect subsea cables, the innovation wind farm Borssele V, located 20 kilometers off the coast of the Netherlands in the North Sea, provided an excellent setting for an oyster reef rehabilitation project. In 2018, the research team, led by Van Oord DMC, began by analyzing the settlement rates of oyster spat on different types of substrate. They then identified the potential logistical obstacles in obtaining the required number of oysters to stock the area, and finally they developed their own brood stock structure to induce reef development via natural spawning and larvae settlement in the offshore wind farm. By designing effective methods for initiating sustainable oyster reefs at the rock material scour protection placed around the base of each offshore wind turbine, the team has added yet another benefit to renewable energy.

Producing Efficiencies

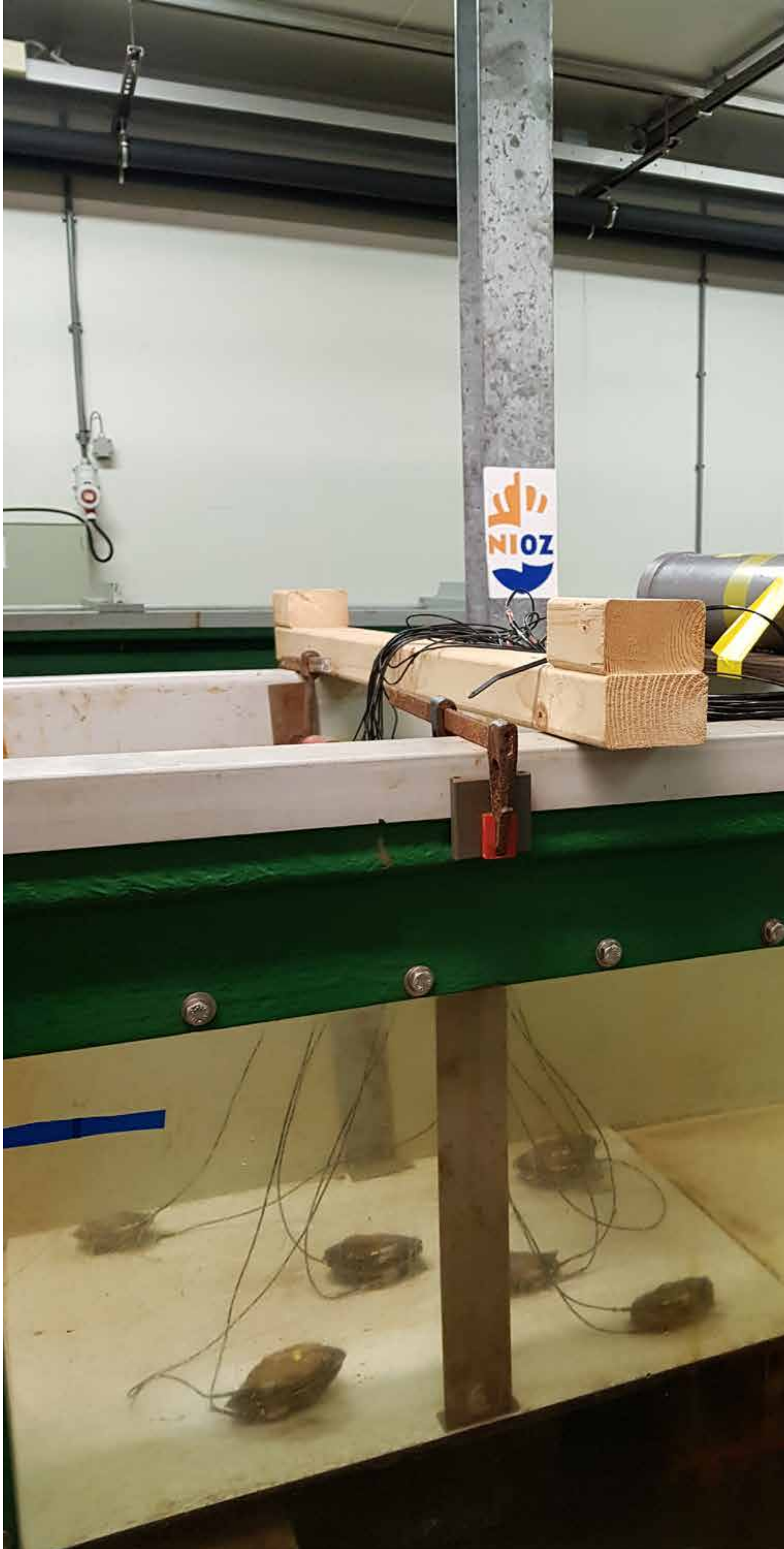
The main purpose of the Borssele V wind farm is to test technical innovations at real scale. Therefore, the knowledge gained of the various procedures, materials, and conditions that encourage oyster reef development will more easily translate to other offshore wind farms. This eliminates the need for further follow-up studies in the laboratory or at other turbines to ensure broad applicability. The most effective substrates and supply chains at Borssele V will also be effective at other offshore wind farms, allowing large-scale deployment of oyster reefs for scour protection and ecosystem recovery.

Using Natural Processes

The wind farm provides a place, undisturbed by trawling, for oyster establishment, growth, and recovery. Determining the most effective life stage, placement method, and substrate to kick-start reef development now allows the oyster reef to be induced, grow, and become self-sustaining. And as the oysters cover the base of the monopiles, they naturally protect the turbines of the wind farm from the scouring that occurs as sediment moving in the current scrapes past the surface of the monopiles. Eventually the oysters may also form a reef between the turbines, stabilizing the sandy seabed.

Previous page: Installing the scour protection at the base of each wind turbine. (Photo by Van Oord)

Right: Flume tank to test behavior of oysters under different hydrodynamic conditions. (Photo by Van Oord)



Broadening Benefits

Offshore wind farms reduce a country's dependence on fossil fuels and reduce their resulting pollutants, benefiting all sectors of society. In the Netherlands, there is an additional regulatory as well as an ethical duty to ensure the designs also include nature-friendly elements. A new wind farm provides an opportunity to benefit the local habitat, aiding the conservation of endangered and threatened species. These efforts to restore the marine environment further contribute to positive public perception of the large-scale roll out of offshore wind.

Promoting Collaboration

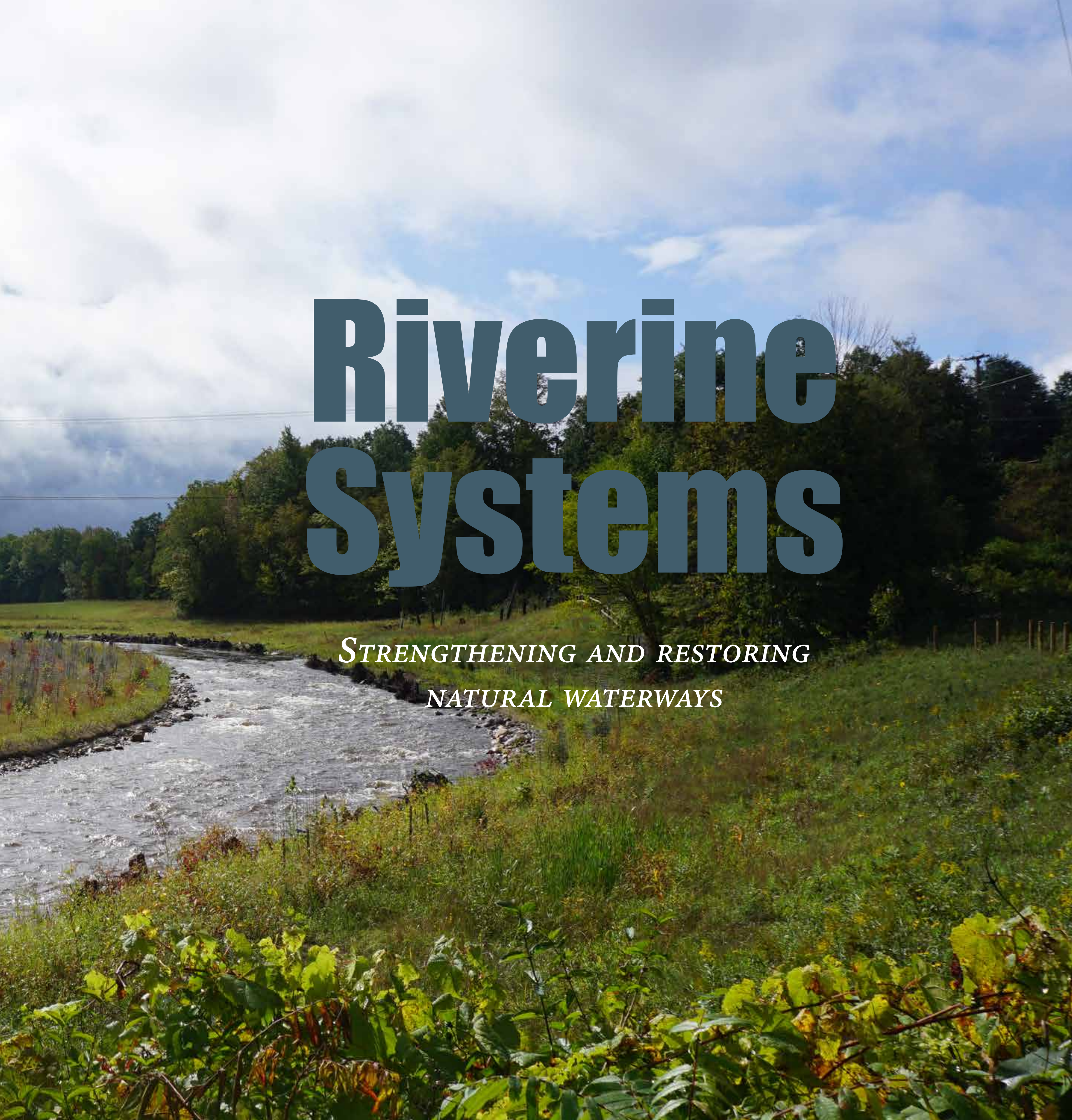
Developing an offshore oyster population for the scour protection of wind turbines required fundamental knowledge of the environmental forces an oyster feature can tolerate in offshore conditions; before the project began it was unknown whether oysters could create self-sustaining reefs in an offshore environment. The project also required an industrial approach to the logistics of procuring and installing the oysters. Only by putting together a team of industry and academic partners under the auspices of the Dutch government and working with energy companies and nongovernmental organizations was the Borssele V project able to innovate at real scale.

Top: Testing the settlement density of oyster larvae using different substrates. (Photo by Wageningen Marine Research)

Middle: Researchers test burial conditions for the oysters. (Photo by Van Oord)

Bottom: Preparing the scour protection prior to installation. (Photo by Van Oord)

Former location of Sabin Dam spillway and powerhouse with fabric-encapsulated soil lifts, rock, root wads, and tree and shrub plantings ensuring a stable stream channel (project details on page 140). (Photo by Kimberly Balke, Conservation Resource Alliance)



Riverine Systems

Strengthening and restoring natural waterways

Introduction

A variety of projects have implemented EWN practices in riverine environments. Some of these projects combined dam removal with the installation of fish ladders to restore fish migrations, greatly enhancing aquatic habitat value. The strategic placement of large wood and other natural features further enhanced these restored riverbeds while improving river processes and increasing the diversity of riparian habitat features and function. Projects in Scotland, Belgium, and the United States made room for the river by increasing space for floodwater storage, reducing flood risk and increasing groundwater recharge. They used natural and nature-based features to reduce or eliminate bankline erosion, thereby reducing dredging needs and protecting sources of drinking water. These projects also provided a number of social and cultural benefits, protecting important endangered species and historic reaches. In addition, they built trails, bridges, and other features to encourage recreation in the newly created habitat by local residents and tourists alike. Finally, all of these projects used hydraulic and hydrological models to guide the design of project features and make meaningful use of collaborative processes.

Boardman River Dam Removals

Traverse City, Michigan, United States

Returning a river to its original channel. The Boardman River is a top-quality trout stream; 58 kilometers have Blue Ribbon status, designating the high quality of the water for fish. For over 100 years, four dams on the river impeded upstream migration of the native fishery and created unnatural thermal impacts to aquatic organisms. With the 2012 removal of the Brown Bridge Dam, the uppermost barrier in the system, and removal of the Boardman and Sabin Dams in 2017 and 2018, respectively, the Boardman River Dams Implementation Team, U.S. Army Corps of Engineers (USACE)–Detroit District, and several other partners used primarily Great Lakes Restoration Initiative funding to reconnect 340 river kilometers to Grand Traverse Bay of Lake Michigan. This project also reinstated natural flow, improved aquatic habitat and reestablished a rare cold-water fishery, improving both the mix and population of various species. Additionally, an innovative and unprecedented venture to allow bidirectional selective fish passage at the lowermost barrier, the Union Street Dam in downtown Traverse City, broke ground in 2020 and will be the largest dam removal initiative in the state of Michigan. Repairing a linkage that has been severed for over a century will guide future efforts in other similarly truncated watersheds in the Great Lakes region.

Producing Efficiencies

Extensive probing documented the location, configuration, and depth of the original channel and adjacent floodplain. The team excavated impounded sediment to reveal the relic river channel and placed the sediment on adjacent upland areas to minimize haul distance while creating wildlife habitat within the river corridor. Sediment traps received sand winnowed from the newly excavated channel, and a siphon system partially dewatered the impoundment, reducing the risk and consequences of dam failure. It also allowed the team to control water surface elevations, making uncovering the buried channel and floodplain more efficient.

Using Natural Processes

The river restoration included active removal of sediment and nature-based approaches to manage the exhumed river banks. During the project, the river was allowed to adapt to the legacy riverbank and floodplain features to form the new bank boundaries. This created scour pools and depositional features, adding to the habitat's natural complexity. Additionally, engineered wood structures placed at critical locations limit the amount of near-term lateral migration, and the constructed riffles limit incision at key locations. Native plantings minimize maintenance and allow the natural wetland and forest succession to take over.

Previous page: The Boardman Dam removal project as the dewatering phase shifted from the siphon system to the temporary spillway. (Photo by Conservation Resource Alliance and AECOM)

Top, second, and third: Respectively, Sabin Dam and pond prior to removal; during drawdown; and in the last stages of drawdown, following demolition of a majority of the powerhouse. (Photo by Brett Fessell, GTB Natural Resources)

Bottom: The restored Boardman River through the former Sabin and Boardman dams and impoundment. (Photo by Conservation Resource Alliance and AECOM)

Broadening Benefits

Dam removals traditionally result in increased property values for adjacent landowners. In this case, the removals will additionally result in a large increase in both recreational boating and fly-fishing. Walking paths allow local residents and tourists to explore the sites, providing numerous outdoor education opportunities. The dam removals convert stagnant lake conditions to free-flowing rivers, which benefit fish, macroinvertebrates, mussels, birds, reptiles, amphibians, and mammal species. This also restores the function of the many tributary mouth areas that join with the Boardman River, providing holistic benefits to an entire ecosystem.

Promoting Collaboration

In 2005, the Grand Traverse Band of Ottawa and Chippewa Indians (GTB), Traverse City Light and Power, the City of Traverse City, Grand Traverse County, the Fish and Wildlife Service, the Michigan Department of Natural Resources, the Michigan Department of Environmental Quality, and the Michigan Hydro Relicensing Commission joined to form the Boardman River Dams Implementation Team. Working closely with USACE, they guided decommissioning and removal of the Boardman River dams and restoration efforts of the overall riverine ecosystem. Through extensive community outreach, the team ensured the general public was involved and informed.

Top: The restored Boardman River meandering through the former Brown Bridge Dam impoundment, looking downstream, 7 years post-removal. (Photo by Brett Fessell, GTB Natural Resources)

Middle: A paddler enjoying the restored river in a constructed riffle just downstream of the former location of the Sabin Dam. A 600-foot-long pool-and-riffle reach was constructed to overcome the legacy of 1930s-era dredging of the downstream river. (Photo by Kimberly Balke, Conservation Resource Alliance)

Bottom: Fly-fishing for trout in the restored river. (Photo by Inter-Fluve)

Old Scheldt and Kalkenvaart

Aard, East Flanders, Belgium

Reclaiming agricultural land in the Scheldt river floodplain for climate mitigation. In the northern half of Belgium in the heavily urbanized Flanders region, the Kalkense Meersen remains one of the few large, open natural spaces. Though historically pasture and hay meadows, changing agricultural practices in the twentieth century left the area stressed and degraded by chemical fertilizers, pesticides, and lowered water levels. As the low point of the catchment area, this area of open water collects excess nutrients and pollutants and had largely lost its original grasslands. Starting with initial planning in 2005, as part of the Sigma plan, the project team devised a strategy for protecting the region from flooding while restoring the natural habitat. Work began in 2010 by converting arable land back to grassland. By the end of 2020, the team had restored the Old Scheldt—a damped river meander—and had dug extra shallow banks along the medieval canal, the Kalkenvaart. They then connected the combined body of open water to the tidal river Scheldt by a special fish ladder and sluice. Now the area's diverse landscape provides a buffer for the surrounding community, containing excess water to protect against flood and providing more stable water levels in the face of climate-change-induced droughts.

Producing Efficiencies

The water system is now more robust and efficient, no longer requiring the day-to-day use of pumps to manage water levels. The pumping station remains in place, to function as a final safety measure in the event of extreme flood events, but changing to gravitational discharge of water through the fish ladder and sluices saves money and labor on daily operation and maintenance. As one of the most studied rivers in the world, the Scheldt's extensive hydrological modeling proved invaluable for the design of the sluice and to prevent flooding in the surrounding community.

Using Natural Processes

Retention of water at peak rainfall will reduce peak tides in the river while replenishing groundwater supplies. This guards against both flood and drought and provides a long-term buffer against climate change. Additionally, before this project, it was deemed nearly impossible to achieve natural two-way fish migration here without creating inundation risks. Valves in the sluices and culverts overcome this. In the flood phase, the river shuts the valve, allowing the fish to migrate between the polder and fish ladder but not to the river. In the ebb phase, the valve again opens and fish can move between the fish ladder to the river. This two-step migration resembles the passing of boats through a lock.

Previous page: The Kalkenvaart (left) and Old Scheldt (right) after restoration. (Photo by Vilda Photo)

Top: The Old Scheldt covered in poplar trees prior to restoration. (Photo by Vilda Photo)

Bottom: The Old Scheldt after restoration, with connection to the Kalkenvaart at right. (Photo by Vilda Photo)

Broadening Benefits

In addition to mitigating the impacts of climate change and assisting with fish migration, the restored reedlands greatly benefit the Eurasian bittern (*Botarus stellaris*), and the wetlands provide habitat for the European eel (*Anguilla anguilla*), a critically endangered species. The project also provided an opportunity to restore and rebuild a missing link in the hiking trails of the Kalkense Meersen. The combination of an additional bridge and walkway in the heart of the Kalkense Meersen opens new possibilities for small-scale hiking loops starting from the adjoining municipalities, a boon for local businesses.

Promoting Collaboration

The partnership between the Agency for Nature and Forest and the Agency for the Environment was the key to securing funding for the "Old Scheldt-Kalkenvaart" project and led in 2019 to an integrated water management plan for the whole Kalkenvaart catchment area, including several stakeholder meetings. Additional funding is allowing the team to dredge the Kalkenvaart, removing historical pollution and enlarging the water body, thus creating extra fish habitat and enhancing the self-cleaning capacity. In collaboration with the municipalities of Laarne and Wichelen, replacing the surface of the dilapidated old road along the Kalkenvaart and banning cars further enhances nature and the visitor experience.

Top: Artist's rendering of the new bridge over the Kalkenvaart with a Eurasian bittern. As a side effect of this image, the bridge has been named the "Bittern Bridge." (Image by Servais Engineering Architectural)

Bottom: Building the fish ladder that connects the combined body of open water to the tidal river Scheldt. (Photo by Dominiek Decleyre)

Eddleston Water

Peebles, Scotland, United Kingdom

Developing the most comprehensive flood management monitoring network in the United Kingdom. Part of the River Tweed basin in the Scottish Borders region, the Eddleston Water's catchment spans 70 square kilometers, flowing 19 kilometers south to join the Tweed in the town of Peebles. Begun in 2010, the Eddleston Water project is the Scottish government's long-term study on the effectiveness of natural flood management to reduce risks to downstream communities and to improve habitats for wildlife. After installing in 2011 the most comprehensive catchment-scale monitoring network in the United Kingdom, the team identified locations to reconnect the Eddleston with its floodplain and reduce flood risk to the surrounding community. Since 2012, Tweed Forum and partners have worked with 20 farmers to deliver a range of natural flood management measures, including 207 hectares of woodland planting with over 330,000 native trees, 116 large high-flow log structures on upper tributary streams, 28 upstream ponds to act as flood attenuation features, 2.9 kilometers of remeandered river with adjacent flood banks removed, and a large floodplain pond able to store water during intense rainfall events. Initial analyses of the impact of these measures show reductions in flood risk and improvements to riverine habitats.

Producing Efficiencies

The team's detailed scientific measurements and technical investigation underpin the Eddleston Water effort. By installing a comprehensive monitoring network two years prior to beginning the natural flood management strategy, the team created a baseline for assessing changes in flood flows and habitats. This information helps to more accurately assess the efficacy of engineering with nature. The results are guiding a flood alleviation scheme for the downstream community of Peebles, assessing the potential for engineering with nature to work alongside structural measures to reduce flood risk emanating from the Eddleston catchment.

Using Natural Processes

This project used a variety of natural engineering techniques: native tree planting in the headwaters, a series of engineered log structures in the upper tributary streams, and floodplain ponds downstream. These natural flood management features reduce flood risk and improve wildlife habitats at a landscape scale, and using the entire range of natural flood management measures will maximize the project's benefit to the region. The monitoring network's data will also help to determine how many of these measures are necessary to make a significant impact on flood risk and where within the catchment deployment could be most effective.

Previous page: Lake Wood in 2019, six years after restoration. (Photo by Tweed Forum)

Top: Looking north towards Lake Wood, the new meander in summer 2017. (Photo by Tweed Forum)

Middle: Sampling the riffles for aquatic invertebrates in June 2015. (Photo by Tweed Forum)

Bottom: Monitoring fish populations after the restoration. (Photo by Tweed Forum)

Broadening Benefits

The study aims to test the effectiveness of engineering with nature measures to reduce flood risk and to improve riparian habitats. As farmer involvement in the project is voluntary, working closely with landowners and the local community is likewise important—not only to ensure the continuing sustainability of businesses in the valley but also to incorporate other project benefits, such as water quality, carbon management, and recreation. As a continuation of the project, a new cycle route up the valley, alongside the restored river, will benefit locals and tourists alike and will provide other opportunities to engineer with nature.

Promoting Collaboration

A project of this scale and length required public outreach and continuous collaboration with local landowners and the surrounding community. The project team, managed by Tweed Forum, worked with 20 different farmers to gain access to the sections of the river where they wanted to undertake restoration activities. Scientists and managers from the Scottish Environment Protection Agency, Scottish Borders Council, University of Dundee and British Geological Survey also worked together on different aspects of the project. Numerous funding partners, including the Scottish Government and the European Union's Building with Nature program were key to the project's progress.

Top: A new meander under construction, July 2013. (Photo by Tweed Forum)

Middle: The new meander pictured above shown six years later with improved riverine habitat. (Photo by Tweed Forum)

Bottom: The old channel (right) connects to the downstream meander (left), one year after construction. (Photo by Tweed Forum)

Deer Island

Little Sioux, Iowa, United States

Doubling the width of the Missouri River. The Missouri River, the longest river in North America, remains an important navigation channel and water source for communities along it. However, it is also one of the most significantly altered and ecologically impacted rivers in North America. Efforts to control its flow have resulted in a narrow, deep, and fast-flowing river with very little depth or flow diversity. Many areas have seen reductions in width from over 600 meters to closer to 200 meters. To solve these problems, the Kansas City, St. Paul, and Omaha U.S. Army Corps of Engineers (USACE) districts teamed up to create high-quality, shallow-water habitat at Deer Island by excavating over 1.5 million cubic meters of material from the top width of a 3.2-kilometer stretch of the river. They widened the channel by 90 to 200 meters and constructed multiple large, permeable rock structures to split the flow of the river, creating a shallow bench with a diversity of depths and velocities adjacent to the main channel of the river. Now the river's main channel supports navigation while new shallow-water habitat benefits the federally endangered pallid sturgeon (*Scaphirhynchus albus*) and other native fish and wildlife.

Producing Efficiencies

A team of engineers from the USACE Omaha and St. Paul Districts conducted a significant hydraulic modeling effort using the USACE Adaptive Hydraulics Model, which had never been used on a shallow-water habitat project. The team ran multiple flow and sediment-load scenarios to determine the right balance of widening and structure to maintain a diversity of depths, flow velocities, and physical habitat without negatively affecting the navigation channel. With guidance from this model, the team doubled the width of the reach and created new habitat.

Using Natural Processes

The rock structures and large, woody debris structures placed on the bench created a dynamic and ever-changing shallow-water habitat area by precisely splitting the flow of the river. This maintained the depth of the navigation channel while allowing enough flow through the constructed shallow-water habitat to prevent it from filling in with sediment. As the sediment dropped out of the water running through these rock structures, it naturally created a range of depths and velocities.

Previous page: Waterfowl using the sandbars in 2015. (Photo by Dave Crane, USACE Omaha District)

*Right: Federally endangered interior least tern (*Sterna antillarum athalassos*) nesting on the sandbars. (Photo by Dave Crane, USACE Omaha District)*

Broadening Benefits

This project created over 40 hectares of critical channel-border aquatic habitat along the Missouri River, designed specifically not to interfere with any of the other congressionally authorized purposes of the river, such as water supply, flood risk reduction, water quality, hydropower, irrigation, and recreation. Monitoring of fisheries shows that there has been great response to this habitat, and waterfowl are using this new area extensively. Further, in contrast with other areas of the Missouri River with primarily deep water and swift currents, this area also provides easier access for various recreational activities.

Promoting Collaboration

Extensive collaboration between USACE, the Fish and Wildlife Service, the Iowa Department of Natural Resources, and the Nebraska Game and Parks Commission ensured the project design incorporated features that would meet the needs of all, including the endangered pallid sturgeon and other game and nongame aquatic species. As outreach, the project team has shared innovations by providing tours for Missouri River Basin Interagency Roundtable, Congressional representatives and state agency directors from Nebraska and Iowa, Iowa State University Extension Office educators, and a University of Montana student filming a documentary on the Missouri River.

Top: Preconstruction view of Deer Island in 2012. (Photo by Dave Crane, USACE Omaha District)

Middle: Center of the project site during construction. (Photo by Dave Crane, USACE Omaha District)

Bottom: A hydraulic dredge in the process of removing approximately two million cubic yards of material to create a shallow-water habitat bench to benefit the endangered pallid sturgeon and other native fish and wildlife, October 2013. (Photo by Luke Wallace, USACE Omaha District)

Rogue River

Grants Pass, Oregon, United States

Building a bioengineered wall to protect a city's water supply. The Grants Pass Water Treatment Facility sits directly adjacent to and above a high bank of the Rogue River that, following a major flood in 1996, was eroding from beneath the facility's foundation. This erosion threatened the city's only water supply for a population of nearly 35,000. Following the 1998 initial site evaluation and then development of a detailed hydraulic model, Inter-Fluve, under contract to the City of Grants Pass, proposed four options: no action, a traditional concrete retaining wall, a bin wall, and a bioengineered wall. Criteria for evaluating the alternatives included cost, aesthetics, constructability, long-term stability, ease of permitting, maintenance requirements, and habitat enhancement potential. The team chose the fourth option, a bioengineered, stacked geocell wall. The U.S. Army Corps of Engineers (USACE)–Portland District performed the actual construction of the 150-meter-long, 15-meter-high structure, adapting the bioengineering technology to a project site that challenges the limits of this emerging technology. The geocell wall reduced the risk of a catastrophic chlorine spill from the treatment facility while also fostering the growth of a diverse vegetative margin along the river.

Producing Efficiencies

In addition to mitigating erosion directly below the facility, the design addressed erosion up- and downstream of the site and prevented sand and gravel deposition, which would restrict flows to the plant's intake structure. The team developed a two-dimensional model to better understand how to counteract the complex hydraulics and intense scour caused by the highway bridge and sharp bend just upstream. Further, the bioengineered approach made the structure much more attractive to the regulatory agencies striving to protect endangered Chinook salmon (*Oncorhynchus tshawytscha*) in the Rogue River.

Using Natural Processes

While traditional approaches to riverbank stabilization—riprap, sheet pile, and concrete—provide structural integrity and long-term protection, they offer no ecological improvements. In contrast, a bioengineered retaining wall using stacked geocells with structural tie backs into the bank provides not only structural protection but also increases internal soil strength through root growth and fosters the development of a diverse vegetative margin that would normally cover a natural riverbank. This provides habitat for a variety of wildlife, such as the federally listed Chinook salmon and the many songbirds and neotropical migrants common to southern Oregon.

Previous page: The river 20 years after stabilization. (Photo by Inter-Fluve)

Top: Barge-mounted equipment provides access during construction. (Photo by Inter-Fluve)

Bottom: Several years after construction , the diversely vegetated riverbank provides habitat for a variety of wildlife. (Photo by Inter-Fluve)

Broadening Benefits

Access to clean drinking water is a basic human need, and many freshwater sources are riverine. Combining the delivery of clean drinking water with ecologically beneficial technology represents an important step in providing clean water to a multitude of species. This site demonstrates how engineering with nature can complement a fundamental societal need as nearly 20 years later, the project continues to perform and provide ecological benefits. Further, protecting the water treatment plant, a designated historic landmark, preserves an important piece of Grants Pass history.

Promoting Collaboration

The city began by hiring a consulting engineering firm to perform the initial investigations and design. Then the city partnered with the Portland District, whose two-dimensional hydraulic model, a cutting-edge tool at the time of the project's construction back in 1998, helped to refine the design. By teaming up with USACE, the city doubled its funding, using federal dollars to match the city's initial investments, and their many public meetings ensured local input and support from constituents, stakeholders, and regulatory agencies.

Top: Geocells connected to the bank with helical micro piles. (Photo by Inter-Fluve)

Bottom: The geocells support native vegetation, offering habitat for songbirds and overhanging cover for migrating fish. (Photo by Inter-Fluve)

Meadowview Stream

Temecula, California, United States

Banding together as a community to tackle a dangerous hazard. The Meadowview Stream Restoration Project is a small, regionally novel project located in the heart of a community-owned open space. The stream was originally a sandy wash that was straightened in the 1950s and then turned into a dangerous chasm with greater than 3-meter-high collapsing banks as a result of hydromodification from upstream development. The community was concerned with the public safety hazard this posed to residents and visitors who use the open space for recreation, especially after a young boy died when the banks collapsed on him downstream from the homeowner association's property line. With assistance from other partners, the association modified the channel and installed a bioengineering component. Instead of an inorganic, concrete channel, the community has a 3:1 slope planted with Californian native plants and stabilized with compost rolls seeded with native grasses. The stream is now a beautiful and peaceful place—a home to wildlife and a much safer place for families. The Meadowview Stream restoration won the American Association of Engineers' Inland Empire Environmental Engineering Project of the Year 2019 award and serves as an example of how nature can be leveraged in engineering projects.

Producing Efficiencies

The project team created an on-site nursery, buying small plants and growing them larger themselves, reducing planting costs by a third. They then enlisted AmeriCorps volunteers to install the new plants, a great service-learning project. Further, at just under 2 hectares, the project's small scale and on-site impact mitigation received an exemption from the California Environmental Quality Act. As similar creek management issues are common for homeowner associations across California, the Meadowview proponents are working to have this type of project more widely adopted for ephemeral streams throughout Southern California.

Using Natural Processes

The team avoided a traditional trapezoidal concrete channel by taking advantage of natural processes and materials. Stream barbs, which force water back into the stream channel, create eddies and encourage sediment placement, which in turn encourages habitat formation. Instead of the more traditional rock riprap, highly absorbent compost rolls stabilize the toe of the eroding banks and prevent transport of pollutants. Willow and mule fat bolster the compost socks, native soil and recycled organics stabilize the toe, and native plants hold the soil in place. Finally, a layer of natural mulch suppresses weedy growth.

*Previous page: The project included strategic placement of riprap, compost socks filled on-site with native soil and native grass seed, logs from on-site to hold soil, pole plantings of mule fat (*Baccharis salicifolia*), and willows (*Salix spp.*), September 2019. (Photo by J. Snapp-Cook, U.S. Fish and Wildlife Service)*

Right: This series of panoramic photo shows the before, during, and after photos of one section of the site. Top, *the 3-to-4-meter-high banks (Aug. 2018).* Second, *the graded bank at approximately 3:1 slope (Sept. 2018).* Third, *the site just after it was planted with native plants, but before they started to grow larger. A break in the irrigation caused erosion that needed to be repaired (Feb. 2019).* Bottom, *the site with the young native plants off to a strong start (July 2019). (Photo by J. Snapp-Cook, U.S. Fish and Wildlife Service)*

Broadening Benefits

This restoration project enhanced the natural beauty of the common area, used by both residents and visitors, while simultaneously eliminating a public safety hazard. Downstream water quality improved because of a reduction in unnaturally high sediment transfer, and the new slope created more edge habitat for wildlife to congregate in the transitions between riparian and upland environments. Economically, the city has reduced costs at a downstream detention basin due to less sediment entering the stream, the district waterline here is protected from erosion, and the slowing down and capturing of precipitation helps recharge the local aquifer.

Promoting Collaboration

Knowing they lacked the experience to undertake the project alone, the homeowners association partnered with the U.S. Fish and Wildlife Service's Partners for Fish and Wildlife Program, the Natural Resources Conservation Service, and the Riverside County Flood Control and Water Conservation District. That expertise in explaining and navigating regulations and devising bioengineering solutions was critical. In all, the association received technical and financial support from 12 different agencies, many going to great lengths to advance the project and all recognizing the benefits of using nature to solve infrastructure issues.

Top: Volunteers from Meadowview, staff and families from Riverside County Flood Control and Water Conservation District, and AmeriCorps National Civilian Community Corps (NCCC) planting native plants on the south bank of Meadowview Stream, December 2018. (Photo by Teri Biancardi, Meadowview)

Middle: Meadowview citizen science volunteers conducting postinstallation monitoring at the project site, June 2019. (Photo by J. Snapp-Cook, U.S. Fish and Wildlife Service)

Bottom: Group photo of volunteers from Meadowview, agency Partners, and AmeriCorps NCCC after a day of planting native plants at the site, December 2018. (Photo by U.S. Fish and Wildlife Service)

River Nairn

Aberarder, Scotland, United Kingdom

Restoring a wandering gravel-bed river using online wetlands. Beginning as a steep mountain stream in the Highlands, the River Nairn historically wandered through a wide valley of wetlands and wooded floodplain. But between 1750 and 1860, the river was straightened and embanked, most likely to improve the valley for agriculture, leaving the channel perched above its floodplain. The gradual in-filling of the channel with gravel had increased flood risk to surrounding property, and the river corridor lacked naturally occurring physical features. In 2013, the landowner and regulator discussed two solutions to address the flood risk of the river: the traditional approach of regular dredging or a process-based restoration approach. They chose the latter for the project, which involved embankment removal, channel realignment, and restoration of wetland areas (creating online wetlands by reconnecting them to the river channel) to facilitate sediment storage without compromising flood risk. The project team also placed large wood in the channel to facilitate natural physical processes such as the development of riverine habitats. Construction began in 2017 and finished in just four weeks. Within two weeks of completion, sea trout (*Salmo trutta*) were already using typical spawning locations, with Atlantic salmon (*Salmo salar*) following a few weeks later.

Producing Efficiencies

The project began with a river reconnaissance survey to identify the main processes operating within the wider river and the reach of interest. The team then used a two-dimensional hydrodynamic and morphodynamic model to design the restored watercourse, a type of modeling never before used in Scotland for this type of project. An iterative modeling-design process determined the optimal restoration approach for the different river sections. Postconstruction monitoring showed that the channel evolved as predicted by the model, validating this approach for future projects.

Using Natural Processes

The project team constructed a simple trapezoidal channel with a gravel bed, anticipating that high-energy flows would quickly and naturally create a dynamic pool-and-riffle morphology characterized by alternating gravel bar features. The day after completion, a high-flow event occurred that adjusted the channel geometry into the predicted dynamic morphology. Reconnecting online wetland floodplain areas helped trap fine sediments and provided extensive low-velocity habitat. Strategically placed large wood structures also forced the physical evolution and associated ecological improvements. The team's work resulted in the project winning the 2019 UK River Prize for "Restoring Natural Processes."

Previous page: The alternating gravel-bar features and large wood structures are evident in the restored channel, which now meanders through low-lying wetlands. (Photo by Scottish Environment Protection Agency)

*Right: Wetland vegetation such as bottle sedge (*Carex rostrata*) thrive in the wetlands adjacent to the constructed riffles. (Photo by Scottish Environment Protection Agency)*

Broadening Benefits

The project site provides important habitat for Atlantic salmon (*Salmo salar*), a species in decline. The project also improved overall water quality by taking advantage of the reconnected wetlands' ability to regulate fine sediment transport, eliminating the need for (and cost of) regular dredging. And together with the lowered channel, meandering curves, and reestablishment of native woodland, these wetlands slow flows, increase water storage times, and prevent excess runoff. The channel evolution has performed as predicted by the team's modeling, proving the efficacy of this holistic approach to habitat restoration and flood risk management.

Promoting Collaboration

To restore the reach within the tight time frame and funding constraints, communication between the landowner, designer, regulatory agency, contractor, and local community was essential. From this communication, the project team developed a restoration strategy that balanced the improved physical and ecological functioning of the river with local landowners' desire to protect agricultural land and access tracks from flooding. In addition, the stakeholder's sense of ownership helped to secure future monitoring and maintenance of the scheme.

Top: The project site lies at the downstream end of the alluvial fan of this gravel-cobble river system. The image shows the historically modified and uniform nature of the channel prior to the works (Photo by Scottish Environment Protection Agency)

Bottom: The realigned channel with pool-and-riffle morphology enters a series of wetlands. The abandoned channel runs along the left bank. (Photo by Scottish Environment Protection Agency)

Environmental Pool Management

Upper Mississippi River, Missouri, United States

Improving ecological conditions through water management. In the early 1990s, state and federal natural resource partners on the Upper Mississippi River asked the U.S. Army Corps of Engineers (USACE)–St. Louis District to modify lock and dam operations at Lock and Dam 24 in Clarksville, Missouri; Lock and Dam 25 in Winfield, Missouri; and Melvin Price Lock and Dam in Alton, Illinois, to improve ecological conditions. To accomplish this, the St. Louis District increased the growth of aquatic vegetation during the summer while maintaining the authorized 9-foot (2.7-meter) navigation channel and staying within existing operating limits, a technique now known as environmental pool management. Over 30–40 days, the decrease in surface water elevations for about 160 kilometers exposes mudflats along riverbanks, around the perimeter of islands, and on the interior sloughs of islands, establishing optimal growing conditions. In 2015, the district began targeting 90 days of operation during the growing season, resulting in over 110 days of plant growth each year and reestablishing a perennial vegetation community of native arrowhead (*Sagittaria latifolia*) last seen in 1993. Monitoring efforts reveal improved sediment consolidation, fish and wildlife habitat, and critical pollinator habitat. With environmental pool management, the district has achieved ecosystem benefits while maintaining a safe and dependable navigation channel.

Producing Efficiencies

Environmental pool management practices have consistently produced over 400 hectares of vegetation per year for little to no additional cost above normal operations. The technique consists of analyzing daily flow conditions and making corresponding gate changes at each of the three locks and dams to maintain targeted surface water elevations while also staying within authorized operating limits. Successful implementation has resulted in one of the largest and most efficient habitat restoration projects on the Mississippi River.

Using Natural Processes

Environmental pool management restores form and function to the river by reestablishing natural processes and reducing large and rapid fluctuations in pool level. Managing for reduced water levels during the growing season mimics the natural cycle that existed prior to construction of the lock and dam system on the Upper Mississippi River system, allowing for the growth of aquatic plants. Environmental pool management has also increased the natural geomorphic processes in the river, such as island building. This sediment consolidation helps maintain and enhance important river habitat types.

Previous page: USACE and agency staff meet on-site in Pool 25 to discuss project results. (Photo by Dawn Lamm, USACE St. Louis District)

*Top: Native nodding smartweed (*Polygonum lapathifolium*) flowering at Stag Island in Pool 25 in 2016. (Photo by Ben McGuire, USACE St. Louis District)*

*Bottom: Alton Lake in lower Pool 26 in August 2017. Photo shows mature annual vegetation with seedheads of native Walter's millet (*Echinochloa walteri*), which provides forage for migratory waterfowl and enhanced habitat for other wildlife. (Photo by Ben McGuire, USACE St. Louis District)*

Broadening Benefits

While mitigating fluctuations in pool level benefits the navigation industry, river-based commerce, and the recreating public, the acres of vegetation produced provide important foraging habitat to waterfowl using the Mississippi Flyway. In 2017, the pools produced an estimated 950,000 kilograms of seeds, which waterfowl use during their winter migration. In duck energy days—the energy used by one duck for one day—these seeds can sustain the metabolic requirements of over eight million migrating ducks for one day. During the migration back north, the decaying plants cause a surge of aquatic invertebrates, fueling waterfowl returning to northern breeding grounds.

Promoting Collaboration

For over 25 years, this project has forged successful relationships, leading to incredible levels of cooperation between federal, state, local, and public partners. Success starts with discussions in early spring and, during active implementation, weekly coordination between all stakeholders. Collaboration with The Nature Conservancy, the Sustainable Rivers Project, The U.S. Fish and Wildlife Service, Missouri Department of Conservation, Illinois Department of Natural Resources, American Rivers, Upper Mississippi Basin Association, Audubon Society, the navigation industry, and numerous other stakeholders has been key to effectively balancing the economic, ecological, and social benefits derived from the river.

Top: Alton Lake in lower Pool 26 showing water elevations at or near normal pool in May 2017. (Image from Digital Globe)

Middle: Photo of Alton Lake in lower Pool 26 in May 2020 when water elevations were lowered for environmental pool management, prior to vegetation growth. (Image from Digital Globe)

Bottom: Alton Lake in lower Pool 26 in July 2018 when water elevations were lowered for environmental pool management, while vegetation is growing. (Image from Digital Globe)

Mill River

Taunton, Massachusetts, United States

Building community consensus to remove four obsolete dams. In the fall of 2005, historic heavy rains in New England threatened the stability of the Whittenton Pond dam on the Mill River in Taunton, Massachusetts. Officials evacuated the City area immediately downstream of the structure due to imminent dam failure. This extreme weather event led to partner collaboration, project planning, and eventual removal of three aging dams and replacement of a fourth dam with a fishway to increase community and ecological resilience of this coastal watershed. In 2012, the team, led by the Massachusetts Division of Ecological Restoration, removed the Hopewell Mill dam, first constructed in 1818. The run-of-the river dam provided no relief from flooding for downstream residents and was the lowermost barrier to river herring migrating to their native spawning grounds. They then removed the Whittenton Pond dam and the West Britannia dam. Finally, the team reconstructed a fourth dam at Morey's Bridge and added a fishway, sustaining recreational activities at Lake Sabbatia while allowing migratory fish to reach upstream natal spawning grounds. These dam removals have reconnected more than 48 kilometers of rivers and streams linked to Narragansett Bay, benefiting multiple migratory fish species and decreasing community flooding.

Producing Efficiencies

Substantial field surveys combined with digital elevation models, hydrologic and hydraulic analyses, and ecological assessments drove the removal of these public safety hazards, which decreased catastrophic flood risk and reduced operation and maintenance costs. The team also solved a contaminated sediment disposal challenge by removing sediments upriver of the Hopewell Dam. They transported, placed, and capped the materials at the nearby State Hospital property, then converted the area to a wildflower and pollinator meadow. This beneficial use of dredged sediment substantially reduced costs and kept the contaminated sediment out of an upland facility.

Using Natural Processes

The West Britannia Dam removal in 2018 finished the reopening of this waterway restoration for species such as blueback herring (*Alosa aestivalis*), American eel (*Anguilla rostrata*), and sea lamprey (*Petromyzon marinus*). Fish can now swim from Narragansett Bay upstream for more than 80 kilometers to Winnecunnet Pond and its headwaters in the 6,859-hectare Hockomock Swamp. The restoration of the watershed also brought back natural sediment transport, riparian floodplain habitat, and processes supporting this watershed ecosystem. Further, removing the dams decreased the 100-year flood depth profiles of the river by up to 3 meters.

Previous page: The Hopewell Dam site after removal and remeandering, 2016. (Map data from Google Earth)

Top: The Hopewell Dam site prior to removal, 2012. (Map data from Google Earth)

Middle: Hopewell Dam prior to removal. (Photo by James Turek, NOAA Restoration Center)

Bottom: The Hopewell Dam site in 2017, five years after removal, has a thriving riparian floodplain habitat. (Photo by Nick Nelson, Inter-Fluve)

Broadening Benefits

The social benefits of reduced flood risk and decreased area within the 100-year floodplain by removing the dams cannot be understated. Additionally, the water quality of Taunton River has also improved—especially important given that the Taunton is a federally designated Wild and Scenic River. With the last dam removal, this was the first time in 200 years that migratory fish could freely pass from the estuary to important upper watershed spawning and rearing habitats. In all, the project has promoted the recovery of vital migratory fish populations in 1,450 square kilometers of watershed.

Promoting Collaboration

Public outreach and education was important to the project's success; frequent public meetings engaged the community and solicited feedback on the design and implementation over the project's 13-year timeline. The Massachusetts Division of Ecological Restoration led a diverse team, including the City of Taunton, Southeastern Regional Planning and Economic Development District, The Nature Conservancy, Massachusetts Division of Marine Fisheries, the National Oceanic and Atmospheric Administration, private dam owners, and many others. Their long-term strategic planning resulted in the successful restoration of the Mill River watershed.

Top: Demolition of the West Britannia Dam in 2018. (Photo by James Turek, NOAA Restoration Center)

Middle: The Mill River floodplain after the Whittenton Pond Dam removal. (Photo by James Turek, NOAA Restoration Center)

Bottom: Sea lamprey in the Mill River upstream of the dam location after the Hopewell Dam removal. (Photo by Mike Trainor, Massachusetts Division of Marine Fisheries)

Wrack marks to the side of the inlet at an off-line pond in Weardale demonstrate water rising against the inlet but not entering until it is needed during the storm event (project details on page 200). (Photo by Alex Nicholson, Arup)

Floodplains

Reducing flood risk through natural processes

Floodplains

Introduction

Across the United States and United Kingdom, the projects presented in this chapter illustrate how EWN principles reduce flood risk to local communities and land-based infrastructure. A number of the projects took advantage of land transfer changes to rebalance the engineering of rivers and streams and to increase human land use opportunities, reducing flood risk and restoring habitat value. Restoring floodplain function takes a number of forms in the chapter, from building kilometers-long revetments in Washington to planting 140,000 trees in England. Project teams are engineering and combining natural and nature-based features with other measures to return natural functions to the ecosystem. Reusing woody debris available on site lowers project costs and efficiently uses nature's energy to more naturally restore the habitat. These restored features create water storage, providing opportunities for migrating fish and other native species to return. In the Pacific Northwest especially, these projects enabled the return of native migratory fish that play important social and cultural roles for indigenous peoples. And for each of these projects, landowners, downstream communities, and local residents have been invited into the decision-making process, creating collaborative successes supported by all.

Smithills

Smithills, England, United Kingdom

Planting 140,000 trees for the Northern Forest initiative. Dean Brook in Smithills, Bolton, in the northwest of England rises 456 meters onto the peatlands of Winter Hill. At its rural source waters, Dean Brook flows off the West Pennine Moor Site of Special Scientific Interest, then through woodlands and agricultural channels before flowing through the urban areas of Smithills. Dean Brook poses a flood risk to Smithills, spilling 12,282 cubic meters of water in a 100-year event, affecting a total of 53 properties and more downstream. In 2015, the Woodland Trust acquired 6 square kilometer flowing down to Smithills; and together with the Environment Agency, Mersey Forest, and the University of Liverpool set to restoring the site through natural flood management. The team began by planting 30,000 new trees; then installed thirteen engineered logjams to function as leaky dams, which intercept flood flows but allow lower flows to pass through; and reconnected parts of Dean Brook with its floodplain by uncovering 150 meters of buried watercourse. The project is planting 140,000 trees on the Woodland Trust's estate as a pilot site through the Northern Forest initiative with support from the Heritage Lottery Fund. Together, these efforts will slow, store, disconnect and hold-up overland flows, in effect holding floodwaters in the landscape.

Producing Efficiencies

The project team used existing one- and two-dimensional models to determine the exact volume of water spilling onto the floodplain during a 100-year flood event for Smithills. Using that volume as a guide, the team—along with volunteers and specialist contractors—planted willows; built various water retention measures, including log jams, clay-core piped bunds (small drained embankments), and detention basins; and took sections of rivers out of constrained buried pipes. Comparing pre- and postconstruction data showed the leaky dams delay and reduce peak flows by around 20%, depending on catchment conditions and the nature of the rainfall event.

Using Natural Processes

The engineered logjams are living barriers that will grow into place over time. As the timber jams degrade and decompose, the dense willows planted behind take root and grow, not only securing the structure but also filtering polluted water. Elsewhere, the team built shallow, piped clay-core embankments to back up flood flow at certain points. Where the team removed streams from pipes (called *daylighting*), they restored floodplains by lowering the land and landscaping. These measures make space for water, particularly for floodwater upstream that would have otherwise passed downstream to the community at flood risk.

Previous page: The cascading series of engineered log jams naturally slows the water flowing downstream. (Photo by Woodland Trust, Environment Agency, and Mersey Forest)

Top: A team member weaves living willow into the log jam structure. (Photo by Woodland Trust, Environment Agency, and Mersey Forest)

Bottom: Water collects in low-lying areas instead of flashing down the catchment. (Photo by Woodland Trust, Environment Agency, and Mersey Forest)

Broadening Benefits

Alleviating flood risk in Smithills represents one of the major successes of this project, but the tens of thousands of planted trees and reconnection of Dean Brook with its floodplain have also led to the reappearance of the keeled skimmer dragonfly (*Orthetrum coerulescens*), unseen in the region for many years. Wading birds and fish will benefit from the new refugia and foraging grounds, and the protection of the peatlands and moorlands will sequester carbon dioxide and methane, greenhouse gases that directly contributes to global heating and climate change—all without lowering the agricultural value of the land.

Promoting Collaboration

As a demonstrator site for the Northern Forest initiative and the Woodland Trust's largest English site (receiving EU LIFE IP funding under project number LIFE14 IPE/UK/027), the Smithills project represents an important opportunity to show local landowners, farmers, and community stakeholders how natural flood management projects can work. Natural Course funded in part the project's communications output. This engagement allowed the project to gain momentum and traction. Through the partnership of the Woodland Trust, the Environment Agency, and the Mersey Forest, thousands of volunteers have supported the project, making the large-scale planting efforts possible.

Top: Deculverting 150 linear meters of stream. (Photo by Woodland Trust, Environment Agency, and Mersey Forest)

Middle: The team works together to move the large, heavy logs into place. (Photo by Woodland Trust, Environment Agency, and Mersey Forest)

Bottom: Dragonflies thrive around the edges of the containment ponds. (Photo by Woodland Trust, Environment Agency, and Mersey Forest)

Kerry Island Estuary

Clatskanie, Oregon, United States

Restoring habitat for a Pacific Northwest icon. Part of the Lower Columbia River estuary, Kerry Island is part of an extensive estuarine system that once produced the most Chinook salmon (*Oncorhynchus tshawytscha*) in the nation. But since the 1800s, the ecosystem has lost half of its historic habitat. Conversion of Kerry Island's estuarine floodplain to agricultural, urban, and industrial uses, including a levee installed in the 1920s, led to severe degradation. The levee disconnected the island from regular tidal fluctuations, halting the floodplain's daily inundation and causing a loss of sediment deposition, nutrient exchange, and salmon habitat. Tidally influenced landscapes such as estuaries and marshes are of critical importance to the life cycle of Pacific salmon, and restoring and expanding these habitats is a key component to salmon recovery. Therefore, in 2004, the Columbia Land Trust acquired the land; and in 2016, they removed the levee during a single tidal cycle, which required nine excavators working in tandem to remove around 8,000 cubic meters of material. The team's efforts converted 40 hectares of agricultural land to native marsh, providing new habitat for Chinook salmon, steelhead (*O. mykiss*), and federally listed species such as coho (*O. kisutch*) and chum (*O. keta*).

Producing Efficiencies

To prepare for the levee's removal and the increase of water flowing through nearby channels, the project team used a two-dimensional hydraulic model to examine potential changes to hydraulic variables up- and downstream of the project. As the ground surface within the levees was approximately a meter lower than unleveed reference sites, the site would be inundated for a majority of the tidal cycle once levees were breached. Therefore, the team carefully sequenced construction, completing it on a single "breach day" during a single low tide, using a barge to remove two excavators that had worked until the tidal water encircled them.

Using Natural Processes

The team's initial site assessment evaluated land use history to understand the geomorphology, hydrology, and hydraulics of this segment of the Columbia River, documenting site-specific tidal processes and the ways fish and other wildlife used the site. They also evaluated the plant community on-site and compared it to reference sites. The thoroughness of this data collection allowed the team to reestablish this estuarine marsh plain through a sustainable progression of natural processes and cycles, creating habitat for salmon and more than 250 species of birds who use it as an important stop along the Pacific Flyway.

Previous page: Reconnecting the tidal channels provides new estuary habitat. (Photo by Inter-Fluve)

Right: The revegetation of this former agricultural site increases biodiversity. (Photo by Inter-Fluve)

Broadening Benefits

The Kerry Island restoration project contributes di rectly to the recovery of Pacific salmon, an important source of food and livelihood for both native tribes and communities throughout the Pacific Northwest. This project and similar restoration projects through-out the state stimulate the economy further by requiring a diverse and skilled workforce and creating a niche market for both engineering and construction services. Socially, restoration efforts unite rural communities for a common goal. Using local equipment operators has the additional benefit of engaging local residents to develop a greater understanding of restoration efforts in their own backyards.

Promoting Collaboration

The Kerry Island estuary restoration is the latest in a long line of Columbia Land Trust projects. Their experience working with local landowners, state and federal regulatory agencies, the region's tribal governments, and the consulting engineer helped to make this project another success. Through these longstanding relationship, the Land Trust pulled together the interdisciplinary team of water resource engineers, fish biologists, ecologists, and geomorphologists they needed to meet their short- and long-term ecological objectives. This project has promoted out-of-region collaboration, too, as communities throughout the Hudson River estuary are working to improve their own resiliency by applying approaches used at Kerry Island.

Top: Each high tide inundates the site, providing additional foraging opportunities for fish. (Photo by Inter-Fluve)

Bottom: Low tide at one of the constructed tidal channels. (Photo by Inter-Fluve)

Wendling Beck

Worthing, England, United Kingdom

Mimicking nature's engineers for flood control and habitat restoration. The village of Worthing is subject to flooding from two incoming rivers, Wendling Beck and the River Blackwater. Attempts to drain and crop the floodplain after World War II left both rivers deepened and straightened, degrading the habitat and increasing arable runoff. As a result, the area lost a great deal of good habitat, and the spoil banks left behind after the dredging meant the rivers rushed downstream towards Worthing instead of spilling onto their floodplains during heavy rainfalls. Between 2017 and 2019, the Norfolk Rivers Trust, a nonprofit conservation organization, worked the landowner and the Environment Agency to improve habitat and store more water on the floodplain. The team removed banks, reconnected meanders, and installed woody debris that mimicked beaver dams, the country's first use of beaver-dam analogs. These techniques lowered dredging embankments and raised the riverbed through natural sediment deposition rather than by importing gravels. Hydrological monitoring and field surveys are ongoing to assess the impacts on fish, invertebrates, and plant life; but now Wendling Beck's complex habitat is thriving—clearer waters, reduced flooding, and increased biodiversity.

Producing Efficiencies

Rather than importing gravel, the team raised the riverbed through natural sediment deposition, and for the structure and function of the engineered log jams, the team took as their inspiration the engineered dams of beavers. Using a single excavator from one end of the reach to the other, they felled trees and laid them in the watercourse and used only materials found on site. This technique minimized fuel and carbon costs and delivered cheap, effective flood control mechanisms that require no ongoing maintenance.

Using Natural Processes

The project aimed to reverse the effects of six decades of intensive management by accelerating natural processes: felling large trees into the river and creating beaver dams in their absence. The team also excavated several ponds and backwaters in the floodplain to mimic features previously filled in to improve grazing. All these processes improve habitat complexity and push water onto the floodplain, where it will naturally be stored. The power of Norfolk's lowland, spring-fed rivers is so slight that the damage would otherwise take centuries to reverse.

*Previous page: With more water stored upstream, aquatic vegetation such as starwort (*Callitriche *spp.) thrives. (Photo by Norfolk Rivers Trust)*

Right: This raised, leaky log dam holds water back and pushes it onto the floodplain in high flows. (Photo by Norfolk Rivers Trust)

Broadening Benefits

This project will reduce the frequency and severity of flooding at 20 different properties and two public highways, preventing future clean-up and recovery costs that would otherwise have been paid for through taxes and private insurance. By storing more water in the floodplain, the project promotes vegetative growth, creating the foundation of a resilient, self-sustaining ecosystem and building habitat for numerous species. The project also improves the overall health of the River Wensum site of special scientific interest, arguably one of the most ecologically and socially important rivers in England.

Promoting Collaboration

Norfolk Rivers Trust coordinated the project on behalf of one of the riparian landowners, who provided the majority of funding. The trust worked with the Environment Agency and local drainage board on the project design and received further public funding from the Environment Agency. The trust also liaised with local councils and neighboring riparian owners, increasing the initial scope of the project significantly and leading to a much broader area of restored riverine and floodplain habitat.

Top: Wendling Beck winds through the East Anglian countryside. (Photo by Norfolk Rivers Trust)

Bottom: Like beaver dams, the woody debris provides habitat for a range of invertebrates and small mammals. (Photo by Norfolk Rivers Trust)

Floodplains

Southern Flow Corridor

Tillamook, Oregon, United States

Converting catastrophic flood recovery into widespread flood reduction. The Southern Flow Corridor project is a landscape-scale effort to relieve more than 1,214 hectares of community from regular flooding and reconnect more than 65 hectares of Tillamook Bay's most productive salmon-bearing habitat to neighboring streams. Over the past 150 years, settlers have drained close to 90% of the Tillamook Estuary's historical tidal wetlands to support other land uses. Levees and dikes constricted and disconnected the natural river channels, causing frequent seasonal flooding that often catastrophically affected landowners in Tillamook County. This habitat loss contributed to winter flooding events, created by a combination of storm surge, heavy rainfall, and snowmelt, and led directly to the decline of the area's salmonid species, including chum (*Oncorhynchus keta*), Chinook (*O. tshawytscha*), and the threatened Oregon Coast coho salmon (*O. kisutch*). To resolve this, Tillamook County acquired 155 hectares of land where the Wilson and Trask Rivers meet and converted retired dairy land into wetlands by removing an extensive system of levees. In addition to restoring 179 hectares of habitat, the project opened 21.2 kilometers of new tidal channels for migratory fish while reducing flooding and protecting private property.

Producing Efficiencies

First the team developed a hydraulic model to design the project. After removing the levees, the team reused the existing tide gate infrastructure for the new setback levees, installed to protect and drain adjacent agricultural land. When the project was complete, they were also able to reuse the original hydraulic model to validate whether the solution achieved the site's flood reduction goal. Simply by removing these levees, the project team reduced flooding on 1200 hectares of land, saving $9.2 million on flood recovery costs over the restoration's expected 50-year lifespan.

Using Natural Processes

Restoring tidal inundation to the marsh habitats opened up 180 additional hectares for Oregon Coast coho salmon and other fish and wildlife species. Over time, the inundation of tidal waters will naturally improve the marsh by adding sediment and reducing invasive plant species. This process will create, enrich, and expand a network of habitats, such as mud flats, aquatic beds, emergent marsh, forested wetlands, and sloughs. By reopening the land and allowing tidal forces to change the landscape, this project will restore the area without further human intervention.

Previous page: A slough in the wetlands after levee removal. (Photo by Tillamook County)

Right: The completed spillway across the middle setback levee. (Photo by Tillamook County)

Broadening Benefits

One of the objectives of the Tillamook restoration was to engineer ecological benefits without negatively affecting local agricultural productivity. Reducing the seasonal flooding events by restoring the floodplain achieves both of these as lowered flood risk raises local property values and ensures crops are not destroyed by floodwaters. It also mitigates the recovery expenses associated with flooding. Recovering salmon populations further contributes to the region's ecological and economic profile, and as in other Pacific Northwest restoration projects, preserves their social and cultural importance.

Promoting Collaboration

The project team included Tillamook County, the Port of Tillamook Bay, the Tillamook Estuary Partnership, and the Tillamook Bay Habitat Estuary Improvement District. For the main project, the team used the Oregon Solutions process, in which the governor designates an impartial convener to help community leaders join together and resolve a challenging issue. Then, the team received funding from the Federal Emergency Management Agency's disaster assistance fund, allowing them to convert catastrophic flood recovery into future flood prevention. To complete the project, these funds were combined with funding from the National Oceanic and Atmospheric Administration Office of Habitat Conservation Restoration Center, the U.S. Fish and Wildlife Service, and the Oregon Watershed Enhancement Board.

Top: The flow corridor before the levee setback. (Photo by Tillamook Estuary Partnership)

Bottom: The flow corridor with restored tidal marsh habitat after the levee setback. (Photo by Tillamook Estuary Partnership)

Low Leighton

New Mills, England, United Kingdom

Alleviating flood risk on the Peak District Pennine fringe. Leighton Brook is a degraded ordinary watercourse that rises in the rural Peak District National Park headwaters and joins with the River Sett in the town of New Mills, Derbyshire. Historical maps of the river-catchment show that the landscape has lost more than 20 hectares of woodlands and trees in the last 100 years. The brook's straightening and entrenchment along with overgrazed, hardened, and treeless hillsides speed up the rate at which rain reaches the watercourse, heightening flood risk in the built-up environment downstream, where no space exists for excess flood water during periods of high flow. This has resulted in 17 floods in the last 10 years. Therefore, in 2017, the Environment Agency, in partnership with Mersey Forest and the Derbyshire County Council conducted a catchment investigation. Piece Farm, a mixed livestock farm under a high-value government agricultural and environmental agreement for wading birds, manages the source waters and had already created two large attenuation ponds. To further mitigate flooding concerns, the project team tested a natural flood management scheme, planting a thousand willow trees and installing engineered logjams in 2019. These solutions create long-term, secure features in the landscape, delivering 3,000 cubic meters of attenuation.

Producing Efficiencies

While the land covers only 1.6 square kilometers of headwaters, the drainage of the area is complex, with many forks and confluences. Therefore, the team used a detailed overland flow routing map created with the Arc Map tool to identify which watercourse put Low Leighton most at risk for flooding. Additionally, the trees cleared in the nearby town of Bury, to make way for a conventional flood defense, became the timbers in the engineered logjams, recycling material and avoiding the need to fell other trees. Volunteers from Transition New Mills, a community sustainability and carbon reduction initiative, planted the supporting locally sourced willows.

Using Natural Processes

Putting dead wood in a river channel alone to naturally manage floods seldom functions as a long-term solution; but these engineered logjams with large, long timbers held in place by stakes at the front and back will naturally slow the runoff from Pierce Farm. As the logs decompose, the dense willows planted downstream take root and grow, securing the structure and filtering the water through the complex system of root fibers. The willows will eventually grow across the stream, providing resilience to the living logjam and the surrounding wet woodlands habitat.

Previous page: Water fills the containment pond. (Photo by Derbyshire County Council, Environment Agency, Mersey Forest, and Transition New Mills)

Right: The log jam does not prevent livestock from accessing the pasture. (Photo by Derbyshire County Council, Environment Agency, Mersey Forest, and Transition New Mills)

Broadening Benefits

The community has noticed that slowing the flow at the top of the catchment, where stream runoff begins, has resulted in a less-flashy watercourse. With reduced flood risk comes reduced costs for flood recovery, but this project also provides numerous ecological benefits. As the willow trees grow, they will provide new habitat for willow warblers (*Phylloscopus trochilus*) and willow tits (*Poecile montanus*). The small woodlands and the willow timber in the logjams will benefit hedgehogs (*Erinaceus europaeus*) and benefit badgers (*Meles meles*). Furthermore, the project's partnership with Salford University has led to much academic research as students monitor the site as part of their coursework.

Promoting Collaboration

The Environment Agency, Mersey Forest, and Derbyshire County Council's partnership, and the landowner's enthusiastic support, allowed the team to draw on multiple funding sources to complete the project. Additionally, by working with the University of Liverpool and Salford University, the team was able to secure monitoring equipment and data processing, saving time and money while creating educational opportunities for students. The project's collaborations have been so successful that they will continue for the next 10 to 20 years, leading to a better understanding of natural flood management's effects across a catchment.

Top: A tree-planting day with local members of the community celebrates the completed project. (Photo by Derbyshire County Council, Environment Agency, Mersey Forest, and Transition New Mills)

Middle: Willows will prevent excess runoff and soil erosion. (Photo by Derbyshire County Council, Environment Agency, Mersey Forest, and Transition New Mills)

Bottom: Log jams and a woodland plot creation with local volunteers, showing Greater Manchester and beyond in the distance. (Photo by Derbyshire County Council, Environment Agency, Mersey Forest, and Transition New Mills)

Weardale

Weardale, England, United Kingdom

Restoring a landscape radically altered for hundreds of years. Part of the UNESCO Global Geopark in the North Pennines, Weardale's history runs long. Since the twelfth century and even before, the area has experienced the degrading effects of deforestation, livestock farming, and lead and fluorspar industrial mining. Now, however, it is the site of an innovated natural flood management demonstration, an approach that reduces flood risk through habitat enhancement. The team enlisted the skills and knowledge of local landowners and farmers to inform an artificial intelligence model of the area, using the data to choose the site where the least number of features would attenuate the most water storage. Working within the archaeological constraints of this historic site and avoiding the nesting bird season and preventing harm to protected species and habitats, the team created 150 hectares of peatland and 75 hectares of woodland and restored 500 hectares of natural habitat, all of which contributed to reduced flood risk and increased water attenuation over 41 square kilometers. This project will help to increase understanding of the impact natural flood management can have on reducing flows along tributaries of the Upper River Wear, enabling scientific evaluation of the effectiveness of natural flood management at a catchment scale.

Producing Efficiencies

The project team mapped water storage opportunities over 100 square kilometers of watershed and entered the data into their optimization algorithm, developed by Arup, which calculated the minimum number of flood-control barriers needed to maximize storage. This process used runoff routes, lidar data, and flow accumulation and vector mapping data to exclude areas near roads, buildings, or mineral extraction sites. With locations determined, the team assessed data for each to select one of five developed "standard" earth, timber, or stone barriers to hold back flood water. This digital approach greatly increased cost efficiency by showing the team the most effective barrier design for a given location.

Using Natural Processes

All of the design types include locally sourced or low-carbon materials and consider local heritage and nature. They are robust enough to handle stormy weather and large livestock and will store excess water without needing a human team to open or close floodgates. The barriers, positioned across either a runoff pathway or landscaped onto a floodplain area, naturally reduce runoff and soil erosion and improve water quality further downstream. They then slowly release water over the course of a day, making themselves available for the next heavy rainfall.

Previous page: The off-line pond works with the natural processes of the channel, filling with water during storm events. (Photo by Jonathan Kellagher, Environment Agency)

*Top: Vegetation, such as peat mosses (*Sphagnum*), sedges (*Cyperaceae*), and grasses and rushes (*Juncus*), has covered the earth exposed during construction, hiding the pond from view. (Photo by Alex Nicholson, Arup)*

Middle: Rising water does not enter the inlet until needed during a storm event. (Photo by Alex Nicholson, Arup)

Bottom: The Bushnell Trophy cam during Storm Ciara shows the inlet functioning as designed. The off-line pond stores water in the attenuation area before discharging it back into the burn. (Photo by Laura Parsons, Environment Agency)

Broadening Benefits

The project has restored 150 hectares of peatland that had degraded into bare peat, not only increasing the capacity of the peatland to hold water but increasing the biodiversity within the area. By paying farmers and landowners to construct the features on their own land, the project provides a direct economic benefit to the local community at the same time it reduces the risk of future costly flood recovery in the years to come. Additionally, the monitoring program feeds into a range of projects for local schools, developing an understanding of natural flood management.

Promoting Collaboration

The Environment Agency led this consensus-building effort by involving local participants as early as possible in the planning and by offering funding so the landowners could construct the features themselves. Working with Natural England, the Forestry Commission, the North Pennines Area of Outstanding Natural Beauty Partnership, and Durham County Council, the project team combined the expertise of a variety of groups with the skills and knowledge of local residents. This empowered the local community and provided critical information for the solution's design.

Top: This section of Middlehope Burn is part of an Area of Outstanding Natural Beauty. (Photo by Jonathan Kellagher, Environment Agency)

Middle: Grip blocking in action to restore peatland, reducing flood risk and enhancing the habitat. (Photo by Jonathan Kellagher, Environment Agency)

Bottom: Now excess water fills the catchment instead of flooding downstream. (Photo by Jonathan Kellagher, Environment Agency)

Puyallup River Revetment

Orting, Washington, United States

Protecting critical transportation infrastructure from flooding and volcanic hazards. In the shadow of Mt. Rainier, the high-energy, glacially fed Puyallup River runs through rural Washington. But a series of river-training facilities, such as traditional levees, and logging in the region have left the Puyallup disconnected from its floodplain and channelized, cutting off side-channel habitat for salmon and other species. Further, the river threatens nearby Orville Road East, a main transportation artery and lahar evacuation route. Using a technique known as *restorative flood protection*, Pierce County staff engineers, biologists, and planners began in 2018 a 1.6-kilometer project to open up approximately 28 hectares of previously disconnected floodplain and by 2022 will remove approximately 800 meters of an existing levee. The project has begun installing a series of discontinuous, engineered logjams to form a 1,200-meter setback revetment and will install approximately 40 more logjams throughout the newly connected floodplain. This will encourage channel braiding and habitat formation and discourage channel avulsion toward Orville Road. Already the work has restored the nature hydrological processes in the floodplain, promoting the recovery of three threatened salmonids: Puget Sound Chinook salmon (*Oncorhynchus tshawytscha*), Puget Sound steelhead (*O. mykiss*), and bull trout (*Salvelinus confluentus*).

Producing Efficiencies

Levee setback projects create additional space for rivers in their natural floodplain and are a more sustainable and cost-efficient approach than long-term levee maintenance. To mimic the naturally occurring logjams common in the region, the project team created engineered logjams consisting of large wood, racking, and slash structures, each ballasted by a 7-tonne concrete structure called a dolos. This innovative design requires less excavation than traditional engineered logjams because it self-settles when exposed to river scour, reducing installation time and cost.

Using Natural Processes

Levee removal and its resulting floodplain reconnection will allow more natural fluvial processes to develop, increasing the quality and quantity of salmon habitat through the river's natural life cycle. The series of logjams slows the flow of water through the river, creating braids in the floodplain over time, encouraging increased water storage at the site, and protecting the region from flash flooding. Protecting Orville Road therefore occurs naturally, since the surrounding terrain is better able to hold water and release it over time without the need for human intervention.

Previous page: A completed series of discontinuous, engineered logjams form a setback revetment on the right with the floodplain on the left.(Photo by Pierce County Staff)

Top: A completed log jam forming one piece of the revetment. (Photo by Pierce County Staff)

Bottom: Dolos on top of the log jam ballast the material beneath. The team will overlay additional large wood and slash material to visually blend them into the natural landscape. (Photo by Pierce County Staff)

Broadening Benefits

An active volcano, Mt. Rainier periodically triggers lahars, mud and debris flows that rush down the slope at speeds of up to 70–80 kilometers per hour. Keeping Orville Road clear as an evacuation route will save lives. The reduced risk and impact of flooding in the area will provide additional important social and economic benefits, as will the $8 million the ongoing project is reinvesting in the local economy. Additionally, creating high-quality habitat for salmon, important to the cultural, historical, and economic fabric of the Pacific Northwest, also creates holistic benefits for the overall ecosystem and the entire region.

Promoting Collaboration

This project built off the work of Dr. Tim Abbe and Natural Systems Design, a consulting firm specializing in replicating natural processes. This collaboration led to combining the concrete dolos with the conifer logs, lowering the project's construction costs. Pierce County took the lead, working with Pierce County Surface Water Management and Tribal government staff and resource managers to ensure the restoration project had full community support from its original design through the committee approval process and final implementation.

Top: Aerial view of the floodplain reconnection area. Orville road runs by the conifers on the middle left. (Photo by Pierce County Staff)

Bottom: The base layer of the engineered log jam during construction. (Photo by Pierce County Staff)

Wood-filled backwater channel and pond in Clackamas (project details on page 228). (Photo by Metro Parks and Nature)

Use of Vegetation and Natural Materials

Exploring alternative interventions

Introduction

The projects in this chapter highlight the innovations possible when using vegetation and natural materials in combination with EWN principles. Designed and constructed in lotic (or flowing water) environments, projects in the Pacific Northwest, the Rocky Mountains, the Great Lakes, and the United Kingdom combined native vegetation with on-site materials such as large woody debris, root wads, engineered log jams, leaky woody dams, and rocks of varying sizes and shapes to meet project objectives. These features naturally reduce flood risk, restore stream and wetland habitats, and restore groundwater recharge. Restoring aquatic habitat remains a common theme, as these projects restore in-stream complexity and pool-and-riffle habitat to promote fish migration. Side channels, floodplain connectivity, riparian habitats, emergent wetlands, stream meanders and bottoms, and peat bogs are natural processes being restored to reduce flood risk, slow water flow, store surface water runoff, aid groundwater infiltration, raise water tables, and restore wetland hydrology. These natural processes are augmented by the strategic planting of native vegetation to reduce bank erosion and provide shade and shelter for migrating fish and other wildlife. Perhaps most impressively, the regular operations of an upstream dam has been adapted to manage stream flows and to conserve hydropower.

Howland Dam Fish Bypass

Howland, Maine, United States

Constructing the largest nature-based fish bypass channel in the nation. Dams in the Penobscot River watershed, which drains into the Gulf of Maine, have blocked fish passage since the early nineteenth century. However, reconnecting this river is a major step towards restoring Atlantic salmon in the United States and the fishery and cultural heritage of the Penobscot Nation. Therefore, in 2016, the Penobscot River Restoration Trust completed a new bypass as part of the comprehensive Penobscot River Restoration. Located on the Piscataquis River just upstream of the confluence with the Penobscot, the effort included decommissioning the Howland hydroelectric station and constructing a 30-meter-wide, 300-meter-long fish bypass channel around the spillway. With the retrofitted dam in place to maintain impounded water levels, the naturalized bypass channel has pool-and-riffle features and natural substrates to provide aquatic organism passage over a range of flows. Overall, the restoration effort is an ecologically sensitive solution to better manage the basin's ongoing hydropower generation needs while facilitating the recovery of federally listed Atlantic salmon (*Salmo salar*) and other native fish. Just two years after completion, fish and eels have returned to the river; and monitoring data provides a valuable record for future nature-based fishway designs.

Producing Efficiencies

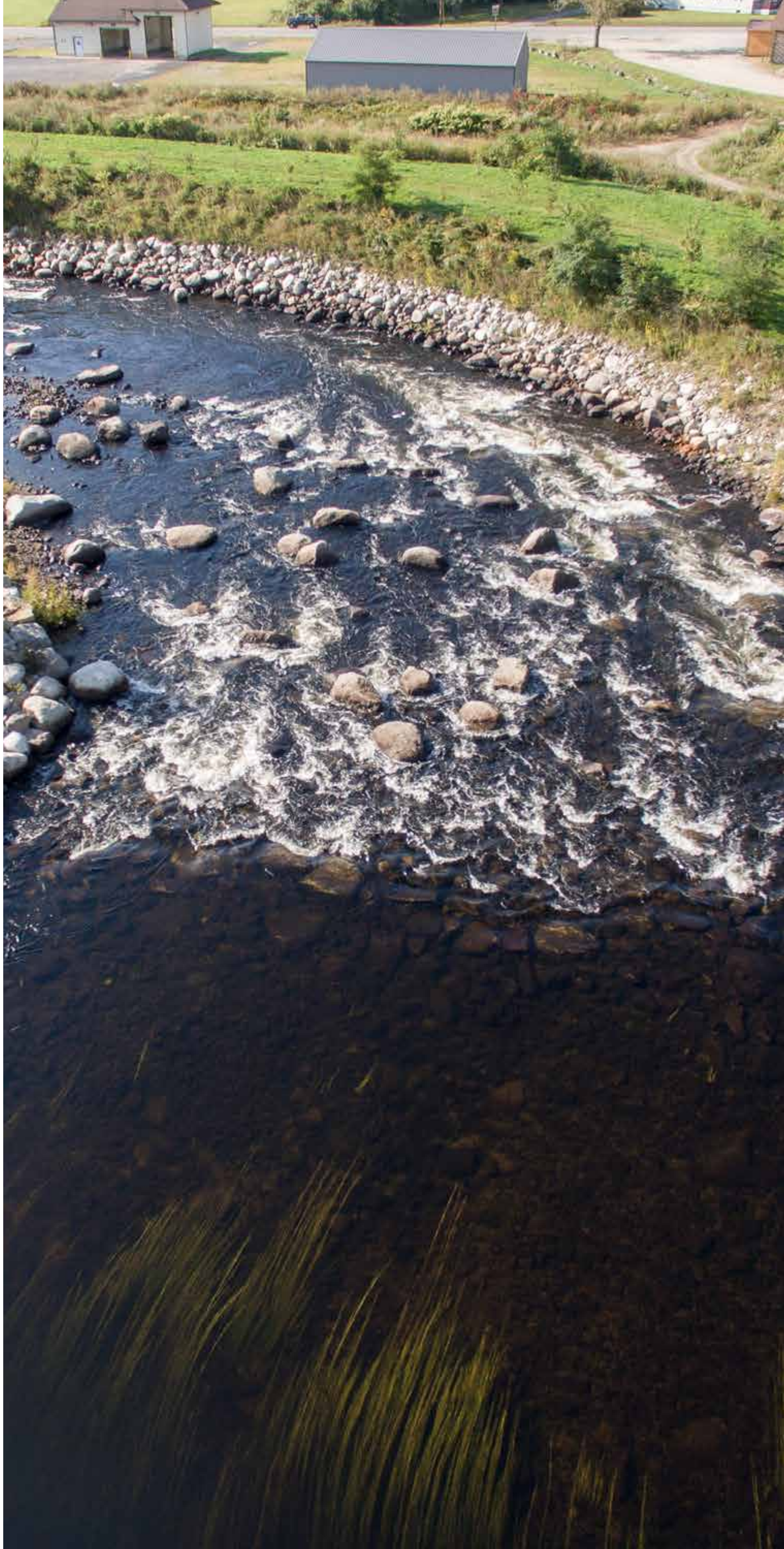
The project required an innovative blend of engineering disciplines to design the decommissioning of the powerhouse, maintain the reservoir level, and regulate high flows while also allowing for effective aquatic organism passage. In sharp contrast to most technical fishways, which have been repeated hundreds of times with relatively straightforward adjustments, natural bypass channel designs have far fewer templates or benchmarks. Therefore, because Howland is the largest and most complex bypass yet constructed in the United States—and has proven to be a successful and functional design—future projects designs now have a reference.

Using Natural Processes

By emulating river patterns and forms closely aligned with those fish experience in a natural river network, this bypass channel will naturally allow a multitude of aquatic species to ascend past the dam. The natural pool-riffle sequences in the bypass, combined with rounded-boulder and cobble-substrate bed forms, give migrating fish a wide range of conditions to choose from, irrespective of flow levels. This bypass stands in stark contrast to traditional pool-and-weir fish ladders, which provide effective upstream passage during only narrow flow conditions.

Previous page: Geomorphic features mimicking a natural stream in the bypass. (Photo by Inter-Fluve)

Right: Pools and riffles designed with hydraulic modeling. (Photo by Inter-Fluve)



Broadening Benefits

Restoring habitat for native fish that the region relies on sustains the local and regional community. Ongoing monitoring studies have documented Atlantic salmon passage survival and efficiency at nearly 100%. Coevolved species, such as alewife (*Alosa pseudoharengus*) and blueback herring (Alosa *aestivalis*), are also using the fish bypass for passage and in some instances as habitat for rearing. Tied into a regional walking trail network along the river front, the project creates amenities for the town to enjoy, too. Economically, the passively functioning bypass structure minimizes ongoing and long-term operations and maintenance needs and costs.

Promoting Collaboration

Visitors marvel at the natural river channel running through the site that was, until recently, a degraded postindustrial eyesore. Led by the Penobscot River Restoration Trust, the project received monetary and technical support from more than ten different organizations, including collaborators in state and federal agencies, nongovernment agencies, the town of Howland, the Penobscot Nation, the hydropower utility in the basin, and design and construction contractors. The project serves as an outstanding example of balancing community needs while providing tangible ecosystem services to the region. Other entities are already looking to this success to inform their own designs.

Top: Pools, riffles, bars, and boulders designed for stability during major flood events. (Photo by Inter-Fluve)

Bottom: A major regional trail spanning the bypass. (Photo by Inter-Fluve)

Jackson Park

Chicago, Illinois, United States

Rehabilitating a historic park while maintaining its cultural character. Jackson Park is situated along the Lake Michigan shoreline in Chicago, Illinois. The landscape was designed by Frederick Olmsted in 1890, and the park was home to the 1893 World's Columbian Exposition. More recently, the park suffered from invasive species, impaired geomorphology, and poor native species richness. Therefore, a collaboration between the U.S. Army Corps of Engineers (USACE)–Chicago District, the Chicago Park District, Project 120, Heritage Landscapes, and the Illinois Historic Preservation Agency, restored 16 hectares of habitat while preserving and rehabilitating the historical and cultural character of Jackson Park. The restored habitat includes fringe marsh, sedge meadow, oak savanna, and oak woodlands adjacent to the western shoreline of Lake Michigan, a globally significant migratory bird flyway. Curvilinear walking paths true to Olmstead design principles run through the park to promote visitors' ability to experience an ecologically restored landscape in an urban setting. Both the design and the construction efforts were funded by the Great Lakes Restoration Initiative. Construction for the project began in 2014 and was completed in 2019, but regular operation and maintenance performed by Chicago Park District will ensure long-term project success.

Producing Efficiencies

The team developed 15 restoration measures, which they analyzed for costs and benefits and combined into a variety of alternative plans. Further cost analysis screened out those options that would produce the same or fewer benefits at a greater cost, allowing the team to select and implement the best plan. One plan element included mimicking the expansive open spaces of Olmsted's vision without the high maintenance of a lawn. To achieve this, the team created a lawn-like look using native oak sedge (*Carex pensylvanica*) and other low-growing species. The successful landscaping drew much public praise.

Using Natural Processes

Much of Jackson Park, particularly the Wooded Island, consisted of degraded oak savanna systems so overgrown with invasive or undesirable tree species that the park provided only very poor-quality habitat. Invasive tree removal allowed more sunlight to reach the ground layer and promoted a more diverse native herbaceous understory. Further, the project team graded over 3,000 linear meters of lagoon shoreline to create a submerged wetland shelf and stabilized it by planting native emergent wetland species. These established wetland shelves help to absorb erosive wave energy and provide valuable fish and wildlife habitat while creating a gentle transition from open water upland areas.

Previous page: Fringe wetland with native emergent plants along the lagoon shore. (Photo by USACE Chicago District)

Right: Restored oak savanna with open canopy and herbaceous understory. (Photo by USACE Chicago District)

Broadening Benefits

The Jackson Park project provides a well-rounded suite of benefits, ranging from the environmental benefits associated with ecosystem restoration to the social and economic benefits created through park improvements such as walking paths and scenic overlooks. The project team undertook significant efforts throughout the planning and construction phases to preserve the historical and cultural character of Jackson Park, including incorporating Olmsted design principles when creating the planting plans and designing the layout of walking paths to promote accessibility throughout the park.

Promoting Collaboration

Jackson Park lies just south of the Museum of Science and Industry, adjacent to the future Obama Presidential Library, and will surround Yoko Ono's public art piece, Sky Landing. Being at the nexus of these resources and amenities demanded extensive collaboration and stakeholder involvement. The participation of the USACE Chicago District, the Chicago Park District, Project 120, Illinois Historic Preservation Agency, Heritage Landscapes, and local community representatives ensured that this was a successful Engineering With Nature application in a historic Olmsted Park.

Top: Olmsted-inspired paths through the park. (Photo by USACE Chicago District)

Middle: Herbaceous and woody species are critical for wildlife habitat and erosion control. (Photo by USACE Chicago District)

Bottom: The sedge meadow replicates the look of an expansive lawn without the associated maintenance costs. It additionally provides ecological benefits that a lawn does not. (Photo by USACE Chicago District)

Flimby

Flimby, England, United Kingdom

Making small interventions to create a big impact. On the west coast of Cumbria, four watercourses run through the village of Flimby, which experienced a major flood in 2015 affecting 100 homes. Three of the four watercourses run under the village, culverted, becoming inundated often. Farming practices have compacted the soil, and increased rainfall combined with decreased tree cover have led to greater overland and coastal flooding. In February 2018, the West Cumbria Rivers Trust partnered with the Environment Agency and the Forestry Commission to address these problems by introducing a number of small, nature-based interventions upstream of the village. The mixed woodland of the area provided a perfect source of local materials to build leaky dams and install woody debris at nearly five dozen strategic locations along the catchment. During periods of high flow, the water still passes through these barriers but at reduced rates, allowing the floodplain more time to store the water. With work scheduled to finish in 2021, these numerous small interventions add up to a larger, incredibly cost-effective solution. They have reduced flood risk and rebuilt habitat by restoring the natural function of the river, its floodplain, and the wider catchment.

Producing Efficiencies

Traditional flood defenses, such as large-scale, hard-engineered floodbanks and coastal engineering, are physically and economically unsustainable. In contrast, natural flood management techniques use natural and locally sourced materials, reducing economic and environmental costs, which makes the project's delivery and maintenance far more sustainable. The reduction in downstream silt also translates to lowered dredging costs and less frequent clearing of the culverts, creating operational efficiencies. The saved money, time, and resources can aid other flood management projects, benefiting multiple communities.

Using Natural Processes

The Flimby project used trees from the local woodland to make leaky natural barriers that slow the flow while still letting water pass through. Combined with tree planting and the creation of new cross-slope bunded hedgerows to hold back water, these strategically placed features work to maximize benefits to the community while creating habitat for wildlife. Other measures such as subsoiling to improve soil structure aim to help kick-start natural processes to further improve soil structure and boost infiltration rates in an agricultural landscape.

Previous page: The leaky barrier functioning as designed during high flow, slowing the flow while letting water pass through. (Photo by West Cumbria Rivers Trust [WCRT])

Right: Hedgerows planted on small embankments, or bunds, across the slope of fields reduce the volume and speed of runoff by creating temporary water storage. (Photo by WCRT)

Broadening Benefits

The Flimby natural flood management project aims to reduce flood risk, protecting the local economy from costly disaster relief and recovery disruptions. But the environmental benefits are also numerous: increased carbon storage through tree planting and improved soil structure, improved landscape character and biodiversity value, habitat connectivity through new hedgerows, and increased farm productivity through better soil productivity and shelter for stock. These measures also enhance the water quality by reducing runoff of nutrients and siltation. Further, natural flood management solutions are less expensive and require less maintenance than upgrading infrastructure.

Promoting Collaboration

A number of stakeholders worked together to make this project a reality, including the West Cumbria Rivers Trust, Forestry Commission, Environment Agency, Farmer Network, Woodlands Trust, Cumbria Woodlands, and Cumbria County Council as well as landowners, farmers, foresters, and the local community. Local volunteers assisted with plantings, and the Flimby Flood Action Group ensured members of the local community were represented and informed during the project's implementation and will continue to represent them during the monitoring period. Further, the Farmer Network and West Cumbria Rivers Trust are working together to engage the farming community.

Top: The leaky barrier is designed to allow water to pass underneath during low flow. (Photo by WCRT)

Bottom: Strategically placed woody debris slow the water during high flow. (Photo by WCRT)

Dry Creek

Sonoma County and Healdsburg, California, United States

Enhancing salmon habitat in Wine Country. Since the mid-1980s, Dry Creek has been highly regulated for flood control by the U.S. Army Corps of Engineers (USACE) and water supply by Sonoma Water, accommodating the water needs of 600,000 consumers. Though the creek historically provided winter habitat and seasonal rearing for steelhead (*Oncorhynchus mykiss*), coho (*O. kisutch*), and Chinook (*O. tshawytscha*) salmon, changes in downstream flows due to the dam significantly degraded salmonid habitat. Therefore, instead of Sonoma Water building a bypass pipeline to convey the water supply and mitigate habitat concerns, the Dry Creek Ecosystem Restoration Project, a joint venture with the USACE San Francisco District, restored approximately 30 hectares of stream, floodplain, and riparian habitat along lower Dry Creek. The 2018 project increased in-stream habitat complexity and improved hydrologic connectivity with the floodplain by constructing combinations of riffles, large wood structures, backwaters, side channels, and alcoves along a portion of the 22 kilometer creek, promoting the recovery of local salmon and steelhead as well as other native wildlife. The current project is in the monitoring and adaptive management phase, but additional restoration projects along the creek will continue.

Producing Efficiencies

The project incorporated an existing long backwater depression that naturally ponded throughout the year and strategically widened the main stem at one location, taking advantage of a flat area to create additional off-channel habitat and enhance riffle formation. Despite cool summer water, Dry Creek provided little salmonid habitat because of the required water management from Warm Springs Dam. So, the restoration project worked with the existing dam operations to support appropriate velocities for salmonids during summer base flow and lower winter flow conditions, avoiding the need for a costly bypass pipeline.

Using Natural Processes

The project team took a dynamic design approach, working with the natural sediment transport processes, vegetation succession regime, and expected periodic overflows to maximize the benefits of the restoration and create more habitat complexity over time. Plantings will evolve into a resilient, diverse riparian habitat that regenerates naturally and supports native plant dominance. And replicating the influences of former large food events by selective vegetation removal and the construction of side channel, alcove, and backwater pond habitats has created new habitats ideal for the rearing and spawning of both coho and steelhead.

Previous page: Large woody debris in the constructed backwater. (Photo by Inter-Fluve)

Right: Monitoring for adaptive management at the Dry Creek Ecosystem Restoration Project site. (Photo by USACE, San Francisco District)

Broadening Benefits

The restored habitat has enhanced an existing walking trail that runs along the site, and Sonoma Water has posted informational signs along the way describing the restoration project and its species and habitat benefits. The improved aesthetic and environmental value of the site have become an attraction for visitors to the local vineyards, driving tourism to the site and providing additional economic benefits. This outcome contrasts starkly with the pipeline alternative, which would have disrupted the local economy for the duration of its construction. Instead, the region presents itself as focused on biodynamic, organic, and salmon-friendly farming.

Promoting Collaboration

The National Marine Fisheries Service and the California Department of Fish and Wildlife both provided project assistance. Further, the project team worked with local landowners, using public meetings, nonstandard estates, and demonstration projects to develop broad support for species recovery and ecosystem restoration on vineyard properties in the study area. Originally, the local landowners were skeptical about future limitations associated with restoration activities on their property. But because of their experience with this project, many landowners have asked to participate in the larger Ecosystem Restoration Project now happening along Dry Creek by USACE and Sonoma Water.

Top: Fabric-wrapped soil lifts interplanted with native willow and dogwood shrubs provide erosion protection to adjoining vineyard lands. Using vegetation to resist erosion has many ecosystem benefits while protecting valuable property. (Photo by Inter-Fluve)

Middle: Constructed backwater habitat for salmonids. (Photo by Inter-Fluve)

Bottom: Dry Creek Ecosystem Restoration Project site postconstruction in summer 2019. (Photo by USACE, San Francisco District)

Clackamas River

Clackamas, Oregon, United States

Reclaiming a river corridor for native wildlife. A tributary of the Columbia River and famous for the quality of its fishing, the Clackamas holds an important place in the history, culture, and economy of the Pacific Northwest. However, large-scale beaver removal, logging, mining, overgrazing, and urban development disconnected the river from its floodplain and left it bereft of its historic populations of fish. Following a 40-kilometer assessment of the lower Clackamas River in 2003, a group of partners, including Portland General Electric and Metro, a regional governance agency, began extensive habitat restoration efforts to help threatened and endangered salmonids. By 2016, the work had reconnected over 60 hectares of main-stem floodplain and reconnected and restored 330 meters of tributary habitat. A pair of projects created dynamic and deformable side channel and floodplain habitats for juvenile coho (*Oncorhynchus kisutch*), Chinook (*O. tshawytscha*), and steelhead (*O. mykiss*) salmon by blending a process-based approach with engineered solutions. A third project, the River Island Project, reclaimed an abandoned gravel mine on the Clackamas River while restoring its confluence with Goose Creek. Each project has included extensive monitoring to evaluate project success and now shows recovering salmon runs and native habitat.

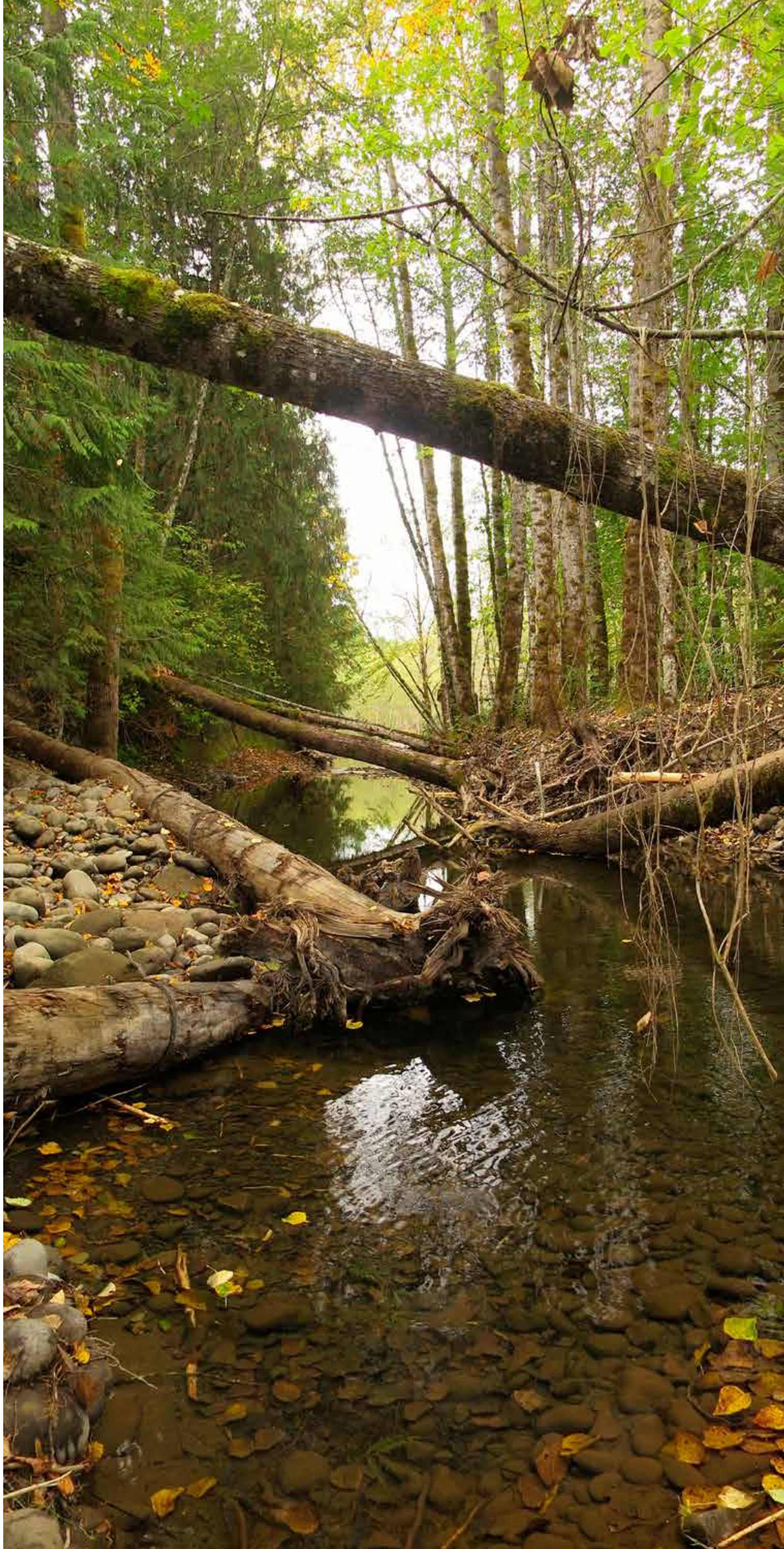
Producing Efficiencies

The two side channel restoration projects designed and created off-channel habitats with structure added from engineered logjams. Jam design followed U.S. Army Corps of Engineers and U.S. Bureau of Reclamation guidelines for watershed restoration practices, ensuring the project was ecologically and economically sustainable. Additionally, by relocating the material locally, the team reduced costs for all three projects from $30–$50 per cubic meter to $8. The savings allowed a four- to six-fold increase in the amount of material the team could use to reshape the channel's habitat.

Using Natural Processes

Dams upstream influence the river's hydrograph and transport of sediment, so relying on natural wood loading or channel processes to restore the river corridor was not possible. Instead, the designers installed more than 3,000 pieces of large wood throughout the project sites to mimic the conditions of the Clackamas River from over 100 years ago. These features emulate the debris and mature vegetative conditions occurring in natural floodplain areas. The designs used vertical logs to ballast large wood structures in place. These vertical elements help anchor other logs while also hydraulically mimicking the roughness of a forested floodplain.

Previous page: Pools and riffles in the restored river. (Photo by Inter-Fluve)



Right: Strategically placed large wood in side channels mimic naturally occurring debris in the floodplain. (Photo by Inter-Fluve)

Broadening Benefits

The Lower Clackamas River is a recreational playground for the Portland Metro Area. Therefore, in addition to the project's environmental benefits, rafters, boaters, fishermen, hikers, and campers visiting Barton Park and Milo McIver State Park benefit—a recent survey found over 400 watercraft users per hour enter the river. This project is also a valuable contribution to the engineering profession because it shows how a large-scale remediation effort is possible when engineers take a creative approach to returning natural physical and biological processes to a historically highly altered site.

Promoting Collaboration

The majority of funds for the River Island project came from a voter-approved bond and levy to improve water quality and restore wildlife habitat. As a result, public outreach and stakeholder communication were critical components of the project, from initial planning to project completion. During the two-year design phase, Metro coordinated and hosted six public meetings to keep the local community informed. And since completion, Metro has hosted four tours for stakeholders and neighbors to see the positive results.

Top: Describing the restoration of the Goose Creek tributary at a site visit. (Photo by Inter-Fluve)

Middle: Juvenile salmonids in the restored river. (Photo by Inter-Fluve)

Bottom: Juvenile salmonids seeking shelter in the woody debris. (Photo by Inter-Fluve)

Horsetail and Oneonta Creek

Corbet, Oregon, United States

Restoring stream and floodplain habitat for migrating salmon. Between 1900 and 1960, land use transformed the Horsetail and Oneonta Creek floodplain, near the confluence with the Columbia River—conversion of a forested wetland to cattle pasture, construction of major transportation routes, the straightening and rerouting of creek channels through borrow ponds remaining from gravel mining activity. All of these changes were problematic for salmon. The cold water from the upstream watershed became too warm in the summer from a stagnant borrow pond; and stretches of the streams lacked shade, limiting its use as a cold-water refuge. Further, salmon could only reliably access the culvert running under the interstate during high water, typically spring. Finally, the straightened streams lacked suitable habitat, like fallen trees, where salmon could hide or rest. Therefore, in 2010, the Lower Columbia Estuary Partnership undertook restoring the streams and former floodplain, aiming to reduce thermal loading and to enhance the habitat quality. With construction complete in 2013, replanting and maintenance of established plants occurred over the next several years. The project is a model for implementing complex floodplain and stream restoration in a heavily impacted area.

Producing Efficiencies

An assessment and feasibility study led to detailed designs. The project team routed flows through the historical channels, avoiding the warm water of the gravel pit. The team also partially filled in the gravel pit to reduce water depths and surface area, which enhanced the floodplain and emergent wetland habitat. To offset the lack of large woody debris for fish habitat and beaver dams, the team installed approximately 700 pieces across the site, using a helicopter due to site access and sensitivity issues. Finally, the team modified the interstate's culvert to provide year-round access by migrating fish, including Pacific lamprey (*Entosphenus tridentatus*).

Using Natural Processes

Placing large woody debris in the restored streams, as well as planting trees in the area, created immediate areas of habitat cover for fish while also providing future sources of woody debris. The channels mimic predisturbance conditions and foster natural system responses on the floodplain and in the stream. The restoration mimics the natural processes of erosion, sediment transport and deposition, channel migration, and large wood recruitment. In this way, the project corrected anthropogenic disruptions, which allows the system to recover with minimal intervention.

Previous page: A new alcove is an example of the created floodplain rearing habitat that was built with in-stream large wood and riparian habitat elements. (Photo by Inter-Fluve)

Right: Woody debris for salmonid refuge and cover being placed by helicopter to minimize land disturbance. (Photo by Inter-Fluve)

Broadening Benefits

The project team took a process-based, interdisciplinary approach that combined engineering, hydrology, geology, geomorphology, botany, fisheries biology, and wetlands science, restoring the balance between human and fish needs. It reduces summer thermal loading in both Horsetail and Oneonta Creeks and improves floodplain habitat quality and access for adult and juvenile threatened and endangered salmonids, such as Chinook (*Oncorhynchus tshawytscha*), coho (*O. kisutch*), and chum (*O. keta*). The newly restored streams now provide migrating salmon another option for suitable habitat as they make their way downstream to the Pacific.

Promoting Collaboration

The project represents a collaboration with local governments, other state agencies in Oregon, U.S. Fish and Wildlife, National Marine Fisheries, and nonprofit and private stakeholders. Additionally, in 2013, a complex construction sequence involved coordination with several other stakeholders, including the U.S. Forest Service, the Oregon Department of Transportation, Cascade Locks Electric, the Union Pacific Railroad, and the many regulatory entities with jurisdiction over the area.

Top: Horsetail Creek at bottom right, now complex habitat for salmonids. (Photo by Inter-Fluve)

Middle: Aquatic Contracting installs a wood habitat structure in the Horsetail Creek floodplain to provide habitat for salmon, steelhead, and lamprey (Photo by Lower Columbia Estuary Partnership)

Bottom: Realigned channel with pools and riffles. (Photo by Inter-Fluve)

Narborough

Narborough Bog, England, United Kingdom

Creating a living laboratory for nature-based flood protection. Lying within the floodplain of the River Soar and just upstream of the city of Leicester, the Narborough Bog nature reserve contains the only substantial deposit of peat in Leicestershire. However, the changing hydrology in the area was drying out the peat; and the River Soar, disconnected from its floodplain, contributed to increased flooding in the area. To combat these problems, the Environment Agency, working with the Leicestershire and Rutland Wildlife Trust, the global engineering firm Atkins, and members of the Soar Catchment Partnership, designed and implemented natural flood management techniques to slow and store water within the nature reserve. In keeping with the regular woodland management at the site, in 2019, the project team felled trees to create openings in the woodland canopy and to yield material for the construction of the natural features. They used the wood to block the flow route of floodwaters from the River Soar, holding it in the wet woodland area for longer, and created a wooden bund at the end of an old oxbow lake. The team designed all features to have the maximum ecological benefit and complement and blend into the nature reserve setting.

Producing Efficiencies

The natural flood management techniques used at the Narborough Bogs project site removed the need for concrete and used locally available natural materials, greatly reducing project cost. Restoring a functioning ecosystem will mitigate flooding recovery costs and will keep the long-term project maintenance costs lower than those of traditional solutions. As one of four sites in the Leicester area using this approach, significant site monitoring is demonstrating how effective the techniques are. This project aims to establish natural flood management as a complementary tool for traditional hard engineering.

Using Natural Processes

Keeping locally sourced deadwood at the site naturally provides invertebrates such as beetles with the habitats they prefer. The felled trees also serve two purposes: creating the barriers to the flow of water and opening up the woodland. Increasing the level of water and light directly benefits wetland plants, which then form the foundation of the entire ecosystem's recovery. And over time the peat underlying the reserve absorbs the water that would otherwise flood nearby communities, storing carbon and adding resilience to the bog.

Previous page: Flooding in 2019 shows how much water the reserve can hold. (Photo by Environment Agency)

Right: Woody debris assembled to fill troughs on the woodland floor to slow water flow. (Photo by Environment Agency)

Broadening Benefits

While this project helps to reduce downstream flood risk, the restoration also provides additional habitat and resilience to climate change. When rewetted, the peat under the reserve will once again be able to act as a carbon sink. The Narborough Bog serves as a living laboratory, showcasing the myriad benefits of natural flood management schemes. By proving that huge gains in flood risk reduction and habitat restoration are possible with small structures, Narborough Bog is an example for other sites looking to install nature-based features in their rivers, creeks, and streams.

Promoting Collaboration

Stakeholders from all sectors worked together to make the Narborough Bog showcase project a success: public, private, academic, and nonprofit. The project team took advantage of the collaborative relationships already in place through the Soar Catchment Partnership to bring together the team, and they sought out the support from the local council and university to assist with the postconstruction monitoring. Because of this collaboration, the partners the project team involved in the implementation now have the tools to carry out natural flood management projects across the wider catchment.

Top: Narborough Bog became a Site of Special Scientific Interest in 1956, having wet woodlands and meadows and one of the largest natural reed beds in Leicestershire. (Photo by Atkins)

Middle: View of the wetland and surrounding woods on the reserve. (Photo by Environment Agency)

Bottom: Woody debris at the end of an old oxbow stores water at the downstream end of the site. (Photo by Atkins)

Chatfield Reservoir–Plum Creek

Denver, Colorado, United States

Developing a unique vegetation monitoring and reporting program. Living with nature is fundamental to Denver's culture. So when reallocated water storage space in Chatfield Reservoir freed 3.6 meters of elevation for municipal use, protecting sustainability of the ecosystem was key. One of two primary tributaries feeding into Chatfield Reservoir, Plum Creek represents a critical source of water for Denver. However, rapid urban development and increased stormwater runoff from impervious surfaces had disrupted the creek's sediment dynamic and caused severe streambed degradation. The water table dropped, drying out the adjacent floodplain and wetlands habitat within Chatfield State Park. The lost wetland eliminated existing habitat for the federally endangered Preble's meadow jumping mouse (*Zapus hudonius preblei*), starved the mature riparian cottonwood forest and wetlands of water, and allowed invasive species to dominate the ecosystem. From 2017 to 2019, the U.S. Army Corps of Engineers, in cooperation with several state and local partners, installed naturalized riffles to raise the streambed's elevation and water table; and they planted 50,500 shrubs, 1,800 trees, 18,000 willow stakes, and 2,200 meters of willow logs. The restoration aimed to sustainably balance human development needs with natural systems, and was critical for supplying additional water to the people of Denver.

Producing Efficiencies

The team removed and repurposed trees lost from degradation and dewatering effects; and the use of naturalized, void-filled riffle structures reduced the conditioning period that traditional solutions require. The conditioning period brings an increased risk of failure, so to further reduce this risk, the team developed a high-resolution, spatially referenced monitoring and adaptive management program to rapidly communicate restoration status during the conditioning phase. Data from restoration monitoring crews upload immediately to a master database. Access to near real-time monitoring data facilitates adaptive decision-making to improve restoration efficiency.

Using Natural Processes

Void-filled riffle structures customized and installed at the project site now divert portions of high flows to dissipate energy and provide surface water to the floodplain. The project team used many of the removed trees to construct beaver-dam analogues to encourage local beavers to take up residence. Others they strategically anchored or used to armor the stream bank and outside bends, providing habitat for the Preble's meadow jumping mouse and for fish and other aquatic organisms. Restoring the streambed elevation on Plum Creek was a catalyst to reviving ecosystem processes, active beaver ecology, and a functional stream fishery.

Previous page: Plum Creek floodplain restoration area (flowing from top to bottom), 2017. (Image from Google Earth)

Top: The same view as on the previous page but prior to restoration, 2017. (Image from Google Earth)

Middle: Incised Plum Creek and dewatered "dead" floodplain prior to restoration. (Photo by Chatfield Reallocation Mitigation Company [CRMC])

Bottom: Repurposed tree anchored for habitat. (Photo by Clayton Ridenour, USACE)

Broadening Benefits

In addition to revitalizing habitat for many native species, the project is providing additional water for Colorado by using environmentally responsible methods. Restoring the Plum Creek floodplain not only reduces flood height and power but also naturalizes sediment dynamics to improve the quality of water delivered to Chatfield Reservoir. Further, Chatfield State Park experienced record visitor use in 2019 despite ongoing construction for the restoration. Momentum from the successful restoration at Plum Creek has served as a case study for water conservation programs in the developing communities upstream.

Promoting Collaboration

The diverse team organized itself into a project coordination team and a technical advisory committee. Thirty members worked on each team, representing stakeholders and interest groups. The Chatfield Reservoir Mitigation Company managed implementation of the project and maintained critical communication with the two teams and the general public through regular meetings, interactive web media, and outreach with the community. Nurturing effective communication among all the partners and stakeholders allowed the collective focus to stay on maximizing the benefits of restoring Plum Creek.

Top: Integrated recreation trail through Plum Creek restoration area. The Park experienced 28% higher visitor use in 2020 than in 2019. (Photo by CRMC)

Middle: Floodplain wetlands and side channels respond quickly to restored water table at Plum Creek. Restored braided and meandering side channels promote ecosystem resilience. (Photo by CRMC)

Bottom: Monitoring and data collection during conditioning at Plum Creek. (Photo by CRMC)

Westmoreland Park

Portland, Oregon, United States

Restoring an urban creek in the middle of a highly developed park. A tributary of Johnson Creek, Crystal Springs Creek runs for 3.8 kilometers through Portland and is the coldest salmon-bearing stream in the city. But channelization for agriculture, large in-line ponds for irrigation, and urban development degraded the floodplain into a disconnected watercourse too warm for salmonids. In 2003, the City of Portland worked with the community to develop the Westmoreland Park Master Plan, which called for creating a healthier park environment for people and native wildlife. The project team, including Portland Parks & Recreation, the Portland Bureau of Environmental Services, and the U.S. Army Corps of Engineers, began by restoring 730 meters of Crystal Springs Creek. Completed in 2013, the restoration removed concrete curbing along the creek and pond's banks, removed the duck pond and replaced it with a wetland, and planted 15,000 native plants to shade the creek and prevent erosion. The project also added logs, pools, and riffles in the creek channel and more than 760 meters of new boardwalks and paths, two new overlooks and a water access ramp, and a number of benches, picnic tables, and additional lighting. Now Crystal Springs is a designated salmon sanctuary—a first for Portland—and a gorgeous natural space for the local community.

Producing Efficiencies

The creek's path through the city meant the team needed to think creatively to engineer the restoration and to design the project so that flood elevations downstream did not rise. The team added large woody debris to the waterway without completely preventing access to this popular park, and they arranged the native plantings to make sure visitors could see into and through the wetland to the creek. Porous pavement managed stormwater and protected the water quality of the creek. To allow fish passage, they replaced the culvert under the nearby four-lane bridge, as it was not only undersized and a velocity barrier for fish but also inverted so the river flowed uphill through it.

Using Natural Processes

The new wetland acts as a sponge for the heavy springtime rains, increasing flood protection without altering the course of the creek. The gentle contours of the restored wetland environment make the habitat more suitable for native fish and other species in the area. The installed features slowed down the water flow, keeping it at the 0.6 meters per second that salmon need to avoid getting flushed back down the creek. Planted trees naturally lower the temperature of the water by providing shade, and the wider culverts create a more natural hydrology that prevents severe erosion.

Previous page: Crystal Springs Creek, just downstream of the former, pond showing the healthy and attractive park environment for both people and wildlife. (Photo by Kerry Solan)

Right: At the northernmost end of the park looking northward, the large woody debris provides habitat for native fish species. (Photo by Kerry Solan)

Broadening Benefits

Already, salmon have returned to spawn along the entire length of the creek, leading to Crystal Springs' designation as a sanctuary for the species. The creek also provides habitat for the culturally important Pacific lamprey (*Entosphenus tridentatus*) and one of the healthiest freshwater mussel populations in Portland. As much of the watershed is publicly owned, the park represents a perfect opportunity to showcase salmon and lamprey recovery to the community. The city added its first Nature Play playground to compliment the restoration, creating a regional destination for children and educators. The park is now one of the top five parks in Portland.

Promoting Collaboration

The project team worked with 21 different partners to make this project a reality. The plan required extensive coordination and outreach to local residents, many of whom had the creek running through their backyard. It incorporated input from stakeholders, including line-of-site tree planting to deter crime and night lighting that projected downward so as not to shine in nearby homes. Convincing residents of the necessity of closure and construction of this very popular park took a team effort but paid off: the walking tours, videos, signage led to a reopening event that has since become an annual community celebration.

Top: Southernmost end of the restored park looking southward. (Photo by Kerry Solan)

Bottom: Woody debris, pools, and riffles in the restored Crystal Springs Creek just downstream of the Umatilla Street culvert. (Photo by Kerry Solan)

Galloway Creek

Rochester Hills, Michigan, United States

Designing a new stream with natural features. The 1987 Great Lakes Water Quality Agreement established urban habitat restoration on the Clinton River as an international priority. A tributary of the Clinton River, Galloway Creek is one of only a few tributaries in the watershed to provide cold-water base flows, which are ideal for trout species. However, residential, industrial, and agricultural land use left Galloway, which runs through the Oakland University golf course, straightened, degraded, and cutoff from its watershed. Additionally, invasive species such as Phragmites had taken over the project site, and the golf course's off-line ponds were not functioning properly. So, with funding from the Environmental Protection Agency's Great Lakes Restoration Initiative, work began in 2015 to remediate and restore the stream habitat for fish and wildlife species by restoring floodplain connectivity, improving geomorphic stability, and providing in-stream habitat. The project team used wood and field stone to construct log and gravel riffles, restoring the stream's profile and reconnecting it with its associated floodplain; and they replaced two stream crossings with wider box culverts to better accommodate flood events. The team anticipates that natural processes will take over in the stream, creating a self-sustaining watershed.

Producing Efficiencies

This project provided a unique opportunity to leverage cold groundwater inputs in an urban system to maximize the benefits to cold-water fishes, such as brown and rainbow trout (*Salmo trutta* and *Oncorhynchus mykiss*). By using hydraulic modeling to determine the new stream channel's alignment and the stream crossings' optimal size, the team implemented a natural channel design to establish a stable channel and associated floodplain. The natural features require minimal operations and maintenance, saving time, labor, and resources both now and as natural processes take over.

Using Natural Processes

Past land use had altered the natural flow of the river, channelizing the river and forcing it out of its natural alignment. The project realigned the channel, shaping it into a more natural design that allows for better sediment transport and will also prove more resilient in the future. Removal of invasive species will allow new herbaceous, shrub, and tree plantings to flourish. During construction, the placement of root wads and boulders created in-stream features that mimicked the natural processes previously restricted by past land use. Over time, the stream will return to its natural flow, providing cold-water habitat to trout and other important fish in the Clinton River system.

Previous page: Riffles created with rocks and logs. (Phil Mlinarich, USACE Detroit District)

Top: Installing root wads and stones to mimic natural features. (Phil Mlinarich, USACE Detroit District)

Bottom: Using natural materials to realign Galloway Creek improves cold-water fish habitat for all life stages. (USACE Detroit District)

Broadening Benefits

As the project is located on the Oakland University golf course, its visibility provides a great opportunity for educating the public on natural riverine processes. The university will use Galloway Creek for research opportunities and as a tool to teach students about the local ecosystem. The fish populations' recovery will increase the recreational fishing opportunities in the local community. Finally, by reducing flood risk and creating a new natural space for residents and visitors alike, the Galloway Creek project has increased tourism and local housing values.

Promoting Collaboration

In addition to the Environmental Protection Agency's guidance and funding, Oakland University; Clinton River Watershed Council; Clinton River Public Advisory Council; the U.S. Army Corps of Engineers (USACE)–Detroit District; and the Michigan Department of Energy, Great Lakes, and the Environment proved critical to the project's success. They provided data, expertise, and personnel to ensure the design met the project and overall region's needs. Further, Oakland University created educational signs around the area and agreed to continue invasive species treatment after construction to allow the native vegetation to establish.

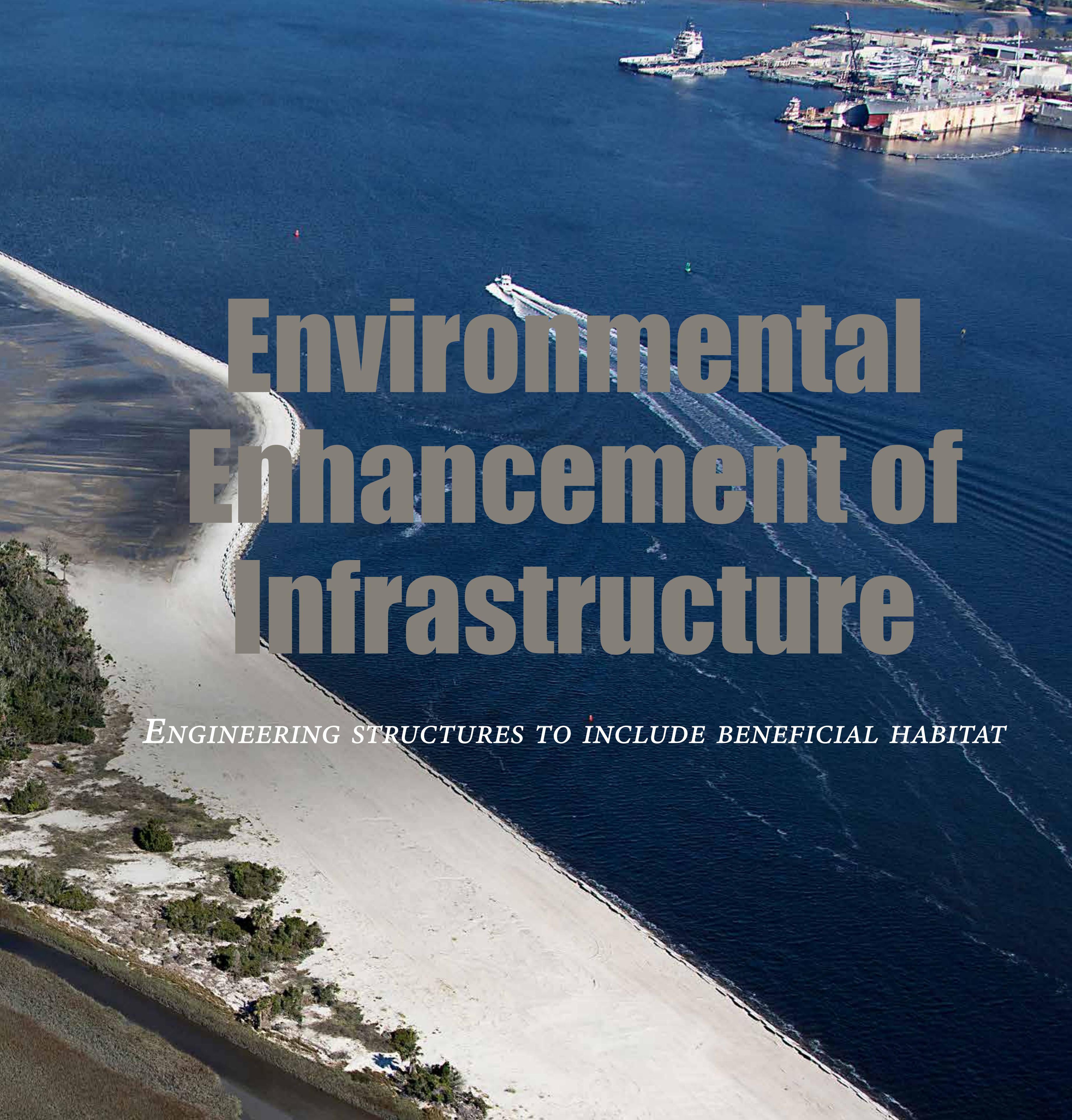
Top: Increasing the size of the stream crossing for better fish passage. (Phil Mlinarich, USACE Detroit District)

Bottom: Restored wetlands after channel realignment. (Phil Mlinarich, USACE Detroit District)

At Mile Point, the placement of dredged sediment for beneficial use restored the salt marsh habitat (project details on page 260). (Photo by U.S. Army Corps of Engineers–Jacksonville District)

Environmental Enhancement of Infrastructure

Engineering structures to include beneficial habitat



Introduction

The environmental enhancement of built infrastructure continues to provide a variety of opportunities to apply EWN concepts and techniques in novel ways. The regular maintenance and repair of existing conventional structures offers project teams a chance to use natural and nature-based materials to create new habitats and to promote wildlife recovery. Modifying these structures according to EWN principles has restored cyclical water flows at Jacksonville Harbor's Mile Point in Florida, created new estuarine habitat at Brooklyn Bridge Park in New York, reconnected river habitat for native migrating fish species at the Lower Yellowstone River in Montana, and reduced erosion and the risk of mudslides at Matarandiba Island in Brazil. In riverine systems, innovative training structures promote a more self-sustaining navigation channel, reducing operation costs for tasks like regular dredging at the Mississippi River between Missouri and Illinois. And project managers reuse dredged sediment in new and unique ways, creating islands that improve natural channel flows at the same time they enhance habitat value and reduce project costs. The novel process of turning accumulated clay sediments from local water bodies into usable clay soil at the Eems Dollard Region in the Netherlands provides an innovative way to repair and strengthen existing dike structures. And finally, a retrofitted existing pump is diverting freshwater for restoring marshland and bald cypress forest in coastal Louisiana.

Brooklyn Tide Pools

Brooklyn, New York, United States

Creating intertidal habitat in a postindustrial urban park. Brooklyn Bridge Park in New York City is a popular park with 2 kilometers of revitalized waterfront and 14 hectares of open space. It is a community and tourist destination on the Brooklyn side of the East River, serving thousands of visitors a day. But as a postindustrial urban waterfront, shorelines had declined in recent decades, losing natural intertidal habitats, biodiversity, and biological productivity. Brooklyn Bridge Park Conservancy's effort to revitalize the park began in 2002, culminating in 2013 with two ECOncrete enhancement projects. The first project features precast concrete tide pools as part of a newly constructed riprap beach at Pier 4, and the second project features the structural repair of the aging piles supporting Pier 6. Using an innovative encasement technology with an ecosystem-specific concrete mix, the physical and chemical changes to the support system created an ecofriendly substrate far superior to standard construction methods. After nine months, the tide pools' installation showed 89%–100% live cover and increased biodiversity; and after fourteen months, the pile encasements' installation showed 70%–100% live cover and increased biodiversity. This was a stark contrast to the surrounding riprap and control piles.

Producing Efficiencies

Integrating environmentally sensitive technologies into the design and construction harnesses natural processes for ecological enhancement and reduces a structure's ecological footprint. ECOncrete's design aims to meet the requirements of marine flora and fauna, and the surface complexity mimics that found in natural habitats. These improvements over traditional concrete designs increase native species richness and biodiversity, reduce dominance of invasive species, and encourage water purification. The concrete mixture also lowers the project's carbon footprint through its low-carbon mix design and the unique ability to enhance biological processes that function as an active carbon sink.

Using Natural Processes

The new tide pools create well-defined elements that retain water and mimic natural rock pools, increasing intertidal habitat in breakwaters, revetments, and riprap. Even though rock armor is made of natural material, its low surface complexity and dense nature provide only limited ecological value to the surrounding environment. These pools replace the standard armoring stones between mean low and mean high water lines, accommodating an array of diverse species typically absent from standard constructions. Finally, the textured surface naturally promotes rich marine growth.

Previous page: Underwater survey of piles at 14 month post deployment showing upwards of 70% surface coverage of marine organisms. (Photo by ECOncrete Inc.)

Right: Ecological monitoring of tide pools in 2014 to evaluate their effectiveness in enhancing the ecological value of the shoreline. (Photo by ECOncrete Inc.)

Broadening Benefits

The tide pools and pile encasements increase biodiversity, creating sheltered habitats and nursing grounds. The installations also provide structural and socioeconomic benefits because biogenic growth of organisms like oysters, tube worms, and barnacles strengthens the structure and add to its stability and longevity. This form of bioprotection reduces the frequency and magnitude of structural maintenance, improving ecological stability and saving time and money. The success of both projects increased community awareness through the park's education program, with local high school students and citizen scientists taking part in the numerous monitoring efforts.

Promoting Collaboration

As a result of the collaborative effort of Brooklyn Bridge Park Conservancy, ECOncrete, and the New York State Department of Environmental Conservation, the Waterfront Alliance has certified the park as a comprehensive, multidisciplinary approach to better waterfront design and adaptive management. The team enhanced the integrity of the structure, improved ecosystem services in an urban marine setting, and increased environmental awareness through public education. The success of these two pilot projects have streamlined the park's environmental permitting scheme, reducing the need for mitigation requirements for future ecosystem services projects.

Top: Underwater survey at 40 months post deployment showing significant increase in biodiversity and abundance of marine species. (Photo by ECOncrete Inc.)

Bottom: Pile encasements at time of installation in 2013 prior to the growth of marine organisms. (Photo by ECOncrete Inc.)

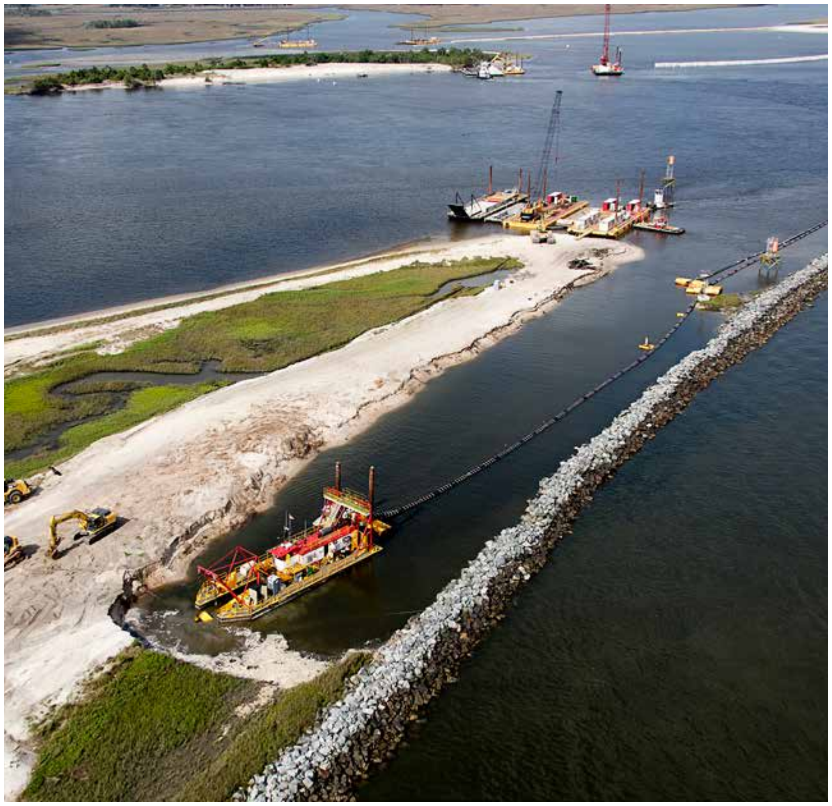
Mile Point

Jacksonville, Florida, United States

Implementing cost-effective environmental mitigation. Designated an American Heritage River in 1998, the St. Johns river is the second largest ecosystem in Florida and the state's most significant river for commercial and recreational use. However, since at least 1986, the area on the north bank of the St. Johns River at Mile Point in Jacksonville has experienced severe shoreline erosion. Additionally, crosscurrents at the confluence of the Intracoastal Waterway and the St. Johns River created hazardous navigation conditions and vessel restrictions. To resolve both these issues, starting in 2015, the U.S. Army Corps of Engineers (USACE)–Jacksonville District removed 950 meters of the existing training wall, relocated and reconfigured the remainder, and installed a flow improvement channel. The team also created a mitigation plan to restore historic salt marsh at Great Marsh Island by placing almost 700,000 cubic meters of dredged sediment. In total, the project team restored 20 hectares of salt marsh, created new oyster habitat, removed hazardous navigational channels—and the resulting navigation restrictions—and reduced risk of future erosion along the north bank of the St. Johns River. Overall, the solutions solved these erosion and navigation problems while protecting and enhancing the environment.

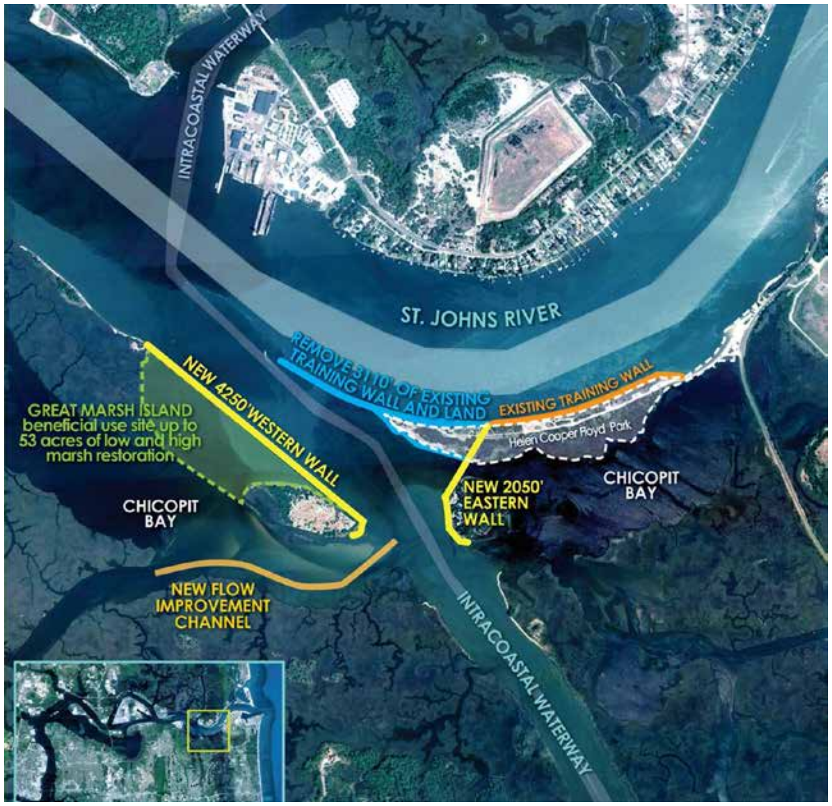
Producing Efficiencies

Hydrodynamic modeling, such as ship simulation testing, streamlined the planning process: the model determined that, of the available options, relocating the training wall was the only solution that would successfully alleviate the crosscurrents at Mile Point. The largest operational efficiency in the project, however, was the use of the material from the approximately 1,100 meters dredged from Chicopit Bay. Placing the dredged sediment on Great Marsh Island instead of at the nearest upland disposal both allowed the team to restore the marsh and saved the project nearly $9 million.



Using Natural Processes

The restoration of Great Marsh Island improves channel navigation naturally. By working with the flow of the waterway and the ecosystem at large, the project team redirected the flow of water and reduced erosion along the northern portion of the Mile Point shoreline. The salt marsh habitat built from the dredged sediment benefits a range of species, from migratory birds to over 30 species of fish, such as the endangered wood stork (*Mycteria americana*) and the commercially important blue crab (*Callinectes sapidus*) and red drum (*Sciaenops ocellatus*).



Previous page: Restored Great Marsh Island, composed of the beneficial use of approximately 900,000 cubic yards of dredged sediment. Strategic planting of tidal marsh plants is currently underway and will be complete in 2021 (Photo by USACE Jacksonville District)

Top: Removal of existing portion of the eastern leg training wall and portion of Helen Cooper Floyd Park. This was necessary for construction of the eastern leg training wall reconfiguration/alignment and to alleviate strong cross-currents in the river. (Photo by USACE Jacksonville District)

Bottom: Selected plan project components. (Image by USACE Jacksonville District)

Broadening Benefits

In keeping with USACE's mission, this project provides economic, environmental, and recreational benefits by removing hazardous navigational conditions and building a shoreline less prone to erosion. Easier navigation will increase tourism revenue and make it safer for tourists and visitors alike. The reduced dredging cost frees up resources better spent elsewhere, providing additional knockdown benefits for years to come. Thus, the newly restored island, 20 hectares of new salt marsh, and oyster habitat will benefit Jacksonville Harbor as a whole, both commercially and environmentally.

Promoting Collaboration

The Jacksonville District worked closely with many groups, including the Florida Department of Environmental Protection; the Florida Fish and Wildlife Service Conservation Commission; the National Park Service; and the project's sponsor, the Jacksonville Port Authority. Working together with the uniform mitigation assessment method as the team's framework, they determined that 7.6 hectares of mitigation would offset jurisdictional wetland losses caused by the reconfiguration of the training wall. The Jacksonville Port Authority, Department of Environmental Protection, and Jacksonville District will continue working together, maintaining and monitoring Mile Point.

Top: Remaining portion of severely eroded East Great Marsh Island. West Great Marsh Island seen in distance with eroded flowway evident between the two. (Photo by USACE Jacksonville District)

Middle: Flow Improvement Channel (Chicopit Bay) dredging and pumping of sediment to the initial containment area of Great Marsh Island. (Photo by USACE Jacksonville District)

Bottom: Beneficial use of dredged sediment and restoration of severely eroded Great Marsh Island. (Photo by USACE Jacksonville District)

Clay Ripener

Delfzijl, Groningen, the Netherlands

Turning dredged sediment into functional clay. On the edge of the Eems-Dollard Estuary in the Wadden Sea, fields of dredged sediment are serving as a pilot study to explore the viability of converting dredged sediment into clay soil. The project lies in a muddy system of tidal flats at the mouth of the Ems River at the border between the Netherlands and Germany, where excess sediment has negatively affected water quality and biodiversity, accumulating in ports and requiring regular dredging. Since 2018, EcoShape, together with the partners of the Eems-Dollard 2050 Program, have tested a variety of methods of dewatering, desalinating, and oxidizing the sediment to convert it into a useful resource—clay soil for reinforcing dikes and raising farmlands. In 2022, if the ripened clay proves to be suitable, 70,000 cubic meters of the new clay soil will be used in a pilot to strengthen a 1-kilometer stretch of the Broad Green Dike. If this pilot is successful as well, the remaining clay soil will be used to strengthen the entire 11.5-kilometer-long Broad Green Dike. This project is part of the larger system-based program Eems-Dollard 2050, which comprises various pilots in the region to develop the natural and economic status of the Eems area.

Producing Efficiencies

Connecting supply and demand is key in this project. Excess turbidity in the Eems-Dollard Estuary causes worsening water quality and high-siltation rates. Therefore, regular maintenance dredging of the Delfzijl Port and dredging to deepen Breebaart, a nature area near the project, supplies dredged sediment for the Clay Ripener. Ripened clay will in turn be used to strengthen and enlarge the nearby Broad Green Dike, which needs to be reinforced to meet the current improved safety standards in response to climate change.

Using Natural Processes

Dutch regulations require that the salty dredged sediment lose salt, water, and organic matter before it can be reused in dikes. To accomplish that, this project relies heavily on natural processes to create the clay: rain and drainage for salt; wind, sun, and infiltration for dewatering; and oxidation for the organic content. Additionally, certain test plots are studying the beneficial effects of planted vegetation on ripening. The team keeps mechanical reworking of the ripening field to a minimum, but it is an available option accelerate the natural processes.

Previous page: The sediment depot in April 2018, shortly after adding the clay ripener. (Photo by Christiaan van Velzen, EcoShape)

Right: The solid clay after the ripening process. (Photo by Wouter van der Star, EcoShape)

Broadening Benefits

With future plans for dike upgrades, the ripened clay will prove useful in a variety of projects. But besides producing clay for dikes by using locally available dredge sediments, this project also delivers technical and operational knowledge as well as a business case evaluation to highlight the most effective way to produce clay in this context. Furthermore, this beneficial use of dredged sediments improves the ecological status of the estuary, potentially sequesters CO2 in the dike, advances the Dutch aim of being fully circular by 2050, engages the local community, and stimulates the local economy.

Promoting Collaboration

This project unites private partners, a nature organization, and national and local government organizations towards a common goal: producing clay from dredge sediments and delivering the correlated technical knowledge and business case. Each partner has its own objectives and responsibilities, outlined in a binding document that provides motivation to deliver. This pilot study stands as a wonderful example of the nature-based engineering possible through public-private partnerships. Collaboration is the critical ingredients that makes these projects possible and that guarantees results.

Top: Monitoring the ripening process in September 2019. (Photo by Ebi Meshkati Shahmirzadi, EcoShape)

Middle: Adding clay ripener to one of the sediment fields in July 2018. (Photo by Ebi Meshkati Shahmirzadi, EcoShape)

Bottom: A plot of ripened clay dries in the sun. (Photo by Ebi Meshkati Shahmirzadi, EcoShape)

Hartlepool Headland Coastal Protection

Hartlepool, England, United Kingdom

Placing rock features strategically for complex habitats. Hartlepool, an internationally important site for waterbirds, is the site of the first known engineering project that used passive ecological enhancement techniques on a rock revetment. The project combined passive and active multiscale ecological enhancements, such as careful positioning of the rocks in the revetment construction and the use of textured form liners to cast the wall panels, both of which provided key habitats for intertidal prey species. Within just two years of project completion in 2018, the area has shown a significantly higher biodiversity. The project proves that simple, inexpensive methods with little change in cost or procedure will improve ecological outcomes of hard engineering structures. The project now serves as an example for the Environment Agency's replacement coastal engineering scheme based in Elmer, England, which uses optimal rock types, the positioning of natural features, and the selection and positioning of rocks with quarrying features such as blastlines and blastholes to mimic natural habitats. These methods increase the local population of intertidal species such as limpets (*Patella vulgata*)—and the oystercatchers (*Haematopus ostralegus*), redshanks (*Tringa tetanus*), turnstones (*Arenaria*), and red knots (*Calidris canutus*) that feed on them.

Producing Efficiencies

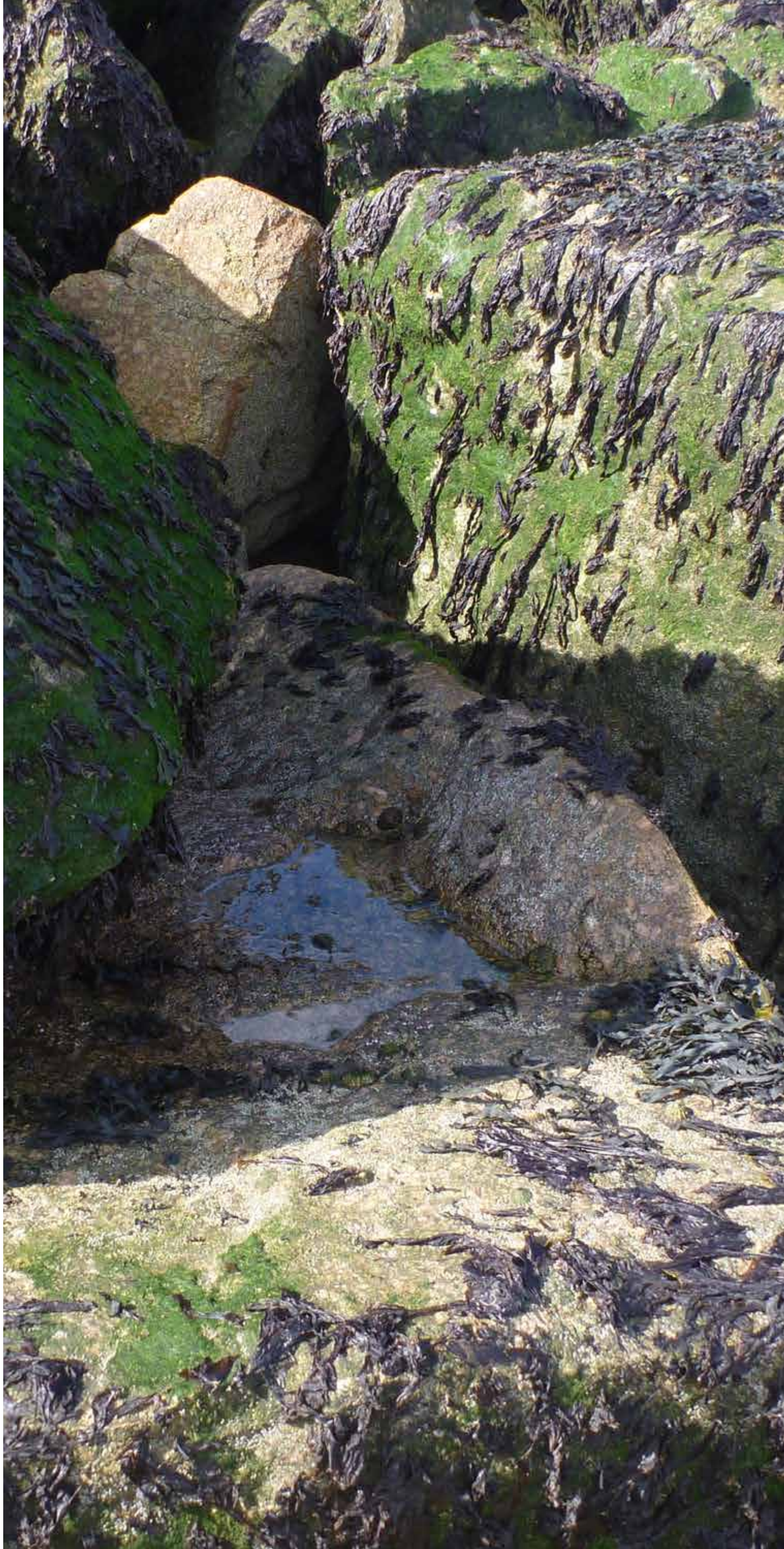
The University of Glasgow provided biogeomorphology guidance on the most ecologically optimal granite: the lightest granite with the coarsest grain and the greatest number of decimeter-to-meter scale features, such as concavities and ledges. The project team used limestone to fill the void spaces in the granite, but the natural limestone along the rocky shore itself was far too difficult and expensive to procure. Instead, the team locally sourced a darker limestone, increasing the long-term ecosystem potential by providing a boreable material for micro- and macroboring species such as cyanobacteria and limpets.

Using Natural Processes

The team maximized available habitat space by carefully selecting, orienting, and modifying topographically complex rocks to mimic natural rocky shore geomorphology. During construction, the project team trained the lead installer to identify features such as depressions, concavities, and ledges that increased the complexity and water-holding capacity of natural rock boulders. Installing the rocks with depressions that faced sufficiently upwards and horizontal trapped water during low tide, which mimicked natural pools. Placing the rocks to create overhangs established shelter from the sun or waves. These measures improved the habitat value of the revetment rocks, increasing limpet abundance compared to nearby rocks without these features.

Previous page: Positioning rocks to use geomorphic features as habitat. (Photo by Larissa Naylor, University of Glasgow)

Right: Passive positioning of rock armor to create a pool and overhang. (Photo by Larissa Naylor, University of Glasgow)



Broadening Benefits

Changes made to the conventional design broadened the revetment's engineering and environmental benefits. The flattened top and strengthened base make it more adaptable and better able to withstand future sea-level rise and climate-change pressures since future rock layers can be added to address these challenges. The various enhancements to the rock revetment created no significant increase in construction or long-term costs while increasing the ecological value of the conventional scheme, adding habitat for intertidal prey species and encouraging biodiversity in an internationally designated bird habitat.

Promoting Collaboration

Altering the original design to include passive ecological enhancement was pivotal to securing time-limited funding for the engineering scheme, a grant-in-aid for flood defense through the UK government's Environment Agency. A team spanning many sectors worked together to design the installation, combining the expertise of Mott MacDonald, the University of Glasgow, the Hartlepool Borough Council, PD Ports, Hall Construction, and Poundfield Products. Further, the Hartlepool Council and PD Ports provided additional funding to the scheme. The support and collaboration resulted in multiple construction excellence awards, including for innovation, value, and sustainability.

*Top and middle: Oystercatchers (*Haematopus ostralegus*), who feed on limpets (*Patella vulgata*), visiting the project area. (Photos by Damian Mooney)*

Bottom: Scheme during construction showing newly colonizing enhanced rocks. (Photo by Hartlepool Borough Council)

Regulating Works

Middle Mississippi River, Missouri and Illinois, United States

Designing innovative river-training structures to achieve multiple benefits. The U.S. Army Corps of Engineers (USACE)–St. Louis District has a congressional mandate to maintain a safe and dependable navigation channel 2.7 meters deep and 91.4 meters wide, with more provided in bends, between the Mississippi River's confluence with the Missouri River north of St. Louis, Missouri, and its confluence with the Ohio River at Cairo, Illinois. The district achieves this mandate through a combination of river-training structures, revetments, and removing rock obstructions from the bottom of the channel. By combining stakeholder feedback with numerical and physical modeling in an iterative design development framework, the St. Louis District has designed and constructed many innovative dike and revetment projects that ensure a sustainable navigation channel while maximizing social and economic benefits and creating diverse natural habitat. They successfully collaborated with local stakeholders for their project designs, ensuring understanding and agreement in the surrounding community, a process for which the physical models proved especially effective. The end result is a navigation channel sustained by river-training structures that provide additional value beyond conventional structures.

Producing Efficiencies

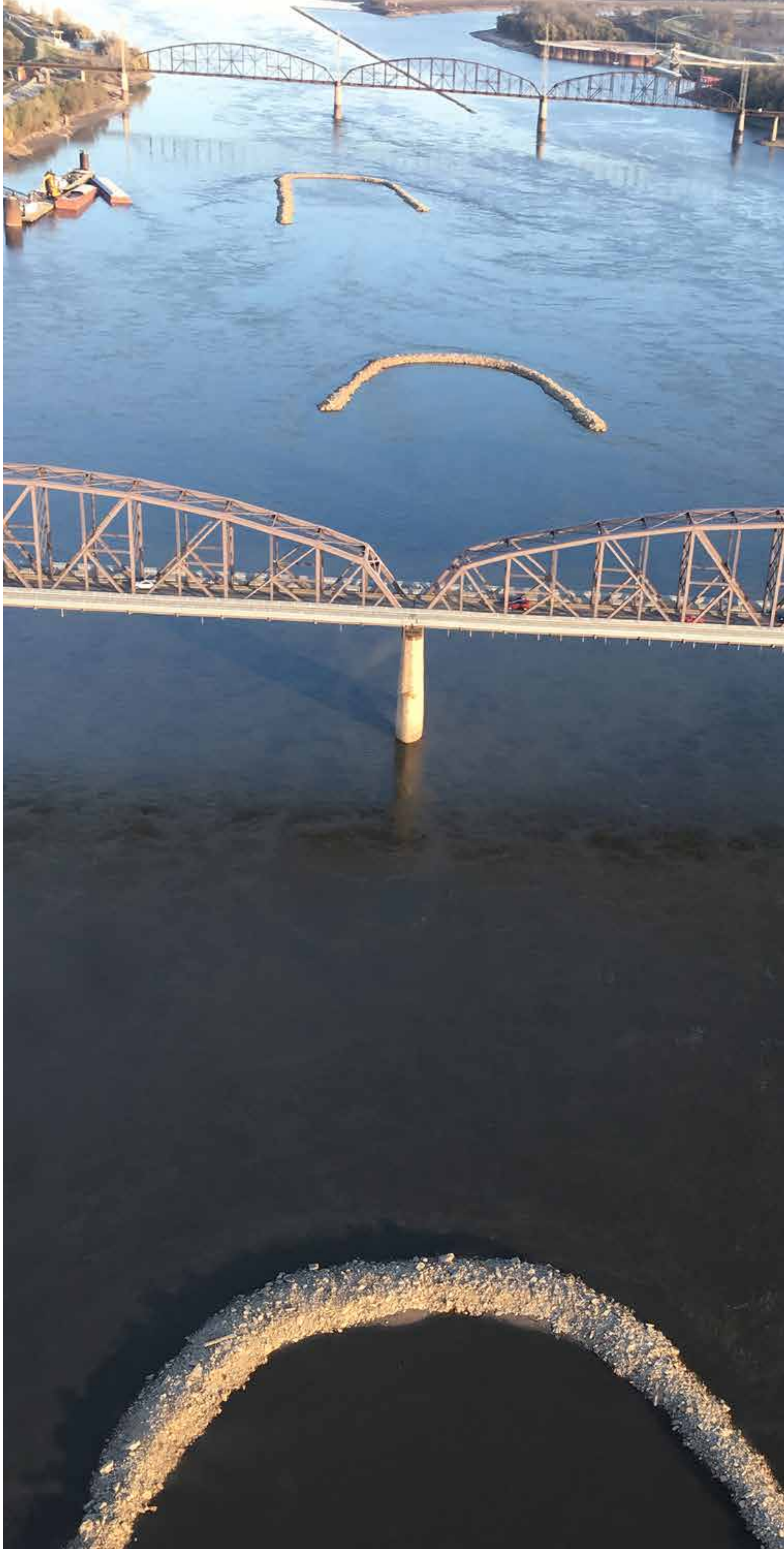
For many of the innovative structures constructed on the Middle Mississippi River, the district used an iterative design process that combined river engineering with stakeholder feedback. The team then tested these joint alternatives with a combination of numerical and physical models. Model testing allowed design enhancements to maximum social, economic, and environmental benefits and prevented costly real-world installation mistakes. Models and field data analysis also ensured that there were no unintended adverse consequences of the project. Because of this, the cost-efficient process avoided unforeseen outcomes that would have disrupted commerce and recreation along the river.

Using Natural Processes

River-training structures increase channel constriction and redirect flow to increase a sand-and-gravel riverbed's natural tendency to self-scour, providing additional depth to maintain navigation at low stages. The unconventional river-training structure designs introduce additional geometric complexity to increase connectivity, induce additional scour, or redirect more flow in beneficial ways. A chevron, for example, concentrates overtop flow to scour a plunge pool, leading to deposition downstream that sometimes results in an ephemeral island. Likewise, stone mounds maintain the upstream-to-downstream connectivity for fish passage, unlike traditional dikes, while promoting scour and thus vertical bed diversity around each mound.

Previous page: A dike and roundpoint structure along the left bank at mile 4.0. (Photo by Dawn Lamm, USACE St. Louis District)

Right: Three chevrons downstream of the Chain of Rocks canal entrance. (Photo by Dawn Lamm, USACE St. Louis District)



Broadening Benefits

The naturally river-scouring features the district installed saved thousands in taxpayer dollars by reducing the need for periodic dredging of the channel. The installed features also preserve or enhance critical side-channel habitat and created diverse, all-new habitat, important for the rivers' communities of fish and benthic invertebrates. For example, the chevrons in the St. Louis Harbor substantially reduced dredging needs; increased reliable port access; and created an abundance of habitat, including deep slack water, ephemeral sandbars, and a secondary channel. The structure designs further achieve the district's goal of maintaining the waterway while enhancing biodiversity in the region.

Promoting Collaboration

The district's success is largely due to efforts to engage with local partners and stakeholders. In addition to project-specific outreach, the Regulating Works Project organizes a regular coordination trip by boat down the Middle Mississippi. This is a chance for river engineers, environmental regulators, and concerned stakeholders to meet, to provide interdisciplinary project updates, and to communicate about the wider needs for river management. These meetings result in new ideas for additional river-training structures, identify potential project sites, and promote a better general understanding of viewpoints by developing relationships.

Top: Looking downstream at the vegetated mile 100 islands. (Photo by Dawn Lamm, USACE St. Louis District)

Bottom: Z dikes installed from miles 68.1 to 67.1. (Photo by Dawn Lamm, USACE St. Louis District)

Emiquon

Havana, Illinois, United States

Installing a gravity-fed water control system for wetland restoration and flood prevention. In the early 1900s, the Illinois River formed one of North America's most ecologically and economically significant river systems, supporting the most productive inland commercial fishery and highest mussel abundance per kilometer of any stream on the continent. However, the land on and around what is today The Nature Conservancy's Emiquon Preserve was drained and converted for agriculture, denying this wetland its water, while the flood control pumps prevented access for aquatic species. A record flood in 2013 presented an opportunity: it left Emiquon without water management capabilities. So, the project team built a new connection between the floodplain and the Emiquon Preserve. This new water management structure, named *Ahsapa*, meaning *web* in Myaamian to honor one of the earlier cultures inhabiting the preserve lands, can use gravity to control flow between the wetland and the river, managing flood threat and restoring river-floodplain connectivity for over 2,700 hectares. These newly restored cyclical water flows will reestablish and sustain one of the highest-quality floodplain complexes in the region, which will encourage healthy fish and wildlife communities throughout the system.

Producing Efficiencies

The Ahsapa structure combined three features into one structure, making monitoring and future maintenance easier and more cost effective. The gated, concrete pathway through the levee will open or close to control the flow of water between the wetland and the river. Pumps will remove water from the preserve when the river is too high for gravity drainage. And the facility includes scientific instruments, nets, and other devices to monitor and possibly restrict the sizes or types of organisms moving through the gates when they are open. This could prevent undesirable, non-native invasive species from passing while allowing multiple routes for other fish.

Using Natural Processes

Depending on the water level differences between Emiquon and the Illinois River, opening gates allows water to flow into or out of Emiquon as needed using only natural gravitational forces. This reduces, and in day-to-day flow eliminates, the need for pumps to move the water, reducing Ahsapa's energy usage and carbon footprint. Because the structure will be restoring a more natural hydrology to the wetland complex, a wide variety of plant and animal communities will benefit, including submergent and emergent plants.

Previous page: Emiquon's water management structure reconnects the preserve to the Illinois River, attracting a wide variety of wildlife, such as these great egrets (Ardea alba). *(Photo by Laura Stoecker Photography LTD)*

Right: The structure facilitates the restoration of a more natural hydrology that is essential for restoring and sustaining the diversity of wetland habitats and the many benefits they provide. (Photo by Doug Blodgett, The Nature Conservancy)

Broadening Benefits

The Ahsapa water management structure will help drain neighboring agricultural lands and protect nearby infrastructure, such as levees and roadways. It will reinstate a more natural rise and fall of the annual water cycle that occurred before the draining of the floodplain almost a century ago. The connection between Emiquon and the Illinois River benefits the agricultural sector, the transportation sector, and the environmental sector, balancing the needs of all three. Further, the water's movement now provides more stable water levels during the summer growing season.

Promoting Collaboration

At Emiquon, The Nature Conservancy partnered with the Illinois Natural History Survey, the University of Illinois, and its own staff and trustees, some of whom have lifelong experience working on the Illinois River. The design and construction of Ahsapa itself would not have been possible without Maurer-Stutz Inc. and Laverdiere Construction Inc. Overall, project's success is a result of this collaboration between the nature preserve, other nonprofit organizations, the university, and the private sector; and research gained will be available to other floodplain scientists and managers throughout the Upper Mississippi River and around the world

Top: The new structure provides a managed connection between the restored floodplain complex of the Emiquon Preserve (upper right) and the Illinois River (lower left). (Photo by Doug Blodgett, The Nature Conservancy)

Middle: Conservancy staffer explaining the multiple functions of the structure to two of the forty thousand visitors who visit the Emiquon Preserve annually. (Photo by Laura Stoecker Photography LTD)

Bottom: Water flowing through the structure and into Emiquon (foreground) from the Illinois River(background) provides fish access for spawning, feeding, and wintering. (Photo by Doug Blodgett, The Nature Conservancy)

Lower Yellowstone River Fish Passage

Dawson County, Montana, United States

Promoting and protecting pallid sturgeon migration by expanding river access. The Lower Yellowstone Irrigation District provides irrigation water to over 23,000 hectares of land. However, the diversion dam on the Lower Yellowstone River impeded upstream migration of pallid sturgeon (*Scaphirhynchus albus*), an endangered species, and other native fish for over 100 years. As part of a Bureau of Reclamation project, the U.S. Army Corps of Engineers (USACE)–Omaha District built a new headworks, weir, and fish bypass channel as a way to provide access to as many as 266 additional kilometers of the Yellowstone River for pallid sturgeon migration, spawning, and larval development. The headworks has 12 cylindrical screens to prevent fish entrainment in the irrigation channel, and the screens can be raised when not in use and during maintenance. The screens are self-cleaning, since the design includes brushes that clean the screens as they rotate. The bypass channel runs for 3,398 meters from the upper end of the existing channel to just downstream of the weir on the south side of the river. A replacement concrete weir will sit just upstream of the existing one and provide sufficient water surface elevation to maintain irrigation diversions through the headworks. Through its efforts, the project contributes to the recovery of pallid sturgeon.

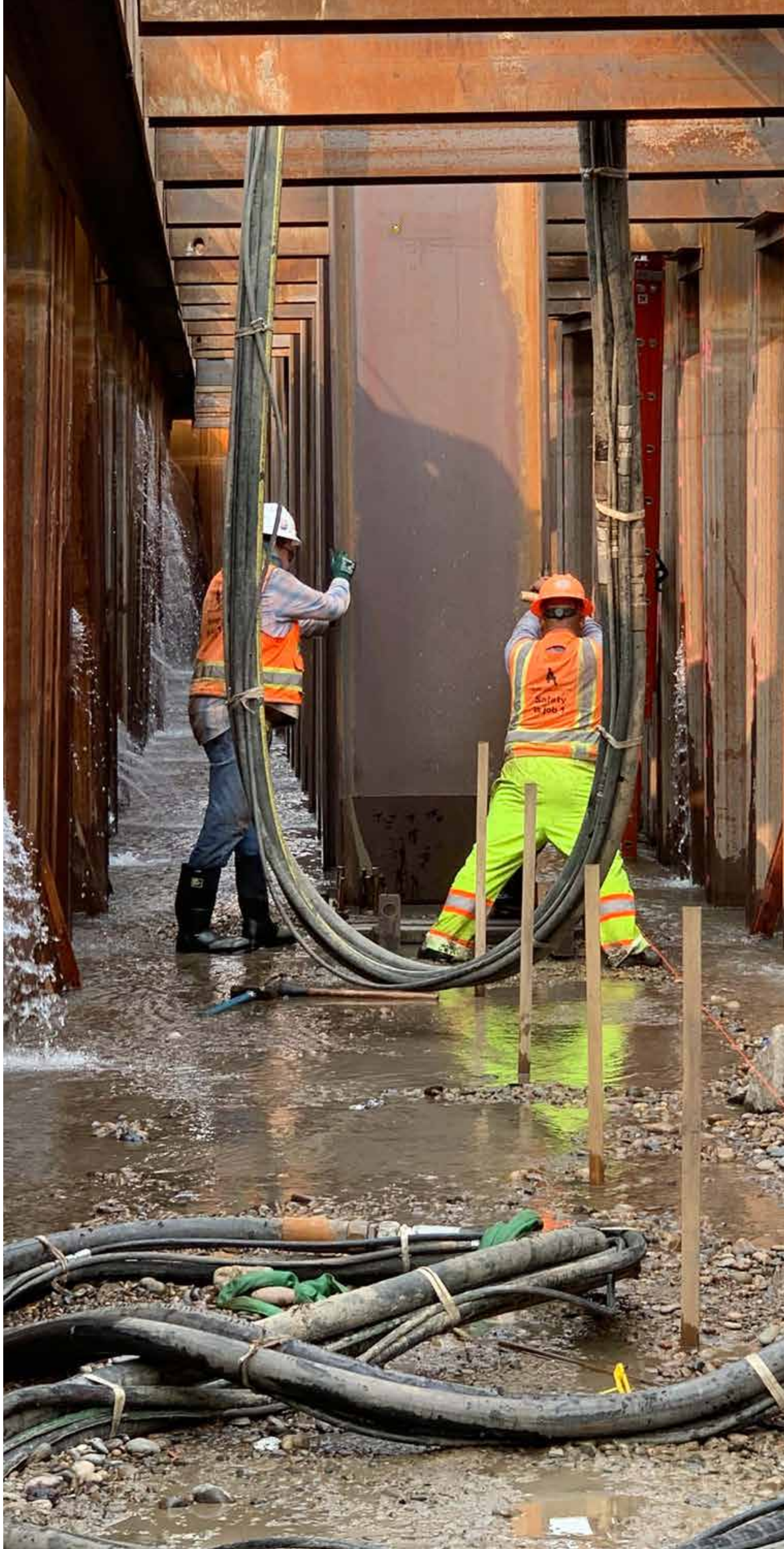
Producing Efficiencies

The irrigation project used all-new technology, incorporating cylindrical screens that reduce the negative impacts on pallid sturgeon and other native fish. The project team used hydraulic models to determine crop consumptive use requirements and to evaluate which option best met the design criteria for the fish passage. These models also ensured enough water flowed through the bypass channel to allow fish to pass while still maintaining adequate flow conditions for irrigation requirements. The bypass channel and downstream face of the weir reused cobbles excavated as part of construction, taking advantage of the locally available materials.

Using Natural Processes

Radio tracking of telemetered wild adult pallid sturgeon indicate that during their upstream migrations, they can and will use side channels. The project team designed the Lower Yellowstone bypass channel with slopes, substrates, depths, and velocities similar to natural side channels used by pallid sturgeon, maximizing the likelihood that pallid sturgeon will use it. The entrance of the bypass channel is also immediately downstream of the rock field below the weir to maximize the potential for upstream migrating pallid sturgeon to find the bypass channel.

Previous page: Looking upstream during construction of the south half of the new irrigation weir, September 2020. The bypass channel is nearly completed and will be opened after construction of the weir is complete. The historic rocking tower will be relocated on the property. The old and new headworks structures are visible on the right. (Photo by Ames Construction Inc.)



Right: Interior of the temporary cofferdam prior to placement of the south half of the new concrete weir. Workers are ensuring correct alignment of piling used to anchor the weir into the bed of the river, September 2020. (Photo by Al Steiner, U.S. Bureau of Reclamation)

Broadening Benefits

Game fish in the lower Yellowstone River include paddlefish (*Polyodon spathula*) and the threatened shovelnose sturgeon (*Scaphirhynchus platorhynchus*). The most popular game fish is the paddlefish, with nearly half of the annual visits to the site occurring during the paddlefish season in May and June. Paddlefish congregate on the downstream side of the dam, presenting an accessible location for paddlefish snagging. Increasing the number of traversable feet of the Yellowstone River for native fish will increase the local populations of game fish and improve the surrounding habitat, creating an additional opportunity for local revenue.

Promoting Collaboration

USACE worked with the Bureau of Reclamation to complete the environmental impact statement. The two agencies then teamed up with the Montana Department of Fish, Wildlife, and Parks; the Montana Department of Natural Resources and Conservation; the Lower Yellowstone Irrigation Project Board of Control, the Fish and Wildlife Service, and the Western Area Power Administration, who provided expertise and local knowledge to ensure the project was a success. Further, a team of pallid sturgeon experts established design criteria to assist with the project and provided input throughout construction.

Top: Cylindrical screens reduce the intake velocity and prevent fish entrainment into the canal when water is diverted for irrigation. The screens rotate, and debris is removed using brushes on the inside of the cylinder. (Photo by Al Steiner, U.S. Bureau of Reclamation)

Middle: New headworks from the land side in 2014. (Photo by USACE Omaha District)

Bottom: Installation of wooden beams near the south abutment, circa 1908. (Photo provided by USACE Omaha District)

Matarandiba Island

Matarandiba Island, Bahia, Brazil

Using a nature-based solution for ensuring safe working conditions. The small island of Matarandiba lies just off the coast of Aratu, Brazil. Here in 2010, Dow cut back an existing hillside to provide access for operations personnel, but unfortunately significant rains and natural erosion resulted in obstructions and unstable and unsafe working conditions for construction contractors at the site. So in 2017, Dow considered three project plans to stabilize the hillside. The first option included blasting and heavy earthmoving equipment to completely remove the slope. The second, and most conventional option, was to drill and install mechanical anchors in the aggregate substrate to serve as tie backs for a steel-reinforced, sloped concrete overlay. The third, and least invasive option, involved constructing a gabion wall at the toe of the slope in conjunction with reestablishing a native vegetative cover to stabilize the upper portion of the slope. Of the three, Dow selected the third option because it minimized environmental impact and cost while maximizing restorative features.

Producing Efficiencies

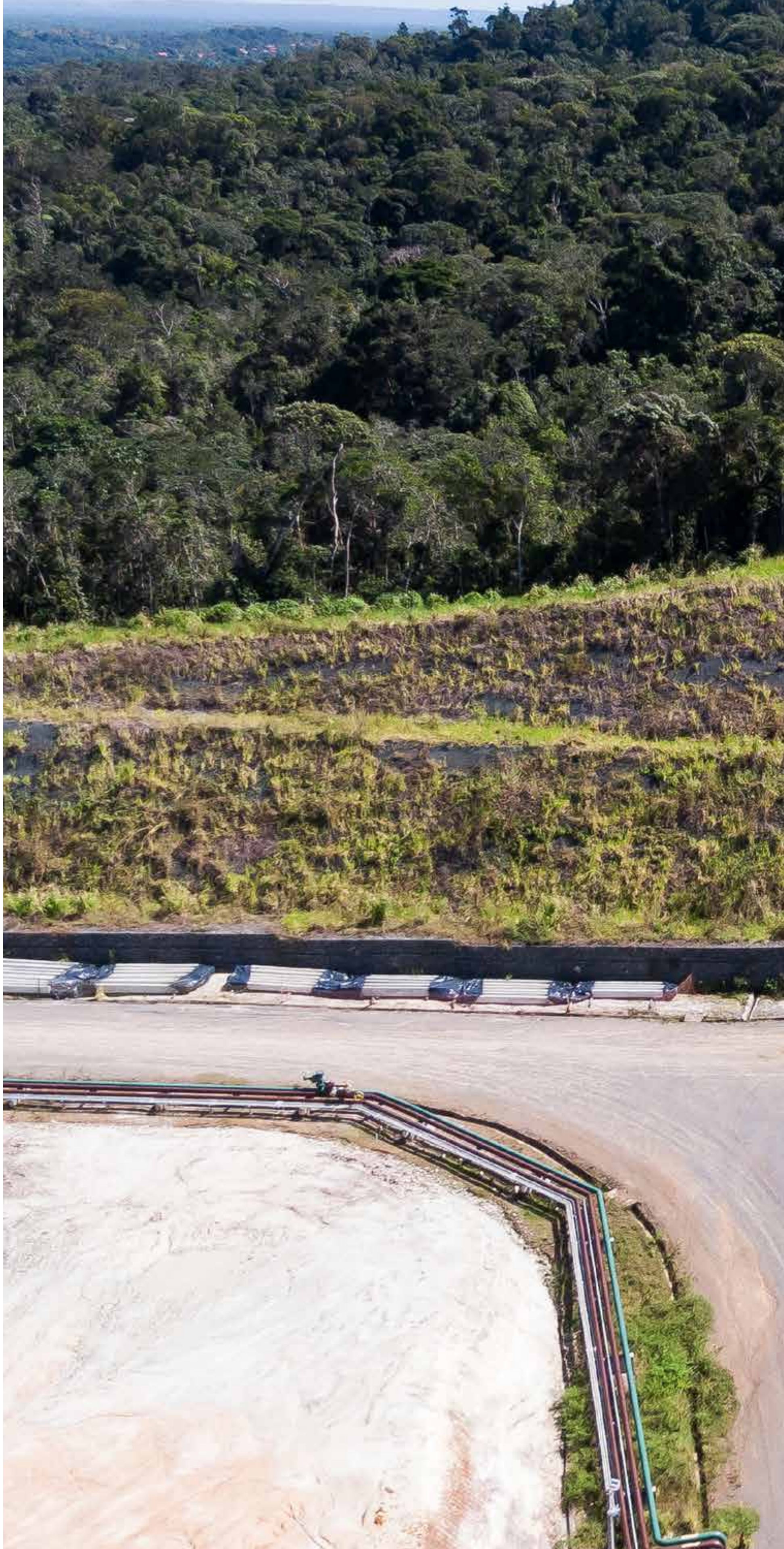
Dow's engineering consultants undertook geotechnical field studies and slope stability analyses to design the combined gabion wall and vegetative cover. They needed to address the challenge of optimizing the existing hill slope and determining the suitability of existing materials for establishing vegetation. To ensure uptake of vegetation, the project team adjusted the pH of surficial soils and added a layer of natural organic material with cellulose along the exposed face of the hillside. Finally, the team installed a geosynthetic mesh to reinforce the vegetative surface cover.

Using Natural Processes

Gravity serves as the main mechanism for stabilizing the base of the slope while the reinforcement of native vegetative root system stabilizes the upper half of the slope. When compared to removing the hillside entirely to alleviate the erosion and hazardous working conditions, allowing vegetation to stabilize the slope restored more native habitat and naturally reduces the amount of rainwater runoff.

Previous page: Aerial view of hillside in 2020. (Photo by Dow)

Right: Stabilized hillside with native forest beyond. (Photo by Dow)



Broadening Benefits

The gabion wall and vegetative cover solution reduced the need for major earthworks, lowering the carbon emissions for the project by 90% and the cost of the project by $1 million. Overall, this solution had the least impact on the local ecosystem. By installing the gabion wall and vegetative cover, the project team reduced the project's footprint from a potential 4 hectares for complete hillside removal to only 0.2 hectares. The result is a restored and stabilized hillside that serves as a nature-based transition to the native forest beyond.

Top: Gabion walls and geosynthetic mesh for vegetative reinforcement during construction. (Photo by Dow)

Bottom: Stabilized hillside at transition to native forest. (Photo by Dow)

Promoting Collaboration

By demonstrating the efficacy of a nature-based solution for the hillside erosion problem on Matarandiba Island, Dow's project team provided the Brazilian government with a successful case study for environmental restoration and remediation. And because the team demonstrated to the Brazilian government the clear economic and ecological benefits of the gabion wall and vegetative cover solution, the approval and permitting process proceeded much more smoothly than had the team used a more traditional mitigation method.

Cypress Reforestation

Montegut, Louisiana, United States

Increasing coastal resiliency by restoring natural wetland systems and surface flows. The vulnerable coastal region of Louisiana represents about 40% of the wetlands in the continental United States—and approximately 80% of the nation's wetland loss. Sea level rise, increased storm surge, extreme weather events, and subsidence have all contributed to this land loss and habitat vulnerability; and they are projected to increase over the next 50 years. To combat this loss, the Restore the Earth Foundation, along with local stakeholders and funding partners such as Dow, have restored 1,600 hectares of critical bald cypress (*Taxodium distichum*) forest at Pointe-aux-Chenes Wildlife Management Area, east of Montegut, Louisiana. The project team also retrofitted an existing pump to divert 40–50 billion liters of fresh water per year into the wetland planting site. This large-scale wetland ecosystem restoration project will help protect local communities in Louisiana from future storm surges and related damages, which in turn reduces economic recovery costs while increasing resilience along the Gulf Coast. Using its EcoMetrics Tool, Restore the Earth was able to further quantify the environmental, social, and economic value the project created, translating that into monetary terms to demonstrate the project's return on investment and social return on investment.

Producing Efficiencies

Given the complex nature of the site—the wildlife management area is protected by an integrated system that includes a parish levee, water control structures, and a federal Hurricane Protection Levee System—the design of the project required careful and strategic planning. The team sought input from local and national experts and existing risk assessments, projections, and state coastal restoration plans before proceeding with implementation. The end result is a landscape-scale project with proven beneficial outcomes.

Using Natural Processes

Once complete, the freshwater diversion will provide 40–50 billion liters per year of freshwater replenishment into the wetland complex. This diversion will reduce salinities in the wetland unit, promoting more vigorous plant production, including submerged aquatic vegetation. The newly planted bald cypress trees will provide habitat needed to support the area's native fish, bird, and wildlife species native to the area. The regular influx of freshwater will also enhance the land-building capacity of the reforestation activities—the Natural Resources Conservation Service estimates the diversion will benefit 800 hectares of marsh.

Previous page: Newly planted native bald cypress seedlings. (Photo by Restore the Earth Foundation)

Top: Healthy bald cypress seedling. (Photo by Restore the Earth Foundation)

Bottom: Native EKOgrown bald cypress trees, grown from seeds collected in the region. (Photo by Restore the Earth Foundation)

Broadening Benefits

The cypress reforestation project will reduce exposure to storm surge by creating marshlands and forested wetlands inside the existing levee protection systems. Neighboring communities will see improved water quality, increased storm protection, and reduced flooding. The project team will monitor the site for water, air quality, and other improvements. Restore the Earth, using EcoMetrics, quantifies in monetary terms the value created by these improvements. They will also register carbon emission reductions with the Climate Action Reserve's Climate Forward Program registry, further demonstrating the broad benefits of coastal wetland restoration.

Promoting Collaboration

The collaboration of local, state, and national experts in conjunction with guidance from Louisiana State's Coastal Master Plan and funding through Dow's Carbon Partnership with the International Olympic Committee and other corporate funders made this project possible. The EcoMetrics Tool was crucial in securing stakeholder and funder engagement. It provided a "business case" for investment in ecosystems restoration, demonstrating that every $1 invested in the restoration project creates $14 in environmental, social, and economic value. These quantifiable outcomes helped the team communicate the value of the project to a broad spectrum of stakeholders.

Top: Before freshwater restoration. (Photo by Restore the Earth Foundation)

Middle: After freshwater diversion, the presence of transitional grasses sets the stage for tree planting. (Photo by Restore the Earth Foundation)

Bottom: Dow volunteers planting over 1,000 native bald cypress trees. (Photo by Restore the Earth Foundation)

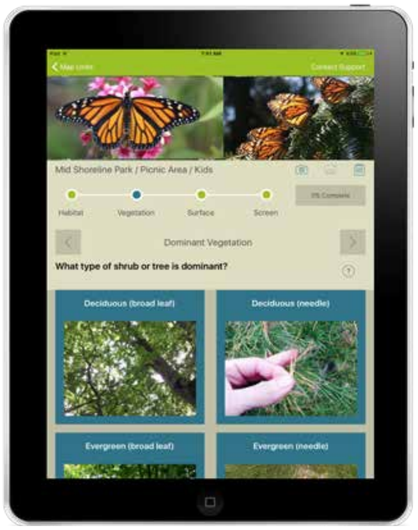
Project Enablers

Tools for Implementing EWN

Ecosystem Services Identification and Inventory

Dow, The Nature Conservancy, and EcoMetrix Solutions Group

Analyzing land-use changes by quantifying ecosystem services impacts. The Ecosystem Services Identification and Inventory (ESII) tool provides users a greater understanding of the benefits they receive from nature and informs decisions to protect, restore, or monitor specific natural assets. It can advise a broad spectrum of stakeholders (including nonecologists) as they make decisions on various land-use alternatives with corresponding quantified ecosystem services. The tool is a free application available online and as an iPad-based app. With the tool, users first map project sites, defining areas where data collection will occur, and run ecosystem function and service models on these areas. Next, users collect data through an image-driven data sheet. After running the models, users can query the results in several formats, including tabular data, graphic representations of the data, and spatially explicit heat maps. Understanding how various designs impact the ecological performance of a piece of land helps drive adoption of nature-based solutions. As in the project on page 44, Dow has incorporated the ESII tool into its land management strategy.



Top: Mercy Corps' Transform Project, Watershed Stormwater Analysis, Semarang, Indonesia. (Photo by Morgan Erhardt, EcoMetrix Solutions Group)

Left: Riparian buffer and bank erosion control analysis, Lake Jackson, Texas. (Photo by Jen Molnar, The Nature Conservancy)

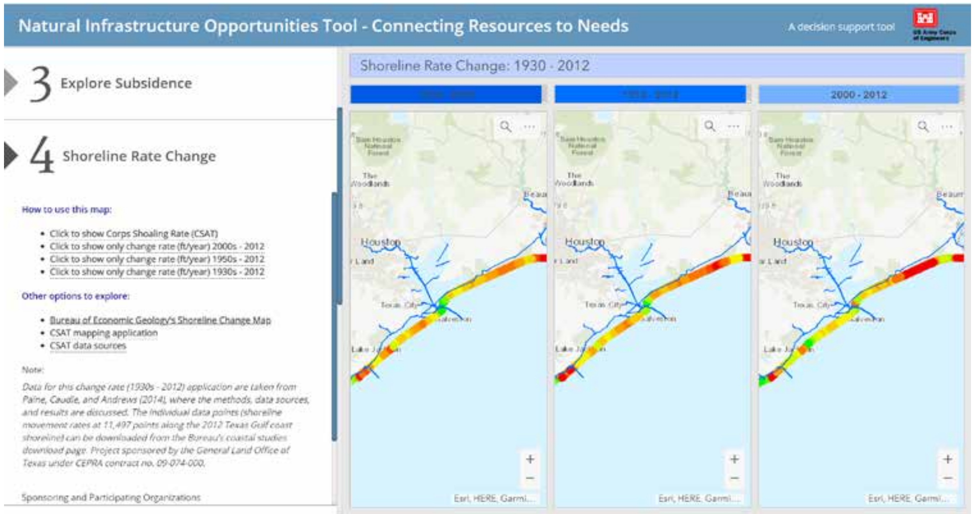
Right: People of any skill level, from experts to those with limited ecological background and training, can use the ESII Field App to collect site-specific data. It runs on an iPad and includes lots of help to support novice data collectors. (Image provided by France Guertin, Dow)

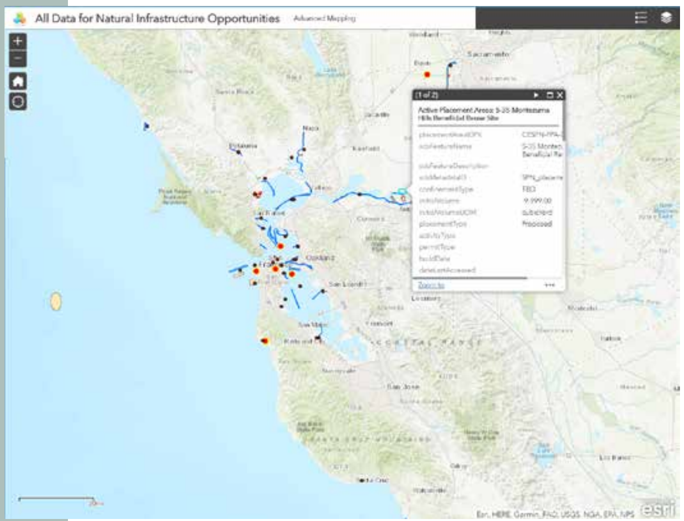
ESII tool

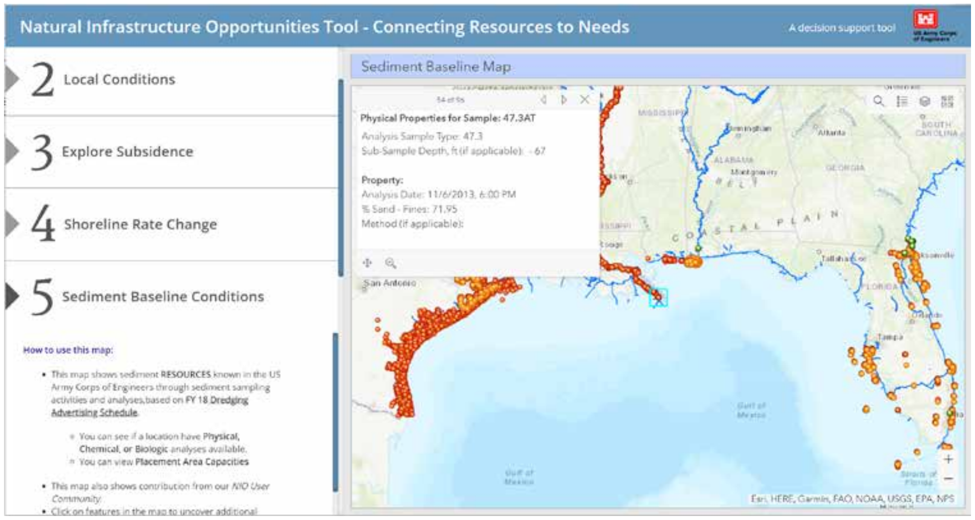
Natural Infrastructure Opportunities Tool

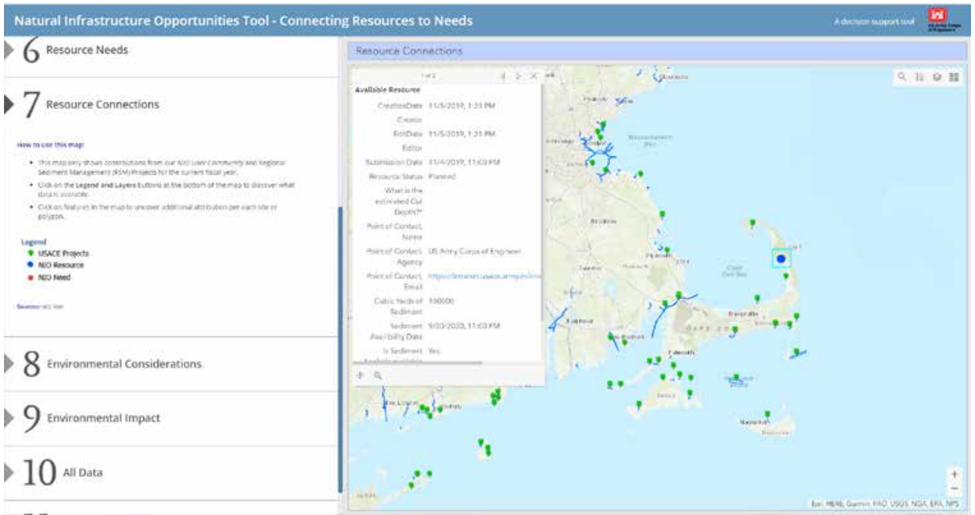
Caterpillar, The Nature Conservancy, Great Lakes Dredge and Dock, AECOM, U.S. Army Engineer Research and Development Center, and U.S. Army Corps of Engineers–Mobile District

Mapping to promote collaborative planning of natural infrastructure. Developed through an iterative collaboration and released in August 2019, the Natural Infrastructure Opportunities Tool (NIOT) focuses on identifying natural infrastructure and beneficial use opportunities through map-based visualizations of environmental, geomorphic, sediment, and upcoming U.S. Army Corps of Engineers (USACE) projects data layers. This portal highlights natural infrastructure connections to inspire opportunities for collaboration and innovation. Within the portal, users can add their own resource needs, highlight available resources, and find mutually beneficial strategies for the creation of natural infrastructure. Best used in the planning stages of a project to generate new ideas about natural infrastructure projects, the NIOT presents multiple data sets in one easy-to-use place. The tool displays data describing local conditions such as shoaling rates, shoreline change, geomorphic and dune features, hurricane tracks, sediment budgets, and subsidence. In addition to local and baseline data layers pulled from sources such as the National Oceanic and Atmospheric Administration, the NIOT allows users to identify current infrastructure projects and directly add resource or project needs. Resource connections, including points of contact, then appear on the map. All that remains is for users to start planning their own natural infrastructure innovations.







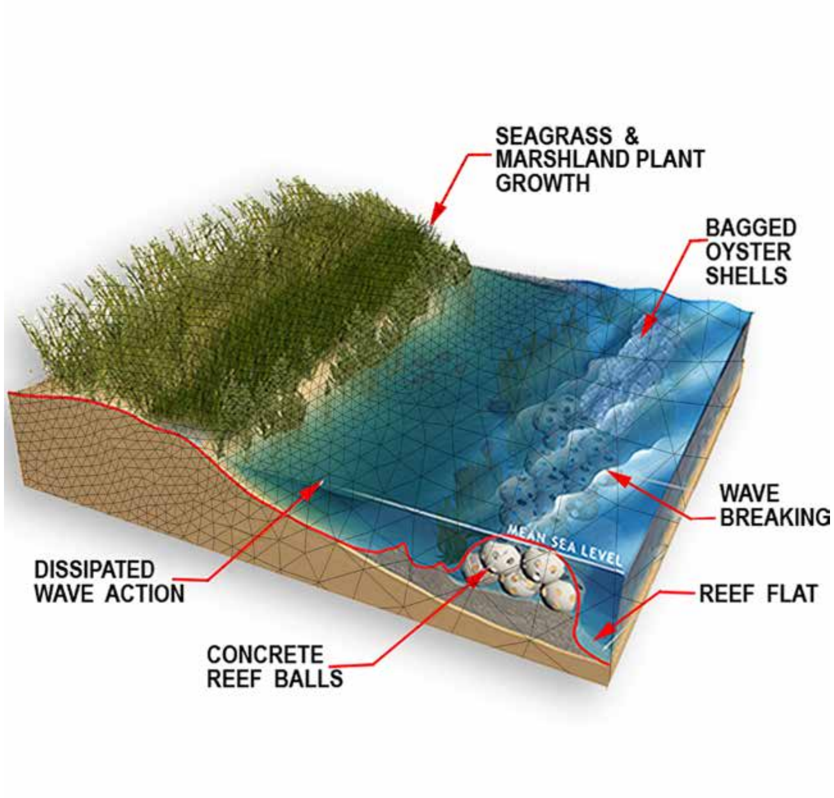


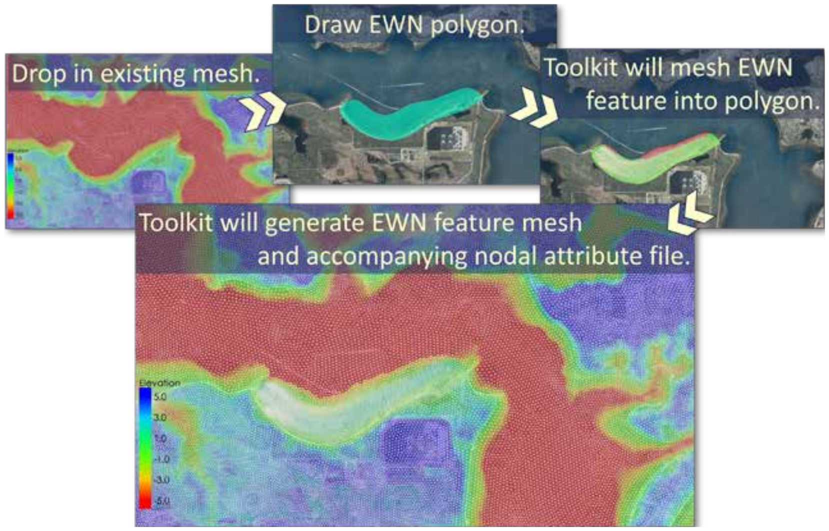
Examples of data provided by the Natural Infrastructure Opportunities Tool (clockwise from top left): The welcome page provides information on how the NIOT works and how to become a contributor; 80 years of shoreline change-rate data; sediment baseline conditions include physical, chemical, and biological sediment data as presented by the NIO User Community; the resource connections includes USACE projects, NIO resources, and NIO needs; and exploring multiple data layers in San Francisco Bay, California (images provided by Safra Altman, U.S. Army Engineer Research and Development Center).

Coastal Storm Modeling System

U.S. Army Engineer Research and Development Center

Integrating physics-based models to create realistic coastal storm risk assessments. Accurate coastal flood risk quantifications saves millions of dollars in construction costs for new structures, but creating those accurate assessments requires robust, sophisticated numerical models integrated into complex statistical frameworks. The U.S. Army Engineer Research and Development Center (ERDC) Coastal Storm Modeling System (CSTORM) provides a state-of-the art standardized approach to high-fidelity coastal storm modeling. The CSTORM modeling system combines physics-based numerical models with an efficient workflow and the ability to analyze risk to coastal communities from storms both now and under future sea level rises. With the toolkit, users can interactively design and add natural and nature-based features (NNBF) to the CSTORM models and quickly manipulate multiple aspects of their design. The workflow is based on ten years of successful CSTORM case studies, and the toolkit's recommended model parameter settings for EWN features are taken from extensive literature review sources. With the higher accuracy results from the CSTORM modeling workflow and the powerful and efficient new capabilities of the EWN Toolkit, engineers and researchers can innovate and confidently assess coastal and riverine resilience design work.



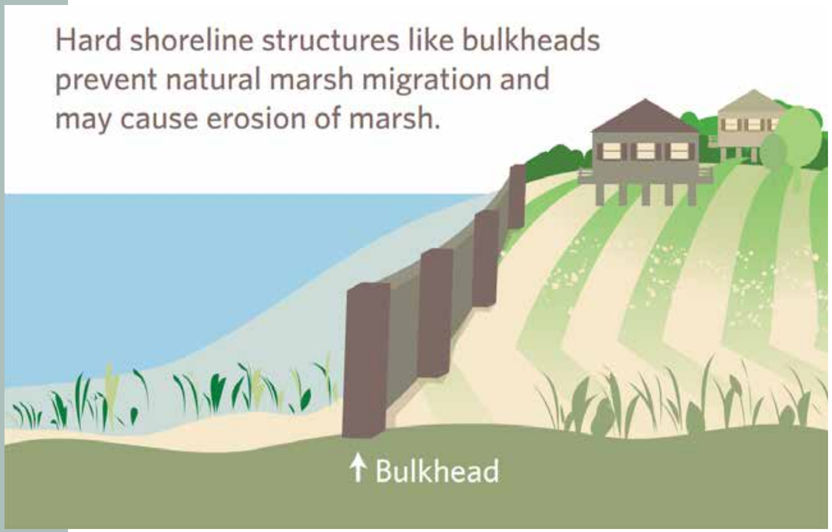


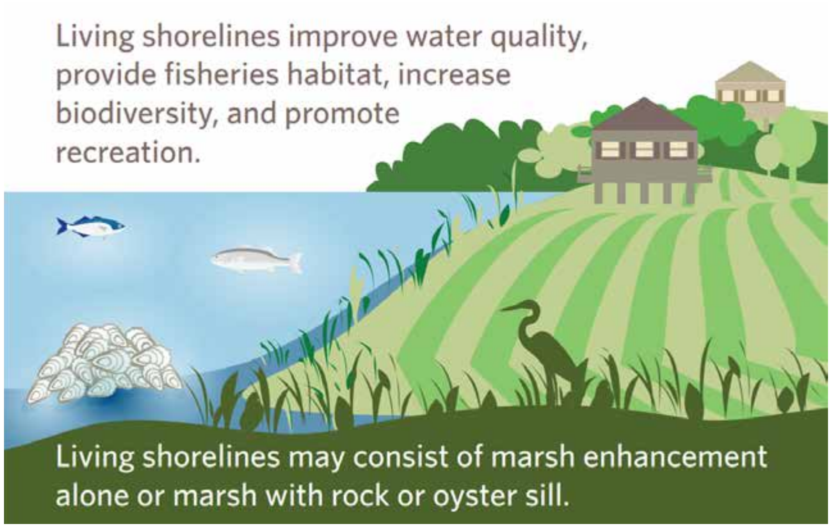
Clockwise from top right: CSTORM reduces uncertainties surrounding a coastal storm's impacts on existing and proposed flood-reduction systems, including natural and nature-based feature (NNBF) projects (image by Chris Massey, ERDC); the EWN CSTORM toolkit streamlines and standardizes the hydrodynamic modeling process for NNBF (image by Chris Massey, ERDC); a vegetated beach with naturally occurring submerged rock breakwater near Simonstown, South Africa (photo by Chris Massey, ERDC); and a stone reinforced shoreline with partially submerged rock breakwater near San Juan, Puerto Rico (photo by Chris Massey, ERDC).

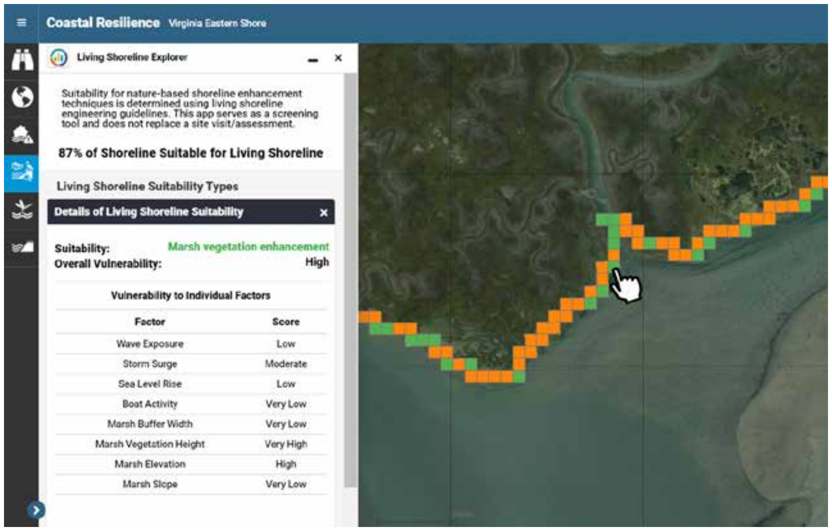
Coastal Resilience and Natural Solutions Toolkits

The Nature Conservancy

Identifying nature-based solutions for coastal communities. To help community planners and decision makers implement projects for hazard mitigation, climate adaptation, and conservation planning, The Nature Conservancy created the Coastal Resilience tool. Developed in 2007 through a public-private partnership, the tool supports the planning process for flood-risk reduction projects with natural and nature-based features. After more than a decade of success, the conservancy used the tool to create the new Natural Solutions Toolkit, or NST: a suite of web-mapping decision support tools for conservation and climate adaptation across marine, freshwater-floodplain, and urban environments spanning from local to global scales. With a portfolio of 100 custom applications across 26 geographies, the NST allows a diverse user base to visualize and assess climate hazards alongside social, economic, and ecological assets. Already, the NST has guided the implementation of more than two dozen restoration and conservation projects around the world—more than 100 communities, public agencies, and stakeholders across 11 countries. From coral reefs in the Caribbean to nature-based solutions in New Jersey, the NST provides a decision-making support system for coasts, oceans, floodplains, and urban environments.







Clockwise from top: The concept of living shorelines explained (image by The Nature Conservancy); the Living Shoreline Explorer web application is part of the Coastal Resilience–Virginia Eastern Shore decision-support platform, which helps planners identify and prioritize where nature-based shoreline enhancement techniques might help reduce coastal marsh loss and sediment erosion (image by The Nature Conservancy); volunteers building oyster castles as part of a living shoreline project in coastal Virginia (photo by Gwynn Crichton, The Nature Conservancy); and planners in Virginia use the Coastal Resilience decision support tool to better understand their community's risk and identify nature-based solutions to reduce that risk and make them more resilient to future climate change (photo by Gwynn Crichton, The Nature Conservancy).

COASTAL RESILIENCE

The newly graded slope at Meadowview created more-suitable edge habitat for wildlife to congregate in the transitions between riparian and upland environments, September 2018 (project details on page 160). (Photo by Teri Biancardi)

Conclusion

Recognizing EWN opportunities and encouraging action

Making the Future

One generation plants a tree; another gets the shade.
—Chinese proverb

The achievements of engineering over the last 100 years are awesome to consider. In fact, these achievements are integral to the foundation of modern civilization. In view of these contributions, what value can engineering produce over the next 100 years? Better still, what expanded value can human engineering create in a partnership with nature?

Innovation is the product of intention. To be sure, some discoveries have occurred by accident, and some advancements have occurred through serendipity. However, in most cases, transforming matured practice requires the energy supplied by deliberation and focused effort. The projects contained in this *Atlas* reveal both the reality and the potential to engineer in partnership with nature. Expanding upon these and other examples to realize the full potential of Engineering With Nature will involve commitments to progress in several key areas.

Innovating through relationships, collaborations, and productive partnerships. Innovation is most effectively achieved through partnership. Collaboration across all sectors is needed to advance sustainable infrastructure. The full progression of engagement will include coordination, collaboration and codevelopment across local, regional, and national government; among government agencies; between the public and private sectors; and between academia and the broader research community and public and private project developers.

Developing new science, engineering, and methods of working. Focused research and development will expand application of nature-based solutions across multiple purposes, including for navigation infrastructure, flood risk management, water operations, and ecosystem restoration, among other areas of application. Building relationships and collaborations across organizations with different perspectives and mandates will foster the development of creative solutions. By drawing together diverse ideas, experiences, and missions, we can accelerate and advance the technical capability to deliver nature-based solutions. The Network for Engineering With Nature (www.n-ewn.org) was formed to support such interactions.

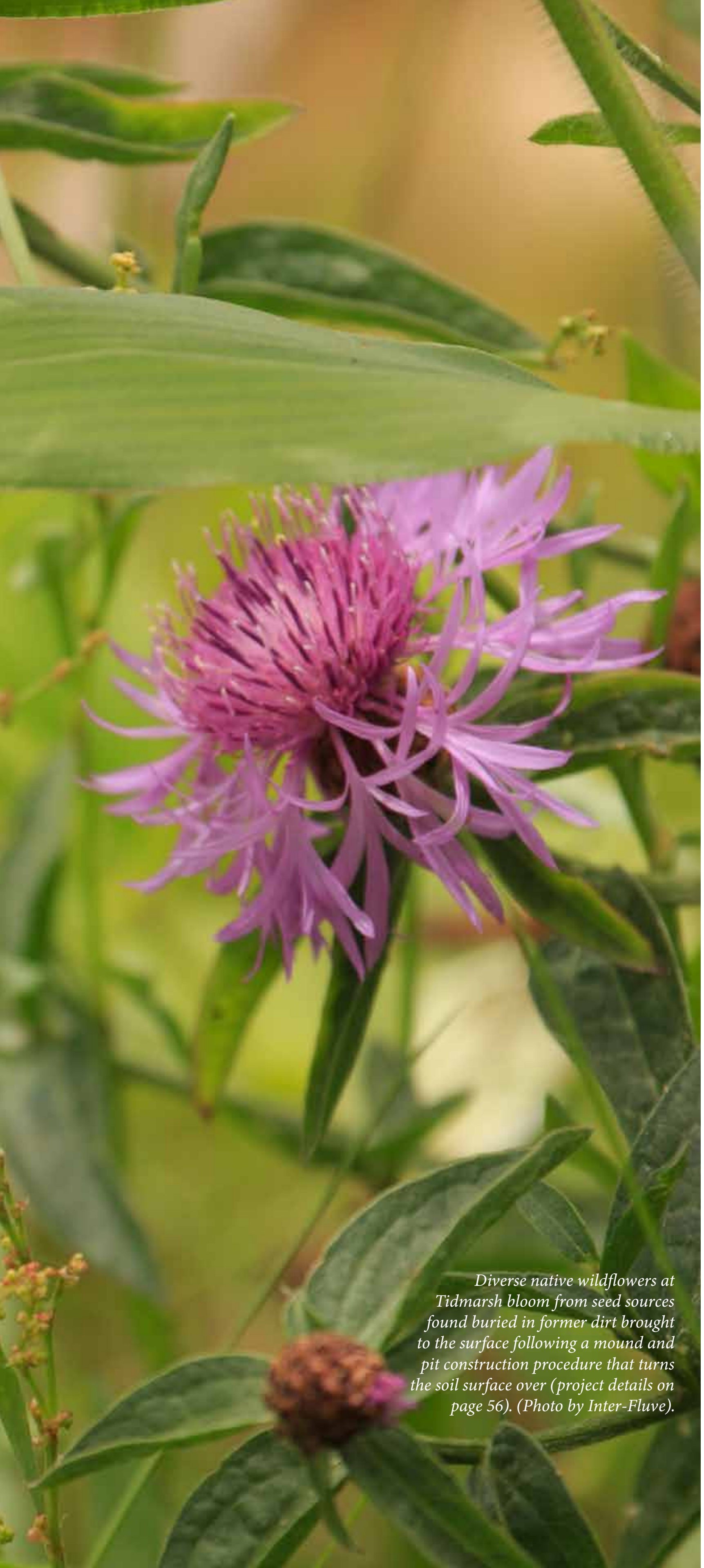
Clockwise: Great Lakes Dock and Dredge's Ellis Island *at the offshore borrow site for Ship Island in 2018 (project details on page 96) (photo by USACE Mobile District); restoration of floodplain areas within the former Boardman River reservoirs included extensive revegetation efforts (project details on page 140) (photo by Inter-Fluve); contractor constructing the coconut coir log containment system, critical to limiting turbidity and containing dredged material at Jekyll Creek (project details on page 64) (photo by USACE Clay McCoy, Jacksonville District); and California native plants growing in the Meadowview community nursery (project details on page 160) (photo by J. Snapp-Cook, U.S. Fish and Wildlife Service).*

Introducing new ideas and methods into practice. While new science, engineering, and technology is being developed, there is an important need for researchers and the practitioners that plan, design, and build nature-based solutions to work together in coordinating the technology "push and pull" that introduces new approaches into practical implementation. This interaction can take a variety of practical forms, including workshops, working meetings, and formal technical engagements among organizations. The goals and outcomes of these engagements should include identifying needs and gaps to be filled; facilitating cross-disciplinary collaboration; and introducing new concepts, science, and engineering practice to project investors, planners, designers, builders, and operators.

Documenting the diverse benefits of EWN approaches and projects. Expanding the capability to describe, quantify, and document the diverse value that can be produced by EWN approaches—including economic, environmental, and social benefits—will be key to delivering innovative infrastructure solutions in the twenty-first century. Understanding both public and private desire for expanded project value, planning and designing projects for diverse benefits, and measuring the performance of projects over time will promote progress in delivering nature-based solutions.

Communicating strategically about innovation, delivery, and progress. Communication is critical to both building and then maintaining momentum. A wide range of communication activities are needed to share best practice, foster technical advancement, and instill confidence in practice. The *Engineering With Nature Atlas* series is one channel for communicating progress and potential. The *EWN Podcast* series and other forms of social media provide a means for sharing ideas and intentions across a broad range of audiences. Effective strategic communication will engage the public as well as practitioners.

Preparing people for the future through education and training. Progress is fueled by learning. This is true for everyone, for research scientists, professional engineers, project owners, and members of a local community. The path to twenty-first-century infrastructure includes meeting both short and long-term educational needs. We need to help everyone become aware of the growing range of possible engineering solutions, including nature-based solutions. Technical professionals that are supporting infrastructure development need opportunities to expand their knowledge, skills,



Diverse native wildflowers at Tidmarsh bloom from seed sources found buried in former dirt brought to the surface following a mound and pit construction procedure that turns the soil surface over (project details on page 56). (Photo by Inter-Fluve).

and abilities to deliver sustainable projects. New educational curricula and courses are needed to support the development of future professionals and tomorrow's nature-based solutions.

The Engineering With Nature Initiative will expand its collaborations across and with government, the private and nonprofit sectors, academia, and communities to achieve the vision of nature and engineering as partners and allies. We are going build productive relationships, learn from others, and share our successes over the next 10 years and beyond.

The future is bright with opportunity for Engineering With Nature!

Wild Angelica (Angelica sylvestris *L.*) *at the outfall of an engineered log jam at Smithills (project details on page 180). (Photo by Woodland Trust, Environment Agency, and Mersey Forest)*

Acknowledgments

The following individuals were members of the project team responsible for developing *Engineering With Nature: An Atlas, Volume 2*: Todd Bridges, Michelle Bourne, Burton Suedel, Emily Moynihan, and Jeff King. 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

Spanjaards Duin is located in ’s-Gravenzande, South Holland, the Netherlands. Project information and photos courtesy of Stéphanie IJff, Deltares. For more information concerning this project, please contact Stéphanie IJff by email at stephanie.ijff@deltares.nl.

Piping Plover Habitat is located in Superior, Wisconsin, United States. Project information and photos courtesy of Amanda Meyer, U.S. Army Corps of Engineers–Detroit District. For more information concerning this project, please contact Amanda Meyer by email at Amanda.R.Meyer@usace.army.mil.

King Fisher Beach is located in Port O’Connor, Texas, United States. Project information and photos courtesy of Seth Jones, U.S. Army Corps of Engineers–Galveston District. For more information concerning this project, please contact Seth Jones by email at Seth.W.Jones@usace.army.mil.

Dangote Sandbar Breakwater is located in Lekki, Lagos State, Nigeria. Project information and photos courtesy of Daan Rijks, Boskalis. For more information concerning this project, please contact Daan Rijks by email at daan.rijks@boskalis.com. Portions of this project’s text have been modified and reprinted from B.-J. van der Spek, E. Bijl, B. van de Sande, S. Poortman, D. Heijboer, and B. Bliek, “Sandbar Breakwater: An Innovative Nature-Based Port Solution,” *Water* 12, no. 5 (2020): 1446, https://doi.org/10.3390/w12051446. Licensed under CC BY 4.0, https://creativecommons.org/licenses/by/4.0/.

Prime Hook Wildlife Refuge is located in Milton, Delaware, United States. Project information and photos courtesy of Bartholomew Wilson, U.S. Fish and Wildlife Service. For more information concerning this project, please contact Bartholomew Wilson by email

at Bartholomew_Wilson@fws.gov. Portions of this project's text have been modified and reprinted from B. Wilson, S. Guiteras, A. Rizzo, and A. Coppola, "Large-Scale Coastal Tidal Marsh and Barrier Beach Restoration at Prime Hook National Wildlife Refuge—Recovering from Hurricane Sandy and Building Resilience in Former Freshwater Impoundments," abstract, Restoration Webinar Series (Shepherdstown, WV: U.S. Fish and Wildlife Service, National Conservation Training Center, 2017), https://nctc.fws.gov/topic/online-training/webinars/restoration.html. Public Domain.

Wetlands

Big Swamp is located in Coralville, New South Wales, Australia. Project information and photos courtesy of Will Glamore, PIANC. For more information concerning this project, please contact Will Glamore by email at will.glamore@pianc.org.au. Portions of this project's text have been reprinted with permission from University of New South Wales Water Research Laboratory, "Big Swamp Restoration Project," Restoration (Sidney, Australia: University of New South Wales, School of Civil and Environmental Engineering, Water Research Laboratory), accessed 19 November 2020, http://restoration.unsw.edu.au/index.php/research/big-swamp-restoration-project/. Copyright © University of New South Wales.

Dow Former Ash Pond is located in Midland, Michigan, United States. Project information and photos courtesy of Betsy Witt, Dow. For more information concerning this project, please contact Betsy Witt by email at bswitt@dow.com. Portions of this project's text have been modified and reprinted from F. Guertin, K. Halsey, T. Polzin, M. Rogers, and B. Witt, "From Ash Pond to Riverside Wetlands: Making the Business Case for Engineered Natural Technologies," *Science of the Total Environment* 651, no. 1 (2019): 419–426, https://doi.org/10.1016/j.scitotenv.2018.09.035. Licensed under CC BY 4.0. https://creativecommons.org/licenses/by/4.0/.

Pierce Marsh is located in Hitchcock, Texas, United States. Project information and photos courtesy of Seth Jones, U.S. Army Corps of Engineers–Galveston District. For more information concerning this project, please contact Seth Jones by email at Seth.W.Jones@usace.army.mil.

Ellis Meadows is located in Leicester, England, United Kingdom. Project information and photos courtesy of Alex McDonald, Environment Agency. For more information concerning this project, please contact Alex McDonald by email at alex.mcdonald@environment-agency.gov.uk.

Tidmarsh Farms Cranberry Bog is located in Plymouth, Massachusetts, United States. Project information and photos courtesy of Greg Koonce, Inter-Fluve. For more information concerning this project, please contact Greg Koonce by email at gkoonce@interfluve.com.

Drake Wilson Island is located in Apalachicola, Florida, United States. Project information and photos courtesy of Jacob Berkowitz, U.S. Army Engineer Research and Development Center. For more information concerning this project, please contact Jacob Berkowitz by email at Jacob.F.Berkowitz@usace.army.mil.

Jekyll Creek is located in Jekyll Island, Georgia, United States. Project information and photos courtesy of Ashby Worley, The Nature Conservancy. For more information concerning this project, please contact Ashby Worley by email at ashby.worley@tnc.org.

Umetco Former Mine Site is located in Hot Springs, Arkansas, United States. Project information and photos courtesy of Jim Strunk, Dow. For more information concerning this project, please contact Jim Strunk by email at jstrunkjr@dow.com.

Clinton River Mouth Wetland is located in Harrison Township, Michigan, United States. Project information and photos courtesy of Amanda Meyer, U.S. Army Corps of Engineers–Detroit District. For more information concerning this project, please contact Amanda Meyer by email at Amanda.R.Meyer@usace.army.mil.

Tomago Wetlands is located in Tomago, New South Wales, Australia. Project information and photos courtesy of Will Glamore, PIANC. For more information concerning this project, please contact Will Glamore by email at will.glamore@pianc.org.au.

Sabine National Wildlife Refuge is located in Cameron, Louisiana, United States. Project information and photos courtesy of Brad Inman, U.S. Army Corps of Engineers–New Orleans District. For more information concerning this project, please contact Brad Inman by email at Brad.L.Inman@usace.army.mil. Portions of this project's text have been modified and reprinted from Coastal Wetlands Conservation and Restoration Task Force, *Sabine Refuge Marsh Creation Cycle I (CS-28-1)* (Lafayette, LA: Louisiana Coastal Wetlands Planning Protection and Restoration Act Program, 2020), https://lacoast.gov/reports/gpfs/CS-28-1_hq.pdf. Public Domain.

Islands

Northerly Island is located in Chicago, Illinois, United States. Project information and photos courtesy of Eugene Fleming, U.S. Army Corps of Engineers–Chicago District. For more information concerning this project, please contact Eugene Fleming by email at Eugene.J.Fleming@usace.army.mil. Portions of this project's text have been modified and reprinted from U.S. Army Corps of Engineers–Chicago District, "Northerly Island," Civil Works Projects (Chicago, IL: U.S. Army Corps of Engineers–Chicago District), accessed 19 November 2020, https://www.lrc.usace.army.mil/Missions/Civil-Works-Projects/Northerly-Island/. Public Domain.

Marker Wadden is located in Lake Marken, Flevoland, the Netherlands. Project information and photos courtesy of Rita Oppenhuizen, Natuurmonumenten. For more information concerning this project, please contact Rita Oppenhuizen by email at r.oppenhuizen@natuurmonumenten.nl.

Cat Island and Ship Island are located in Cat Island and Ship Island, Mississippi, United States. Project information and photos courtesy of Justin McDonald, U.S. Army Corps of Engineers–Mobile District. For more information concerning this project, please contact Justin McDonald by email at Justin.S.McDonald@usace.army.mil. Portions of this project's text have been modified and reprinted with permission from J. McDonald, "The Power of Partnerships in Coastal Restoration," abstract, 2019 National Coastal Conference Abstracts (American Shore & Beach Preservation Association, 2019), https://asbpa.org/conferences/2019-national-coastal-conference-program/2019-national-coastal-conference-abstracts/. Copyright American Shore & Beach Preservation Association.

Pool 8 is located in Brownsville, Minnesota, United States. Project information and photos courtesy of David Potter, U.S. Army Corps of Engineers–St. Paul District, aand Chuck Theiling, U.S. Army Engineer Research and Development Center. For more information concerning this project, please contact David Potter by email at David.F.Potter@usace.army.mil.

Unity Island is located in Buffalo, New York, United States. Project information and photos courtesy of Tony Friona, U.S. Army Engineer Research and Development Center. For more information concerning this project, please contact Tony Friona by email at anthony.m.friona@usace.army.mil.

Swan Island Restoration is located in Chesapeake Bay, Maryland, United States. Project information and photos courtesy of Paula Whitfield, National Oceanic and Atmospheric Administration. For more information concerning this project, please contact Paula Whitfield by email at paula.whitfield@noaa.gov.

Reefs

Goldbug Living Shoreline is located in Sullivan's Island, South Carolina, United States. Project information and photos courtesy of Joy Brown, The Nature Conservancy. For more information concerning this project, please contact Joy Brown by email at joy_brown@tnc.org.

Brunswick Town / Fort Anderson is located in Cape Fear River, North Carolina, United States. Project information and photos courtesy of Phillip Todd, Atlantic Reef Maker. For more information concerning this project, please contact Phillip Todd by email at P.Todd@atlanticreefmaker.com.

Bonner Bridge is located in Oregon Inlet, North Carolina, United States. Project information and photos courtesy of Phillip Todd, Atlantic Reef Maker. For more information concerning this project, please contact Phillip Todd by email at P.Todd@atlanticreefmaker.com.

Mangrove Reef Walls is located in Englewood and Fort Pierce, Florida, United States. Project information and photos courtesy of Keith Van de Riet, The University of Kansas. For more information concerning this project, please contact Keith VanDeRiet by email at kvdr@ku.edu.

Wind Farm Oyster Reefs is located in Borssele, Zeeland, the Netherlands. Project information and photos courtesy of Remment ter Hofstede, Van Oord. For more information concerning this project, please contact Remment ter Hofstede by email at remment.terhofstede@vanoord.com.

Riverine Systems

Boardman River Dam Removals is located in Traverse City, Michigan, United States. Project information and photos courtesy of the Paul Powell, U.S. Army Corps of Engineers–Detroit District and Greg Koonce, Inter-Fluve. For more information concerning this project, please contact Paul Powell or Greg Koonce by email at paul.a.powell@usace.army.mil and gkoonce@interfluve.com.

Old Scheldt and Kalkenvaart is located in Aard, East Flanders, Belgium. Project information and photos courtesy of Dominiek Decleyre, Vlaanderen. For more information concerning this project, please contact Dominiek Decleyre by email at Dominiek.Decleyre@vlaanderen.be.

Eddleston Water is located in Peebles, Scotland, United Kingdom. Project information and photos courtesy of Christopher Spray, University of Dundee. For more information concerning this project, please contact Christopher Spray by email at C.J.Spray@dundee.ac.uk.

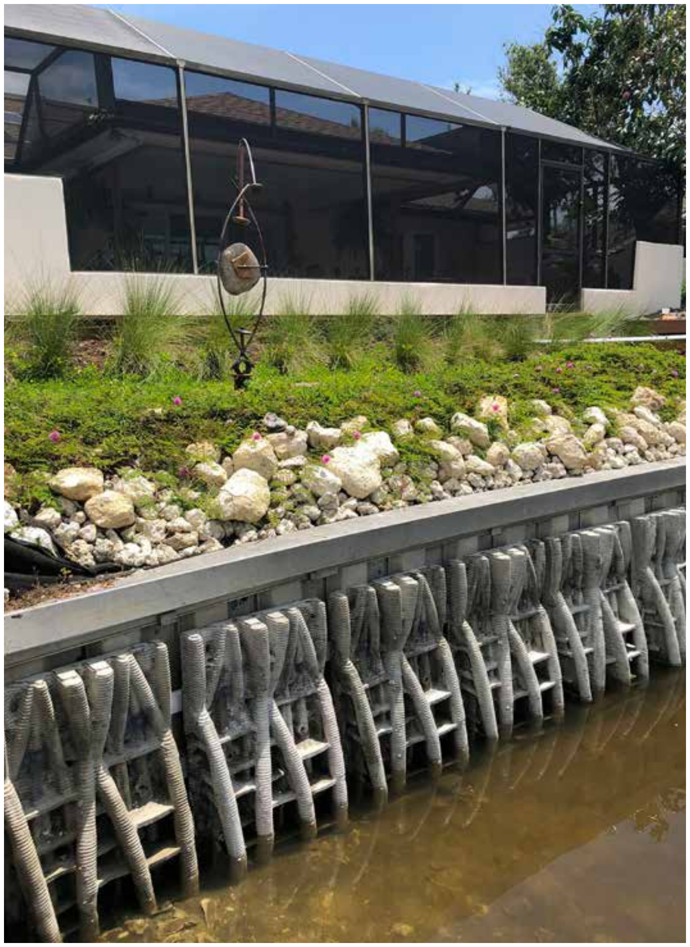
Deer Island is located in Little Sioux, Iowa, United States. Project information and photos courtesy of Luke Wallace, U.S. Army Corps of Engineers–Omaha District. For more information concerning this project, please contact Luke Wallace by email at a.luke.wallace@usace.army.mil.

Rogue River is located in Grants Pass, Oregon, United States. Project information and photos courtesy of Greg Koonce, Inter-Fluve. For more information concerning this project, please contact Greg Koonce by email at gkoonce@interfluve.com.

Meadowview Stream is located in Temecula, California, United States. Project information and photos courtesy of the Teri Biancardi, Meadowview Homeowners Association. For more information concerning this project, please contact Teri Biancardi by email at teribiancardi@icloud.com.

River Nairn is located in Aberarder, Scotland, United Kingdom. Project information and photos courtesy of the Alasdair Matheson, Scottish Environment Protection Agency. For more information concerning this project, please contact Alasdair Matheson by email at alasdair.matheson@sepa.org.uk.

Environmental Pool Management is located in the Upper Mississippi River, Missouri, United States. Project information and photos courtesy of the Benjamin McGuire, U.S. Army Corps of Engineers–St. Paul District. For more information concerning this project, please contact Benjamin McGuire by email at benjamin.m.mcguire@usace.army.mil.



Clockwise: At Bonner Bridge, the Reefmaker provides substrate for oysters and barnacles to grow (project details on page 124) (photo by CSA Ocean Sciences Inc.); preparing to plant over 1,000 native bald cypress trees (project details on page 288) (photo by Restore the Earth Foundation); fabricated mangrove reef walls replace traditional, flat seawalls, providing habitat while preventing shoreline erosion (project details on page 128) (photo by Keith Van de Riet); and the dredge Victory *excavating a 40-foot channel, side-casting the material in the shallow open water basin (project details on page 32) (photo by U.S. Fish and Wildlife Service).*

Mill River is located in Taunton, Massachusetts, United States. Project information and photos courtesy of the Janine Harris, National Oceanic and Atmospheric Administration. For more information concerning this project, please contact Janine Harris by email at janine.harris@noaa.gov.

Floodplains

Smithills Flood Management is located in Smithills, England, United Kingdom. Project information and photos courtesy of Tracey Garrett, Environment Agency, and Mike Norbury, Mersey Forest. For more information concerning this project, please contact Tracey Garrett by email at TraceyGarrett@woodlandtrust.org.uk.

Kerry Island Estuary is located in Clatskanie, Oregon, United States. Project information and photos courtesy of Greg Koonce, Inter-Fluve. For more information concerning this project, please contact Greg Koonce by email at gkoonce@interfluve.com.

Wendling Beck is located in the Worthing, England, United Kingdom. Project information and photos courtesy of Jonah Tosney, Norfolk Rivers Trust. For more information concerning this project, please contact Jonah Tosney by email at jonahtosney@norfolkriverstrust.org.

Southern Flow Corridor is located in Tillamook, Oregon, United States. Project information and photos courtesy of Janine Harris, National Oceanic and Atmospheric Administration. For more information concerning this project, please contact Janine Harris by email at janine.harris@noaa.gov.

Low Leighton Flood Management is located in New Mills, England, United Kingdom. Project information and photos courtesy of Peter Hewitt, Environment Agency, and Mike Norbury, Mersey Forest. For more information concerning this project, please contact Peter Hewitt by email at peter.hewitt@environment-agency.gov.uk.

Weardale is located in Weardale, England, United Kingdom. Project information and photos courtesy of Kirsty Hardy, Environment Agency. For more information concerning this project, please contact Kirsty Hardy by email at kirsty.hardy@environment-agency.gov.uk. Portions of this project's text have been modified and reprinted from Environment Agency, "Events to Find Out More about North East Natural Flood Managment," press release, 26 March 2018, https://www.gov.uk/government/news/events-to-find-out-more-about-north-east-natural-flood-management. Contains public sector information licensed under the Open Government Licence v3.0, https://www.nationalarchives.gov.uk/doc/open-government-licence/version/3/.

Puyallup River Revetment is located in Orting, Washington, United States. Project information and photos courtesy of David Davis, Pierce County Planning and Public Works. For more information concerning this project, please contact David Davis by email at david.davis@piercecountywa.gov.

Use of Vegetation and Natural Materials

Howland Dam Fish Bypass is located in Howland, Maine, United States. Project information and photos courtesy of Greg Koonce, Inter-Fluve. For more information concerning this project, please contact Greg Koonce by email at gkoonce@interfluve.com.

Jackson Park is located in Jackson Park, Chicago, Illinois, United States. Project information and photos courtesy of Eugene Fleming, U.S. Army Corps of Engineers–Chicago District. For more information concerning this project, please contact Eugene Fleming by email at Eugene.J.Fleming@usace.army.mil.

Flimby is located in the Flimby, England, United Kingdom. Project information and photos courtesy of Philippa Chadwick, West Cumbria Rivers Trust. For more information concerning this project, please contact Philippa Chadwick by email at philippa@westcumbriariverstrust.org.

Dry Creek is located in Sonoma County and Healdsburg, California, United States. Project information and photos courtesy of Tessa Beach, U.S. Army Corps of Engineers–San Francisco District, and Greg Koonce, Inter-Fluve. For more information concerning this project, please contact Tessa Beach by email at Tessa.e.bernhardt@usace.army.mil or Greg Koonce at gkoonce@interfluve.com.

Clackamas River is located in Clackamas, Oregon, United States. Project information and photos courtesy of Greg Koonce, Inter-Fluve. For more information concerning this project, please contact Greg Koonce by email at gkoonce@interfluve.com.

Horsetail and Oneonta Creek is located in Corbet, Oregon, United States. Project information and photos courtesy of Greg Koonce, Inter-Fluve. For more information concerning this project, please contact Greg Koonce by email at gkoonce@interfluve.com.

Narborough is located in Narborough Bog, England, United Kingdom. Project information and photos courtesy of Alex McDonald, Environment Agency. For more information concerning this project, please contact Alex McDonald by email at alex.mcdonald@environment-agency.gov.uk.

Chatfield Reservoir–Plum Creek is located in Denver, Colorado, United States. Project information and photos courtesy of Clayton Ridenour, U.S. Army Corps of Engineers–Omaha District. For more information concerning this project, please contact Clayton Ridenour by email at clayton.j.ridenour@usace.army.mil.

Westmoreland Park is located in Portland, Oregon, United States. Project information and photos courtesy of James R. Adams, U.S. Army Corps of Engineers–Portland District. For more information concerning this project, please contact James R. Adams by email at james.r.adams@usace.army.mil.

Galloway Creek is located in Rochester Hills, Michigan, United States. Project information and photos courtesy of Amanda Meyer, U.S. Army Corps of Engineers–Detroit District. For more information concerning this project, please contact Amanda Meyer by email at Amanda.R.Meyer@usace.army.mil.

Environmental Enhancement of Infrastructure

Brooklyn Tide Pools is located in Brooklyn, New York, 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. Portions of this project's text have been modified and reprinted with permission from Michalt, "Tide Pools and Pile Encasement Brooklyn Bridge Park Case Study," ECOncrete, 27 January 2018, https://econcretetech.com/tide_pools_pile_encasement_brooklyn_bridge/. Copyright Econcrete Tech Ltd.

Mile Point Wall Reconfiguration is located in Jacksonville, Florida, United States. Project information and photos courtesy of Aaron Lassiter, U.S. Army Corps of Engineers–Jacksonville District. For more information concerning this project, please contact Aaron Lassiter by email at James.a.lassiter@usace.army.mil.

Clay Ripener is located in Delfzijl, Groningen, the Netherlands. Project information and photos courtesy of Carrie de Wilde, EcoShape. For more information concerning this project, please contact Carrie de Wilde by email at carrie.dewilde@ecoshape.nl.

Hartlepool Headland Coastal Protection Scheme is located between Hartlepool, England, United Kingdom. Project information and photos courtesy of Larissa Naylor and team, University of Glasgow and Hartlepool Borough Council. For more information concerning this project, please contact Larissa Naylor by email at Larissa.Naylor@glasgow.ac.uk.

Regulating Works Project is located in Middle Mississippi River, Missouri and Illinois, United States. Project information and photos courtesy of Eddie Brauer and Timothy Lauth, U.S. Army Corps of Engineers–St. Louis District. For more information concerning this project, please contact Timothy Lauth by email at Timothy.J.Lauth@usace.army.mil.

Emiquon Water Management is located in Havana, Illinois, United States. Project information and photos courtesy of Doug Blodgett and Noel Rozny, The Nature Conservancy. For more information concerning this project, please contact Noel Rozny by email at nrozny@tnc.org. Portions of this project's text have been modified and reprinted with permission from Illinois Rivers Decision Support System, "Emiquon," Illinois Rivers Decision Support System, (Champaign, IL: Illinois State Water Survey, 2018), http://ilrdss.sws.uiuc.edu/emiquon/. Copyright © 2018 Illinois State Water Survey.

Lower Yellowstone River Fish Passage is located in Intake, Montana, United States. Project information and photos courtesy of Jeremy Szynskie, U.S. Army Corps of Engineers–Omaha District. For more information concerning this project, please contact Jeremy Szynskie by email at jeremiah.j.szynskie@usace.army.mil. Portions of this project's text have been modified and reprinted from U.S. Bureau of Reclamation and U.S. Army Corps of Engineers–Omaha District, *Lower Yellowstone Intake Diversion Dam Fish Passage Project, Montana: Final Environmental Impact Statement* (Billings, MT: U.S. Bureau of Reclamation 2016), https://www.usbr.gov/gp/mtao/loweryellowstone/EIS/2016feis.pdf. Public Domain.

Matarandiba Island is located in Matarandiba Island, Bahia, Brazil. Project information and photos courtesy of Todd Guidry, Dow. For more information concerning this project, please contact Todd Guidry by email at TOGuidry@dow.com.

Cypress Reforestation is located in Montegut, Louisiana, United States. Project information and photos courtesy of Taylor Marshall, Restore the Earth. For more information concerning this project, please contact Taylor Marshall by email at tam@restoretheearth.org.

Nesting boxes at Tidmarsh provide habitat that in the future will be available as planted trees mature and die, forming snags with cavities (project details on page 56). (Photo by Inter-Fluve)

Project Enablers

The Ecosystem Services Identification and Inventory (ESII) tool information and photos courtesy of France Guertin, Dow Inc. For more information concerning this tool, please contact France Guertin by email at fmguertin@dow.com.

The Natural Infrastructure Opportunities Tool (NIOT) information and photos courtesy of Safra Altman, U.S. Army Engineer Research and Development Center. For more information concerning this tool, please contact Safra Altman by email at Safra.Altman@usace.army.mil. Portions of this tool's text have been modified and reprinted from Safra Altman, "Tools: Natural Infrastructure Opportunities Tool," Engineering With Nature, accessed 13 August, 2020, https://ewn.el.erdc.dren.mil/Tools.html. Public Domain.

The Coastal Storm Modeling System (CSTORM) tool information and photos courtesy of Chris Massey, U.S. Army Engineer Research and Development Center. For more information concerning this tool, please contact Chris Massey by email at Chris.Massey@usace.army.mil.

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Engineering With Nature: An Atlas, Volume 2 showcases EWN principles and practices "in action" through 62 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, non-governmental 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.

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