NATIONAL ACADEMIES Sciences Engineering Medicine

Proceedings of a Workshop—in Brief

Benefits, Applications, and Opportunities of Natural Infrastructure

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Natural infrastructure is the practice of using naturally occurring aspects of the landscape and/or nature based solutions that use or imitate natural processes (e.g., wetlands, living shorelines, municipal green infrastructure) to support natural hazard resilience, climate change adaptation, and other benefits to people and ecosystems. Recognition of the multiple benefits of natural "green" infrastructure has increased over the past several decades, used alone or in combination with built "gray" infrastructure solutions, such as seawalls and levees. Yet many potential opportunities remain untapped. On **May 10–11, 2022,** the Resilient America program at the National Academies of Sciences, Engineering, and Medicine (the National Academies) convened a workshop to explore opportunities to link the benefits of natural infrastructure across geographic scales and multiple objectives. Sponsored by the U.S. Army Corps of Engineers (USACE) and hosted by the Institute for Resilient Infrastructure Systems at the University of Georgia (UGA), the hybrid workshop was targeted to the engineering community, as well as scientists, policy makers, planners, and others involved with designing, developing, and funding natural infrastructure.[1]

[1] The agenda, speaker biographies, presentations, and recordings can be found at https://www.nationalacademies.org/event/05-10-2022/workshop-on-benefits-applications-and-opportunities-of-natural-infrastructure.

WELCOMING REMARKS AND CONTEXT

In welcoming participants, **S. Jack Hu** (UGA) recognized the value of bringing together experts from the higher education, industry, government, and nonprofit sectors to discuss how natural infrastructure can mitigate climate change and other hazards. "This workshop reflects the fact that solutions to large and complex societal problems require expertise from many different disciplines. Interdisciplinary collaborations are key," Hu said.

Planning committee chair **Hussam Mahmoud** (Colorado State University) outlined the workshop goal to explore the benefits, applications, and opportunities of natural infrastructure to advance and mainstream solutions in public and private engineering practice. He acknowledged the need to look at the tradeoffs between sustainability, alignment between competing priorities, and resilience at different scales and the variety of methods and settings to consider in decision making (Figure 1). Mahmoud explained the committee structured its agenda around four themes: (1) application of natural infrastructure; (2) elements of implementation; (3) making timely progress; and (4) syncing with policies.

FIGURE 1 Natural infrastructure in different settings.
SOURCE: Hussam Mahmoud, workshop presentation, May 10, 2022.

Todd Bridges (USACE) set the context for why the agency sponsored the workshop. "We live in a multi-hazard world," he pointed out where human-made and natural hazards occur in different combinations and sequences. This complexity calls for systems thinking, rather than the single-purpose projects that characterized the 20th century, he continued. Bridges called attention to President Biden's April 2022 executive order (EO 14072) that includes a section on nature-based solutions (NBS).[2] From an engineering perspective, he noted that while some engineers say they need to see detailed technical standards and guidance to implement NBS, an American Society of Civil Engineers past-president has commented that engineering judgment, beyond standards, is a hallmark of the profession. "We need guidance," Bridges concurred, but also urged that the lack of published code and standards not hold back innovation.

According to Bridges, USACE's Engineering with Nature (EWN) initiative provides an opportunity to develop intentional alignment between natural and engineering processes.[3] EWN produces non-technical materials to spark conversation and new ideas. It also advances technical tools for modeling, documents benefits of NBS, conducts benefit-cost analyses, and supports first-of-their-kind field applications. EWN led a 5-year effort to develop guidance for flood risk management, but, he noted, even the guidance's more than 1,000 pages "cannot answer every question nor should it."[4] Rather than an "either/or" choice between natural and structural engineering, Bridges reflected on the value of combining solutions for a particular context. He asked participants to consider how to make stepwise progress to develop natural infrastructure in combination with conventional infrastructure.

Providing a big-picture perspective, **Gerry Galloway, Jr.** (University of Maryland) recalled discussing the value of natural systems and wetlands more than 40 years ago and the related concepts that have developed over the decades.[5] He noted the initial ecological focus has broadened to encompass economic, environmental, and social benefits. He called for action to use natural and nature-based features (NNBF), rather than reports that conclude "further study is needed." Barriers to action

[2] In particular, Section 4 of EO 14072 is entitled: "Deploying Nature Based Solutions to Tackle Climate Change and Enhance Resilience." The executive order can be found at https://www.federalregister.gov/documents/2022/04/27/2022-09138/strengthening-the-nations-forests-communities-and-local-economies.
[3] For more information on EWN, see https://ewn.erdc.dren.mil/.
[4] International Guidelines on Natural and Nature-Based Features for Flood Risk Management, see https://ewn.erdc.dren.mil/?page_id=4351.
[5] In addition to "natural infrastructure," Galloway called attention to related concepts mentioned in the International Guidelines for Natural and Nature-Based Features for Flood Risk Management, including natural and nature-based features, green infrastructure, and building with nature, and others.

include overcoming skepticism that NNBF take too long for effectiveness, cannot handle major hazards, vary in performance, or require too much land. Uncertainty about hydrologic conditions, land use, and standards are raised as an impediment, yet, he commented, uncertainty affects all development. Other challenges include lack of understanding within agencies, lack of local interest to provide pressure to implement NNBF, and silos that impede more comprehensive funding and implementation. Examples of NNBF in use include on the Mississippi River, the Yolo Bypass in California, and Sponge Cities in China.[6]

Galloway reflected on a recent study on climate-resilient infrastructure that stresses interdependencies within and across systems.[7] From his work internationally, he reported a move to deal with climate change at the watershed level, across entire river basins, not individual projects; understand the importance of uncertainty; build resilient communities with social and gender equity as goals; and strengthen resilient security for vulnerable and marginalized groups. NNBF has been and must continue to be integral to water resource management, applied in a systems approach, better communicated to the public, and receive full endorsement (not just weak support) by policy makers, he stated. He noted the consequences of inaction, such as for national security if military installations on the east and Gulf Coasts become unavailable because of climate change impacts. Drawing on a baseball analogy, Galloway closed, "Nature bats last."[8]

THEME 1: APPLICATION OF NATURAL INFRASTRUCTURE—CONTEXT, FEATURES, AND BENEFITS

In introducing the first panel, planning committee member **Paul Freedman** (LimnoTech) commented that nature has shown its resiliency for millions of years. "Why *not* take those lessons learned?" he asked rhetorically.

[6] "Sponge cities" use parkland, green roofs, and other measures to manage urban flooding. For more information, see Chan et al. (2018). "Sponge City in China—A breakthrough of planning and flood risk management in the urban context. *Land Use Policy*, 76: 772-778. https://doi.org/10.1016/j.landusepol.2018.03.005.

[7] Hill et al. (2019). Ready for Tomorrow: Seven Strategies for Climate-Resilient Infrastructure. Hoover Institution. https://www.hoover.org/research/ready-tomorrow-seven-strategies-climate-resilient-infrastructure.

[8] i.e., natural phenomena can occur in ways that are beyond human control.

Theme 1: Keynote

Mike Donahue (AECOM) shared examples of problems that natural infrastructure can help solve through such methods as beneficial use of dredged material, living shorelines, marsh and wetland creation, mangrove forests, and barrier islands. What these projects have in common, he said, citing Resources for Future, is they "rely on services produced by ecosystems, often utilizing natural landscapes to minimize flood damages, purify and store water, and reduce urban stormwater runoff."[9] Donahue said infrastructure improvements are not keeping pace with needs. He stressed that, "it is not an either/or proposition. Conventional infrastructure has its place, augmented by NBS."

Natural infrastructure represents a $40 billion annual market, he estimated. "One person's waste is another's treasure," he added. "In some regions, dredged material is a 'waste' product, which in other regions it is valued for land rebuilding, coastal protection, and ecological restoration." Donahue's case studies highlighted AECOM coastline, riverine, and urban projects. Among challenges and opportunities, he listed the importance of education for clients and practitioners, formalized standards of performance and costs, documentation, and incentives. He also noted multiple sources of federal funding, including the recent Infrastructure Investment and Jobs Act (IIJA).[10]

Theme 1: Panel and Discussion

Providing a district-level perspective, **Edward Brauer** (USACE) said practitioners need tools and guidance to do more natural infrastructure (NI). That said, each NI project is unique and constantly evolving, making up-to-date guidance for all NI projects a challenge. He also related that a common concern is how to get a project through review if it does not follow current technical guidance or has no applicable guidance at all. To overcome guidance challenges, he identified the value of partnerships, especially when stakeholders push for innovation; a community of practitioners; case studies and other resources to inform design; trust in

[9] Resources for the Future. Natural Infrastructure. https://www.rff.org/topics/adaptation-and-resilience/natural-infrastructure/.

[10] The full text of the Infrastructure Investment and Jobs Act (H.R. 3684) can be found at https://www.congress.gov/bill/117th-congress/house-bill/3684/text.

engineering judgment; and pilot projects. He also pointed to leadership's willingness to try new approaches.

Tools are important, but Brauer warned about overreliance on them, given real-world complexity. EWN has provided technical support and connected practitioners, such as through a website to share experiences and information. He also noted the USACE River Engineering Working Group envisions the overlapping of engineering and nature themes to remain relevant in the future. Brauer shared several riverine case studies that involved multiple partners working together in the nation's "inner coast," the river systems throughout the interior regions of the country. The cases included modeling techniques and pilot projects to re-create habitat features, a project at Dogtooth Bend on the Mississippi River, and environmental pool management to modify dam operations.

Hollie Schmidt (Jacobs) presented about the need for resiliency and sustainability, using Tyndall Air Force Base (TAFB) as an example. Challenging the "business-as-usual" focus of physical infrastructure at most military installations, the TAFB rebuild after Hurricane Michael focused on the health and wellness of "the people who enable our national security," she said. Her team developed numerous business cases to prioritize the interaction of the natural and built environments. An increase of 23 percent in initial costs would save more than $90 million over 30 years and more than double the non-financial scoring factors of resiliency, sustainability, and smart systems. An important component at Tyndall and elsewhere, Schmidt said, is "myth-busting," for example countering the claims that nature-based infrastructure will require more maintenance, cost too much, present a security concern, or restrict future options. Jacobs is working on several other coastal projects, developing typologies of coastal resilience, and sharing design and development guidance developed for Tyndall.[11]

Mangroves are a strong option for coastal restoration, stated **Tori Tomiczek** (U.S. Naval Academy). She referred to recent international guidelines on coastal wetlands and tidal flats, in particular that wave height reduction depends on topography, vegetation, and storm characteristics.[12] Tomiczek's and her colleagues' damage assessments in the Florida Keys after Hurricane Irma found that residential properties with mangrove shorelines experienced less damage than similar properties without mangrove shorelines.[13] The challenge has been quantifying performance metrics. They created a physical model and conducted a LiDAR characterization of the project area, and determined the drag coefficient under various wave conditions. She suggested something akin to the Moody diagram for common engineering practice be developed to support NNBF.[14] Tomiczek concluded that field observations and reduced- and full-scale physical model experiments show the potential of red mangroves as effective NNBF solutions for coastal protection, with ongoing tests to assess the impacts from the laboratory to the field. She commented that her students are excited about learning and implementing NNBF.

Launching the discussion, Freedman asked how to broaden acceptance for NBS. Brauer stressed a role for case studies. Donahue called for education because an educated client will give a private firm the opportunity to present NBS alternatives. Challenging the status quo requires showing how NBS is equal or superior to conventional solutions, said Schmidt. Tomiczek added the need for research on managing risks and tradeoffs.

In response to participants' questions about costs, Donahue favored looking at long-term operations and maintenance (O&M) beyond capital costs. Schmidt called for a holistic circular economy strategy that considers cost avoidance. Tomiczek added a lifecycle analysis could show higher upfront costs but lower O&M costs, increased self-recovery after storms, and other benefits.

More broadly, Freedman pointed to the usual focus on building costs but less quantification of other benefits.

[11] See https://www.tyndallifs.com/.

[12] Piercy et al. (2021). Coastal wetlands and tidal flats. Chapter 10 in International Guidelines on Natural and Nature-Based Features for Flood Risk Management. https://ewn.erdc.dren.mil/?page_id=4351.

[13] Tomiczek et al. (2020). Rapid damage assessments of shorelines and structures in the Florida Keys after Hurricane Irma. Natural Hazard Review, 21(1). https://ascelibrary.org/doi/abs/10.1061/(asce)nh.1527-6996.0000349.

[14] A Moody diagram is a graphical method used by engineers to calculate friction, which can then be used to determine pressure drop or flow rate. See https://www.thermal-engineering.org/what-is-moody-diagram-definition/.

Bauer said these types of analyses require money that is usually unavailable. Galloway urged consideration of hidden beneficiaries usually not at the table, such as vulnerable communities and downstream populations. Public support can contribute to or stop a project, several presenters noted. To Schmidt, the biggest obstacle is risk aversion, and she suggested youth as strong advocates and the usefulness of case studies. Despite case studies, a participant commented, some people will not engage in NBS without guidance. Tomiczek noted engineering is based on experience and observation; maybe the guidance should be a set of principles and practices. Donahue suggested a requirement or standard operating procedure that both conventional and NBS are considered. Brauer said a key to more widespread NBS adoption is to quantify benefits. Freedman urged embedding NBS throughout the engineering curriculum, as is done for communications skills.

Theme 1: Breakout Groups

In-person and virtual breakout groups responded to several prompt questions. **Scott Pippin** (UGA) reported his group identified innovation as a core issue. **Braden Foster** (Fisheries and Oceans Canada) noted his group argued the importance of considering the interaction between all natural infrastructure benefits, keeping long-term sustainability in mind. **Mindy Simmons** (USACE) said her group suggested aligning funding sources and understanding the "hot buttons" for different stakeholders. **Rob Lammers** (Central Michigan University)'s group suggested building on society's increased demands for access to nature. **Emily Corwin** (Conservation International) reported her group acknowledged the era of POP (public owns the project) versus DAD (decide, announce, defined). **Dave Hampton** (LimnoTech) said his group urged a reframing of expectations and perceived benefits that often disadvantage NBS. For example, he posed, "Why should natural infrastructure be expected to do something different than we ask of traditional infrastructure?"

THEME 2: ELEMENTS FOR IMPLEMENTATION—PHYSICAL, ECOLOGICAL, SOCIAL, AND ECONOMIC CONSIDERATIONS

Planning committee members **Hans Louis-Charles** (Virginia Commonwealth University) and **Eileen Shader** (American Rivers) introduced the speakers and moderated the discussion on the workshop's second theme.

Theme 2: Keynote

Jenniffer Santos Hernández (University of Puerto Rico Río Piedras) drew from her research to discuss the role of bottom-up, applied planning research and, in particular, ensuring community leaders are involved. As co-lead of San Juan's Urban Resilience to Extreme Sustainability Research Network, she was facilitating stakeholder workshops after Hurricane Maria when a sequence of earthquakes further exposed communities to the uncertainty of climate change. Furthermore, she said, Puerto Rico is recovering from disaster in the midst of a debt adjustment plan that greatly limits resources. She differentiated between restoration, rebuilding, and what should be the goal—recovery.[15] Rather than look at "natural" hazards as isolated events, she underscored dealing with systemic problems created as part of development. Sharing examples, she said, "Ultimately, we are addressing sustainability questions. We can't compartmentalize different hazards."

Working with communities takes time, she reminded the group. Processes of social change are slow and funding is difficult. True representation requires interviews, focus groups, and surveys. Transformative change is nonlinear, she stressed, which goes against the tendency to identify a problem, find a solution, and proceed. She also noted the value of transformative action research and of listening to and working with local researchers and engineers.

Theme 2: Panel and Discussion

Moving the needle from unequal protection toward leveling the landscape in communities of color motivates the Stormwater Infrastructure, Resilience, and Justice (SIRJ) Lab, said **Marccus Hendricks** (University of Maryland). The environmental justice and social vulnerability literature has shown that laws, regulations, and social processes disparately impact infrastructure and communities.[16] Sharing a conceptual framework to

[15] Dynes, R.R., and E.L. Quarantelli. (2008). A brief note on disaster restoration, reconstruction, and recovery: A comparative note using post-earthquake observations. Working paper. http://udspace.udel.edu/handle/19716/3058.

[16] Examples cited by Hendricks included: Taylor, D. (2014). *Toxic Communities*. New York: NYU Press. D.S.K. Thomas et al. (eds.). (2013). *Social Vulnerability to Disasters*. Boca Raton, FL: CRC Press. Bullard, R. (1994).

connect social and neighborhood factors with hazard risks, exposure, and recovery,[17] SIRJ uses a social lens in what has been largely studied as a physical process. In addition to exposing disparities, SIRJ partners with communities, for example to develop master plans. Especially in urban areas, a hybridized approach may be needed, Hendricks added.[18]

Hendricks concluded that equity in infrastructure includes procedural, distributive, and restorative justice; the built environment must be recognized as a continuation of social circumstances; infrastructure dynamics impact risk exposure and ecological and public health outcomes; and participation and partnerships are needed for a more healthy, just, and resilient society.

Jeff Opperman (World Wildlife Fund) discussed scaling up natural infrastructure from accidental models to intentional use. He noted the historic roots of natural infrastructure. After the 1927 Mississippi River flood, USACE developed the River and Tributaries Project. After multiple levee failures in the Sacramento Valley, the Yolo and Sutter bypasses were created. Although not the original goal, ecological restoration and wildlife habitat creation were other benefits. Opperman noted that in these examples, flood managers drew on analysis and experience to reconnect large areas of the natural floodplain—interventions comparable to natural infrastructure projects today. As two examples of institutional support, he noted Room for the River in the Netherlands[19] and multi-benefit flood management

to guide new investments in California. Looking ahead, climate change will increase flood risks globally, he said, and rivers in many of the highest-risk areas are not subject to legal regulations. Opperman urged sharing success stories about natural and hybrid solutions to use in these areas.

Julie Beagle (USACE) said the climate crisis led her to join the agency's San Francisco District last year to scale up NBS in the region, especially in marginalized communities that flood most regularly. As her USACE colleagues described (see above), she sees EWN as a way to leverage natural and economic processes to deliver multiple benefits. Challenges to wider use within USACE include limits of the federal standard; lack of multi-benefit approaches, budgeting, and related issues; knowledge gaps and inability to measure benefits equitably; top-down and internally driven approaches; and institutional inertia. However, she said, momentum is growing to be more strategic across projects with EWN. Doing so requires building multidisciplinary teams and providing training and knowledge development. Beagle shared examples of projects that are benefitting from EWN approaches. She also called attention to changes in USACE's Comprehensive Documentation of Benefits[20] and the need to grow partnerships.

During the discussion, Beagle raised the need for long-term and regional monitoring. Hendricks acknowledged finding land for and maintaining NBS is hard, especially in marginalized communities in densely populated areas. Research and practice are needed to find the balance between green infrastructure and affordable housing. A participant raised equity concerns when land must be purchased for nature-based infrastructure. Beagle noted small-space solutions should also be considered. Hendricks added "thinking big" in dense areas, such as with green roofs and other assets.

Most community engagement strategies are insufficient, Santos Hernández said. Public hearings involve few people and rarely address representation. In addition to training and skills for agency teams, Santos Hernández also observed the need for intellectual humility, rather than coming from the outside with "the perfect solution." Hendricks said from a planning perspective, mitigation of "disaster displacement" is necessary in areas with large economic disparities before mitigating

Overcoming racism in environmental decisionmaking. *Environment: Science and Policy for Sustainable Development, 36*(4): 10–44. S. Van Zandt et al. (2012). Mapping social vulnerability to enhance housing and neighborhood resilience. *Housing Policy Debate*, 22(1):29–55. S. Wilson et al. (2008). How planning and zoning contribute to inequitable development, neighborhood health, and environmental injustice. *Environmental Justice, 1*(4):211–216.

[17] Hendricks, M., and S. Van Zandt. (2021). Unequal protection visited: Planning for environmental justice, hazard vulnerability, and critical infrastructure in communities of color. Environmental Justice. https://doi.org/10.1089/env.2020.0054.

[18] Dowtin, A., and M. Hendricks. (2020). Gray, green, and brown for blue: Historical perspectives and future directions toward a hybrid approach for resilient stormwater management. *IMPACT Magazine.*

[19] For more information about Room for the River, see https://www.dutchwatersector.com/news/room-for-the-river-programme.

[20] See https://planning.erdc.dren.mil/toolbox/library/FactSheets/ComprehensiveBenefitsFactsheet_March2021.pdf.

climate-induced disaster.[21] Ensuring residents who are indigenous to the space have a social, economic, and political stake, such as through community land trusts and mixed housing stock, are emerging promising practices, he reported. Santos Hernández suggested better documentation of community land trusts and relocation as an opportunity for research. To build trust between communities and agencies, she said time and local expertise are important, and save money in the long run. Hendricks warned against superficial and misleading levels of participation.

Theme 2: Breakout Sessions

In considering physical, ecological, social, and economic elements when implementing natural infrastructure, **Todd Bridges** reported his group recognized the need for legal and financial innovations, in addition to engineering. They thought a workshop to bring finance, legal, engineering, and scientific experts would be useful. A group led by **Dipanjana Maulik** (Engineering Department, West Bengal, India) discussed decision support systems to provide real-time, field-level data algorithms with robust forecasting and feedback systems. **Sara Burns** (Ducks Unlimited) reported her group's push to consider systems-of-systems approaches and to look ahead, especially for disaster recovery funds. Eligibilities and guidance for these funds should incentivize planning for human health and safety, the group suggested. **Robert Prager** (Strategic Value Solutions) related community buy-in was a common theme in his group. Better data on non-coastal communities are needed, as are inspirational frameworks and branding to allow people to imagine possibilities, he added.

Wrapping up the first day, **Brett Wylie** (Jacobs) shared a visual summary of highlights. He noted participants' recognition of diverse solutions when designing for a dynamic future in a multi-hazard world (Figure 2), caution against an overreliance on models, and calls for collaboration and action.

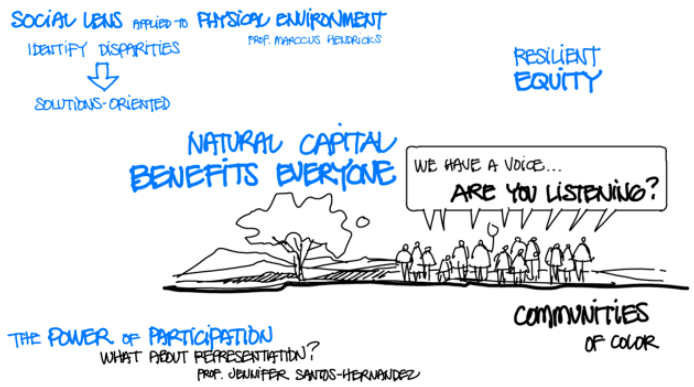

FIGURE 2 Day 1 visual wrap-up.
SOURCE: Brett Wylie, Workshop Presentation, May 10, 2022.

THEME 3: MAKING TIMELY PROGRESS—NEEDS FOR DESCRIPTIVE METHODS, MANUALS, AND STANDARDS

As planning committee member **Brian Bledsoe** (UGA) noted, a limitation to wider use of natural infrastructure is the perceived lack of standards and guidance for practitioners. He called attention to the American Society of Civil Engineers (ASCE) initiative on sustainable (not just natural) infrastructure with performance-based standards as a grand challenge.[22] He and committee member **Oluponmile Olonilua** (Texas Southern University) moderated a session on how to address these issues.

Theme 3: Keynote

Emily Corwin (Conservation International) proposed a multi-disciplinary collaboration to create "21st-century engineering guidelines to meet our 21st-century challenges." Given the lack of accepted norms and standards for natural infrastructure, the challenge is to increase the experience, familiarity, and confidence of engineers, developers, and others in the reliability and application of green-gray approaches, she stated. Moreover, the International Institute for Sustainable Development calculated substantial savings from nature-based infrastructure.[23] Barriers to greater use of gray-green infrastructure include lack of confidence in its reliability and inequitable availability of technical knowledge and data, Corwin said. While acknowledging few accepted engineering standards for nature-based infrastructure exist, many guides and

[21] The Nansen Initiative Protection Agenda defines disaster displacement as "situations where people are forced to leave their homes or places habitual residence as a result of a disaster or in order to avoid the impact of an immediate and foreseeable natural hazard." See https://disasterdisplacement.org/the-platform/key-definitions.

[22] For more information, see https://www.asce.org/communities/institutes-and-technical-groups/sustainability/sustainability-roadmap.

[23] For more information, see https://www.iisd.org/articles/nature-based-infrastructure.

resources provide information to begin, including the International Guidelines on Flood Risk Management discussed earlier and two outputs developed by the Global Green–Gray Community of Practice: *Practical Guide to Implementing Green–Gray Infrastructure* and *Mangrove–Seawall Engineering Guidance*.[24] Many engineers who are "early adopters" and/or feel comfortable using best practices and principles are fully engaged with natural infrastructure, Corwin said, while others will continue to hesitate without more standards and guidance. To involve more engineers, it is important to continue learning-by-doing, recognizing that flexibility is often required and that competent engineers will innovate by applying and improving upon best practices and principles.

To strengthen evidence-based decision-making, which is one of the 10 principles of the International Good Practice Principles for Sustainable Infrastructure from the United Nations Environment Programme, Corwin encouraged increased monitoring and data-sharing.[25] She proposed a data-sharing platform, or Natural Infrastructure Engineering Hub, across disciplines and geographies. Built by and for users, it could crowd-source information on technology, performance, and cost to inform descriptive methods; link to and provide consistent key performance indicators; and enable sharing of successes and failures. The International Stormwater BMP Database,[26] which has been critical in advancing the application of green stormwater infrastructure, could serve as a model, she posited. A hub could close and shorten the feedback loop between discovery, application, and advancing practice, and strengthen pre-competitive collaboration. The resulting methods, manuals, and standards could become available to practitioners around the globe. Questions include how to fund implementation of a hub, who might host it, and how to require or incentivize stakeholders to provide input and use it. In the absence of traditional engineering standards, Corwin urged a hub to address barriers and increase global implementation of natural infrastructure.

[24] For *Green–Gray*, see https://www.conservation.org/docs/default-source/publication-pdfs/ci-green-gray-practical-guide-v08.pdf. For information about Conservation International's work with mangroves in Guyana, see https://www.conservation.org/gcf/projects/unlocking-the-potential-of-guyana-s-inland-and-mangrove-forests.
[25] For more information, see https://www.unep.org/resources/publication/international-good-practice-principles-sustainable-infrastructure.
[26] For more information, see https://bmpdatabase.org/.

Theme 3: Panel and Discussion

Bruce Ellingwood (Colorado State University [CSU]) said he agrees with Corwin but with a different perspective as a structural engineer. He explained building codes are specific about some natural hazards but less so about others, especially related to climate change. He stressed that uncertainty characterizes engineers' decision-making. Uncertainty leads to risk, which can be managed but not eliminated. While standards for traditional engineering approaches also have limitations, he commented that uncertainties related to performance, cost, and other factors make engineering using natural infrastructure more difficult in building a business case.

Ellingwood supported Corwin's idea of an engineering hub. For engineers to become involved and take on the liability of engineering in the public interest, he also pointed to a performance-based engineering (PBE) framework, which he described as a mix of traditional and innovative methods with peer review as an important ingredient. Risk across the lifecycle can be modeled to build the case for public investment. Ellingwood discussed these concepts as they relate to climate variability and community resilience.

Ducks Unlimited's engineering staff have been involved in projects that illustrate the points made by Corwin and Ellingwood, said **Ellen Herbert** (Ducks Unlimited). As a turnkey organization, Ducks Unlimited identifies locations, forms partnerships, and is involved in permitting and construction in natural infrastructure projects that manage hazards and provide other benefits, such as the Sonoma Land Trust and the Richland Creek Wildlife Management Area.

Herbert delineated between performance-based and prescriptive standards. She noted learning-by-doing can happen through leveraging networks and investing in monitoring. She called for convening stakeholders, developing process-based standards, identifying common tools and frameworks, and sharing learning. As a model from another sector, Herbert cited the Field to Market

process developed for agricultural sustainability.[27] To develop process-based standards for natural infrastructure, she suggested establishing outcome goals based on design and scale, defining system boundaries, and estimating trajectories of function over time. Bledsoe concurred that natural infrastructure must be considered not just as "things in space, but as processes over time."

Ram Mohan (Anchor QEA; Texas A&M University) reflected on highlights of the previous presentations: nature heals best over the long term; challenges are evolving; case studies exist for nature-based structures in coastal and fluvial systems, although maybe not enough information on failures; learning-by-doing and adaptive management require flexibility; and a lack of uniform standards or guidelines. Based on his own work developing guidelines for shoreline protection, he cautioned against total standardization for nature-based infrastructure because of the myriad of variable, dynamic situations. In applying NBS, he noted the need to look at the time horizon for the intended design and clear communication about expected results. He also pointed out that using performance rather than prescriptive design assumes a certain level of contracting and design expertise. A key element is how to assess if a proposal meets minimal standards, which is easier with prescriptions. "We know how to evaluate structural benefits, but not other benefits," he said.

System-wide projects may need decades to fully show impacts and benefits, so maybe a phased approach should be encouraged, he said. Social and environmental justice aspects must be considered in all projects and across the long term. The initial cost for a project may be low, but who pays over time, especially in uncertain, dynamic situations, he posed. Regulators may also impose hurdles, such as about the re-use of dredged materials. Mohan said he supports the concept of a hub but commented on the need to include innovative approaches, provide enough data to make the hub robust, and share information on under-performing projects and corrective actions. Standards and guidance are useful to provide basic information and control liability, but they should be adaptable and not handcuff engineers, he concluded.

In discussion, Bledsoe observed different understandings of what constitutes a standard, from a general "consider this" to a four-inch binder. A participant noted the move away from prescriptive standards puts more burden on entities that issue permits to evaluate the work proposed. Corwin agreed permitting is more difficult but opined that performance-based standards should also include investing in post-project monitoring and documentation. Ellingwood suggested giving the move from prescription to performance "time to work." As an analogy, performance-based standards to deal with seismic events became accepted over several decades. Thus, natural infrastructure performance standards might be more acceptable in the near future.

Olonilua asked the engineers on the panel how to involve the public. Herbert commented on instances of communities' fear as well as overenthusiasm for natural infrastructure projects. Corwin advocated for further exploration of how citizen scientists can co-create, monitor, and manage projects. A participant encouraged engineers to connect with people to better understand what they deal with in their everyday lives. .Mohan urged outreach as part of a project's goals and objectives. Rather than just explain risks and uncertainties, he suggested building excitement in a local community, for example by involving students in baseline monitoring. Ellingwood said several testbeds at CSU are using the "roadmap" in the National Institute of Standards and Technology (NIST)'s Community Resilience Planning Guide.[28]

Several participants asked about learning-by-doing. Herbert suggested accelerating the process for successful pilots based on basic first principles and then modeling performance under a range of conditions. Corwin suggested designing projects as experiments to answer research and performance questions. Mohan noted natural infrastructure projects may involve defining a broad band and timeframe of success. Bledsoe reflected

[27] For more information, see https://fieldtomarket.org/.

[28] For more information, see https://www.nist.gov/community-resilience/planning-guide.

this paradigm shift requires training the next generation and infusing it into the mainstream of engineering practice through education at all levels.

Studying failure is valuable, but organizations do not want to share failures, a participant observed. Bledsoe agreed a critical step is creating a safe space. Mohan suggested maintaining confidentiality and establishing labs and experimental spaces to evaluate concepts.

Theme 3: Breakout Sessions

Breakout groups considered the mix of needed qualitative and quantitative methods and standards. **Michelle Covey** (UGA) said her group stressed that complex systems need multiple measures and standards. They also observed some expectations set for natural infrastructure are not set for conventional infrastructure, for example the expectations related to environmental justice. **Dave Hampton's** group suggested managing uncertainty could be cast as an opportunity, with shorter time horizons for better predictions and addressing stakeholder concerns. **Dan Walker** (EA Engineering; University of Maryland) related his group had a "holistic discussion" to figure out which tools, especially quantitative tools, to develop to meet future needs. **Dipanjana Maulik**'s group agreed to have predominantly quantitative methods with qualitative methods for contextualizing risk and public communication. The group called for widespread knowledge sharing. **Charles Van Rees** (UGA) said his group sees pilot projects important, but warned about putting everything on hold while waiting for the results, given each project is different in any event. **Trevor Meckley** (National Oceanic and Atmospheric Administration [NOAA])'s group suggested reviewing existing standards to consider how they apply to natural infrastructure. Rather than engineer "asset by asset," the group called for corridor-wide planning.

THEME 4: SYNCHING WITH POLICIES—REQUIRED EFFORTS AND PARTNERSHIPS TO SCALE UP

In launching the last panel, planning committee member **David Waggonner** (Waggonner & Ball, LLC) noted infrastructure must be designed and built for the everyday and chronic, not just for catastrophes, and at all scales, in both urban and edge conditions, and with decarbonization prioritized. Also, legal and policy guidance for local governments is critical.

Theme 4: Keynote

As described by **Shana Jones** (UGA), modern environmental law embodies cooperative federalism with both carrots and sticks at the local, state, and federal levels. Local jurisdictions in coastal areas, for example, must piece together multiple laws administered by multiple agencies. Governments, industry, private property owners, nongovernmental organizations, and others all have interests to meet. Jones reported on a National Science Foundation-funded project to examine shoreline stabilization laws and policies in seven states (Florida to Delaware).[29] The study documented the multiple values and interests proliferating across the states; erosion is the primary factor guiding most stabilization structure choices; armored shorelines are almost always held to a lesser standard than nature-based living shorelines under approval processes; and connectivity in armored areas, rather than ecological connectivity, is embedded in many regulatory frameworks. Many laws and regulations come from an era when environmental protection focused on a single resource or individual threat, she added. In addition, a strong need exists to influence shoreline stabilization decision-making before the permitting process begins, as neighbors and contractors greatly influence property owner preferences. Planning and regulatory systems must better recognize the varied dynamics of natural systems and the complexities of human demands on them.

Highlighting the history of USACE's policies, Jones noted the six principles for water resources planning and evaluation contained in the Principles, Requirements, and Guidelines (PR&G). Despite stated support for natural infrastructure, she noted the need to update relevant polices, such as engineering regulations, circulars, and manuals, because "at the project level, natural infrastructure is still not implemented at scale." She also

[29] For a table of relevant laws and policies by state, see https://www.vims.edu/ccrm/research/climate_change/adaptation/nsf-2/_documents/state-by-state-living-shoreline-regulations-112821.pdf. See also S. Jones and J.S. Pippin. 2021. Stabilizing the edge; Southeastern and Mid-Atlantic Shorescapes Facing Sea-Level Rise, *Columbia Journal of Environmental Law*, 46(S). https://doi.org/10.7916/cjel.v46iS.8003.

urged reconsideration of the floodwall reliance in the Miami-Dade Back Bay Coastal Storm Risk Management Feasibility Study[30] to deploy the NBS favored by developers, environmentalists, and community members. More broadly, Jones urged "shorescape" decision-making rather than stopping at a jurisdictional or other human-imposed boundary. Examples of partnerships to accomplish this include the South Atlantic Salt Marsh Initiative[31] and EWN for Climate Resilience on Military Installations.

Theme 4: Panel and Discussion

Jessica Ritter (National Wildlife Foundation [NWF]) highlighted natural infrastructure partnerships with which NWF is involved. She said she has seen progress and welcomed the attention to natural infrastructure at the federal level, including at USACE, but noted a void between support and ground-level action. She commented on a negative feedback loop present within USACE and the field more broadly, in which there is a reluctance to be the first to try new and innovative approaches, yet examples are needed to build confidence and experience. Go-to solutions are still often single-purpose projects, which she attributed to a cultural challenge and policy dynamic between USACE and nonfederal project sponsors. If a community requests a levee, for example, that is what the agency delivers rather than proactively suggest other solutions. Recognizing the importance of local cost concerns, Ritter offered two areas of recommendations to break negative feedback loops.

First, she suggested, creating policy incentives so communities ask for natural infrastructure, referring to the Environmental Protection Agency's Green Project Reserve as an example. USACE could set targets so that a certain percentage of new projects incorporate a natural infrastructure feature by 2030, she posited. The SHORRE (Shoreline Health Oversight, Restoration, Resilience, and Enhancement) Act[32] moving through Congress has a provision to lower the nonfederal cost share for these projects, which would provide another incentive. She also recommended removing difficulties in permitting to achieve "regulatory parity" between natural and conventional projects. She noted property owners can become more interested through policies such as permitting fee waivers or tax incentives.

Second, looking at USACE, Ritter reminded the group that EWN principles can apply anywhere in a project lifecycle. USACE has broad authority to make modifications to existing projects, which Ritter commented is currently underutilized. Pending implementation of the Principles, Requirements, and Guidelines represents a "big opportunity to flip the script," Ritter said. She urged looking more holistically at watersheds, first considering natural infrastructure options or hybrid solutions, only then moving on to structural solutions when nature-based or hybrid solutions are insufficient.

Sarah Murdock (The Nature Conservancy) continued to discuss federal policy making. Consideration of climate impacts when making investments and incentives for natural infrastructure across agencies unlock resources and opportunities, as does the Infrastructure Investment and Jobs Act. To operationalize investments in natural infrastructure through these opportunities, Murdock called attention to challenges to more easily and accurately value natural infrastructure to capture the full suite of ecosystem service benefits. She added this need ties in with updating USACE' PR&G and how USACE conducts benefit-cost analyses. There is not a full capturing of all benefits from natural infrastructure, Murdock said, adding that single-purpose design and scoping misses maximizing benefits for other purposes. Additionally, water quality, recreation, aesthetic, and other benefits are hard to translate into dollars, and she called for qualitative ways to capture such benefits. Updating the guidelines should be accompanied with outreach, training, and education for district-level Corps staff to aid in the application of any new guidance on valuation coming out of the PR&G update.

Agreeing with the need for engineering guidance on the performance and effectiveness of NBS, especially related to metrics, Murdock warned against striving

[30] For more information, see https://www.saj.usace.army.mil/MiamiDadeBackBayCSRMFeasibilityStudy/.
[31] For more information, see https://serppas.org/focus-areas/south-atlantic-salt-marsh-initiative/.
[32] For more information, see https://www.congress.gov/bill/117th-congress/house-bill/6705?s=1&r=2.

for engineering specifications that would apply to all projects. As others during the workshop stated, no one size fits all. "What we need is innovation and continued adaptive management," she concluded. "We need outside-the-box thinking and creativity."

As chief resilience officer, **Dale Morris** (City of Charleston) spoke from a local government perspective dealing with politics, citizens, businesses, tidal creeks, marshes, voter expectations, and much more. Morris provided background about how his metropolitan area is dealing with compound flooding and sea-level rise. A 2019 analysis identified physical and social vulnerabilities, and recent floods that occurred without direct hurricane hits galvanized community interest. The city spent 25–30 percent of its budget on drainage this year. A 2021 City Comprehensive Plan[33] was recently adopted with water as the organizing principle, the first in the nation. Morris summarized development by the city and USACE of the Charleston Peninsula Coastal Storm Risk Management Study (CSRM). He reported that stakeholders have reacted that the plan only deals with storm surge, and not tidal or stormwater flooding, and has little in the way of nature-based features.

Morris said policy challenges include how to modernize law so USACE can help coastal communities respond to diverse and compounding flood risks beyond storm surges, and how to better factor analysis of nature-based features into feasibility alternatives and design efforts. International efforts can provide experience and analytical support, he said, as can pilots and learning projects. "Without increased flexibility on increased flood risk management and a mandate to include natural and nature-base features or hybrid infrastructure, USACE risks becoming a post-disaster response agency and not a pre-disaster mitigation agency," he warned.

In discussion, a participant questioned whether a minimum investment requirement for nature and social elements in all projects would help overcome the "structure-first" thinking within USACE, while another said the agency should have the flexibility that other agencies have in considering qualitative benefits.

[33] For more information, see https://www.charlestoncityplan.com/.

Murdock agreed with the need to place all benefits on a level playing field. She expressed hope that revision of the PR&G could help move in the right direction. Another need is to address relevant Benefit Cost Analysis policies and discount rates, which do not take into account the benefits of natural infrastructure. She said the current Office of Management and Budget (OMB) discount rate is a huge deterrent.[34] Ritter suggested setting targets within the USACE's portfolio and depending on a project's needs. Jones agreed a portfolio target makes sense. When Bridges suggested "for discussion" setting a minimum level of 10 percent for natural and social investment in every coastal storm risk management project, Morris noted a minimum requirement would have resulted in a different outcome in the Charleston CSRM.

Several participants commented about terminology. One suggested the term "buffer" to explain green infrastructure to the public. Lack of clarity around the terms "mitigation" and "adaptation" was raised, as well as a suggestion about using lifecycle benefit (not just cost) analysis. Beagle noted a January 2021 USACE memo instructs districts to evaluate for all four accounts, as opposed to basing planning decisions solely on the least-cost option (or the National Economic Development account).[35] Tools are needed to do this, she said. She also noted the role of multipurpose business lines to address challenges of the future. Schmidt urged looking at all water types in large-scale projects. Ritter added the importance to break down silos within USACE and across other agencies. Waggoner underscored the value of pre-disaster cases.

In response to a question about strengthening the state-federal interface, Jones said state resilience officers can help coordinate multiple agencies and jurisdictions. Murdock noted coordination across state-level agencies unlocks the potential to combine funding, programs, and processes. Comprehensive watershed planning that involves stakeholders is a good model, pointing to

[34] Discount rates are used to come up with a calculation of the trade-off between present and future benefits. Calculations of non-monetary benefits, such as ecosystem services, can be challenging. The 2021 discount rates can be found at https://www.energy.gov/sites/default/files/2021-04/2021discountrates.pdf.

[35] See https://planning.erdc.dren.mil/toolbox/library/MemosandLetters/ComprehensiveDocumentationofBenefitsinDecisionDocument_5January2021.pdf.

Louisiana and Iowa as recent examples, she added. A participant suggested more state voices should be heard in workshops like this, and that the federal government can incentivize state-level leadership by providing funds that states can funnel to local communities. Jones emphasized a need for "people capacity" to work on the ground across interfaces. There are many impactful local activities but systemic approach to coordinate across jurisdictions in a landscape is needed. Collaboration is extremely important but requires time and resources, several participants observed. Jones related a concern about capacity expressed to her by federal agency staff who will have to do more consultations under new legislation. "Perhaps this crisis of capacity is an opportunity to introduce new ways of doing things," she suggested. Ritter urged building back capacity within USACE and other agencies to the greatest extent possible to ensure both thorough and efficient review.

Theme 4: Breakout Groups

One group reported out on this theme. Robert Prager reported his group urged adapting existing policy to include natural infrastructure, developing an equal playing field to evaluate different options, and engaging with communities. While not ideal, sometimes it takes a disaster to bring partners together. It is also important to "expand the conversation and engage the opposition," to bring more attention to the issue, the group opined.

CONCLUDING COMMENTS

In sharing graphics to summarize the workshop, Brett Wylie observed that relating complex ideas to non-technical experts may benefit from the format he used, along with other communication tools. Looking across both days, Wylie observed many speakers addressed how USACE can enable and amplify implementation of natural infrastructure. He noted the first day of the workshop concentrated on ***why*** use natural infrastructure; the second had healthy dialogue that focused on ***how.*** Even without total agreement on the direction and tools, he commented on the need to take action and move forward (Figure 3).

Bledsoe related final thoughts from Gerry Galloway. Galloway said the presentations and discussions highlighted that natural infrastructure is at the point where it should not be an afterthought but instead a full partner at the table. "Now is the time to act and not be embarrassed by being pushy," Galloway said. "Natural infrastructure is ready."

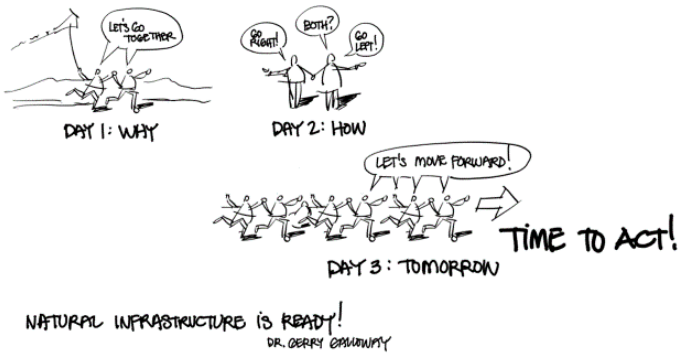

FIGURE 3 Day 2 visual wrap-up.
SOURCE: Brett Wylie, Workshop Presentation, May 11, 2022.

DISCLAIMER This Proceedings of a Workshop—in Brief was prepared by **DANIELLE GOLDSMITH, BERNA OZTEKIN-GUNAYDIN, NEGIN SOBHANI,** and **PAULA WHITACRE** as a factual summary of what occurred at the workshop. The planning committee's role was limited to planning the workshop. The statements made are those of the rapporteurs or individual workshop participants and do not necessarily represent the views of all workshop participants; the planning committee; or the National Academies of Sciences, Engineering, and Medicine.

REVIEWERS To ensure that it meets institutional standards for quality and objectivity, this Proceedings of a Workshop—in Brief was reviewed in draft form by **BRIAN BLEDSOE,** University of Georgia; **SARA BURNS,** Ducks Unlimited; **JANINE CASTRO,** U.S. Fish and Wildlife Service; **DAVE HAMPTON,** LimnoTech. The review comments and draft manuscript remain confidential to protect the integrity of the process.

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