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Perspective

Investing in Natural and Nature-Based Infrastructure: Building Better Along Our Coasts

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Abstract: Much of the United States' critical infrastructure is either aging or requires significant repair, leaving U.S. communities and the economy vulnerable. Outdated and dilapidated infrastructure places coastal communities, in particular, at risk from the increasingly frequent and intense coastal storm events and rising sea levels. Therefore, investments in coastal infrastructure are urgently needed to ensure community safety and prosperity; however, these investments should not jeopardize the ecosystems and natural resources that underlie economic wealth and human well-being. Over the past 50 years, efforts have been made to integrate built infrastructure with natural landscape features, often termed "green" infrastructure, in order to sustain and restore valuable ecosystem functions and services. For example, significant advances have been made in implementing green infrastructure approaches for stormwater management, wastewater treatment, and drinking water conservation and delivery. However, the implementation of natural and nature-based infrastructure (NNBI) aimed at flood prevention and coastal erosion protection is lagging. There is an opportunity now, as the U.S. government reacts to the recent, unprecedented flooding and hurricane damage and considers greater infrastructure investments, to incorporate NNBI into coastal infrastructure projects. Doing so will increase resilience and provide critical services to local communities in a cost-effective manner and thereby help to sustain a growing economy.

Keywords: coastal resilience; restoration; sustainability; infrastructure; ecosystem services

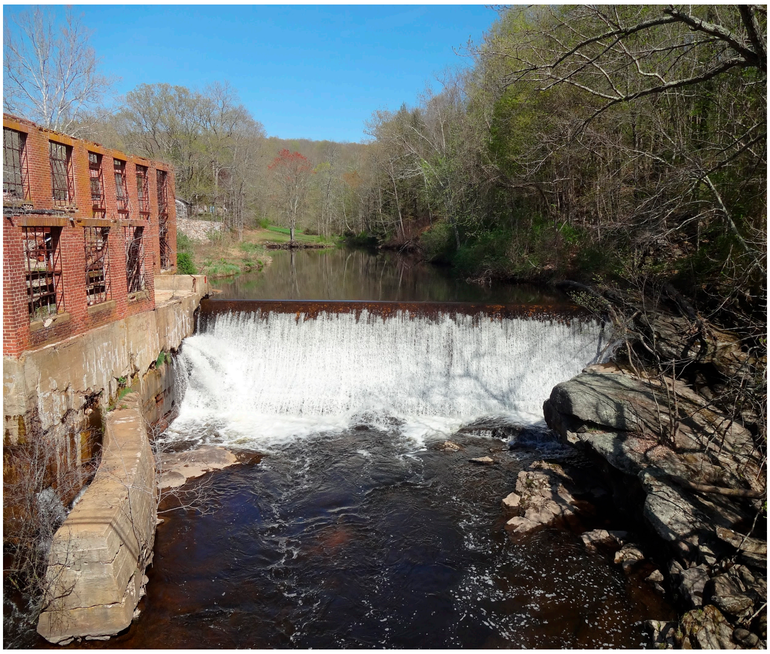
1. Introduction

Infrastructure in the United States—including roads, bridges, dams, levees, sewer and stormwater systems, and other built structures—is vital to the nation's security, economy, health, and safety [1]. Yet much of this critical infrastructure is either aging or in need of repair and/or replacement and is putting people and property at risk. For example, by 2020, up to 70% of U.S. dams will be over 50 years old [1]. Recent infrastructure failures, such as the Oroville Dam spillway collapse and the catastrophic flooding in Houston during Hurricane Harvey, demonstrate the significant consequences of failing to address our nation's crumbling and outdated built infrastructure [2]. In addition to these potential impacts, it is estimated that by 2025, 2.5 million jobs will be lost as a result of failing infrastructure if gaps in U.S. infrastructure investment are not addressed [1]. Investing in maintenance and repair of aging infrastructure must continue to be a priority but investment in the removal of outdated and vulnerable infrastructure, as well as investment in new infrastructure, is also necessary.

Society has learned much since the great "built" infrastructure projects of the 20th century, such as the Hoover dam, the Mississippi River levee system, and the Eisenhower interstate highway system. Dams, levees, canals, and bridges constructed in and across U.S. rivers and waterways have created drinking water reservoirs, reduced flood risk for people and property, generated hydroelectric power, expanded transportation options, improved navigation, and helped grow the U.S. economy, but not without significant socio-ecological consequences [3,4]. In some cases, built infrastructure (e.g., dams, undersized culverts, seawalls, and water-diverting levees and canals) has resulted in significant declines in the abundance of aquatic organisms (e.g., economically valuable anadromous fish species) and the diversity of key habitats, such as the Florida Everglades [4–9]. Further, this infrastructure has resulted in flood-related human fatalities and property damage when it has failed [10,11].

Societal recognition of these socio-ecological consequences has contributed to the decision to remove some built infrastructure where it has been deemed a hazard, is no longer needed or is too costly to repair or replace [6,12]. For example, in Taunton, Massachusetts, in 2005, heavy rain caused the near-failure of the neglected 170-year-old Whittenton Pond Dam. The flooding prompted costly evacuations and emergency action in order to prevent the dam from failing. To eliminate future threats, the town removed the dam and restored the river back to its natural form [13]. Dam removal is just one example of how communities are opting to remove old and deteriorating built infrastructure and restore ecosystems to enhance their resilience to future natural hazards (Figure 1).

Engineers and scientists have grown savvier about how to build new infrastructure with natural landscape features, thereby harnessing the emergent socio-economic benefits that come from natural and "hybrid" or nature-based solutions [3,4,14–16]. Natural infrastructure is also sometimes called "green" infrastructure and can be defined as "a network of natural or semi-natural features that has the same objectives as gray [built] infrastructure" [4]. Nature-based infrastructure can be defined as infrastructure that mimics characteristics of natural infrastructure but "is created by human design, engineering, and construction to provide specific services such as coastal risk reduction" [3]. The integration of natural infrastructure into built solutions delivers the added benefit of conserving, sustaining, and restoring valuable ecosystem functions and services to local communities [3,4,15–20]. Because green infrastructure is sometimes limited to urban areas [21] or more narrowly defined as simply "an interconnected network of green space" [22], we have elected to use the broader term natural and nature-based infrastructure (NNBI) to describe the types of infrastructure being considered in this paper.



(**A**)

(**B**)

Figure 1. The Norton Mill Dam (**A**) was located on the Jeremy River in Colchester, CT. The 12-foot high dam served an adjacent paper mill until the mill closed in the 1960s. Removal of this dam (**B**) opened 17 miles of high quality, forested, 'trout-stream' habitat and will benefit Atlantic salmon (*Salmo salar*), sea-run brown trout (*Salmo trutta*), sea lamprey (*Petromyzon marinus*), American eel (*Anguilla rostrata*), and Eastern brook trout (*Salvelinus fontinalis*). In addition, the dam was a threat to public safety from both upstream flooding and downstream flooding resulting from its failure. A submerged broken gate opening at the dam was an ongoing danger to boaters and swimmers who could have been trapped and drowned. The leaking dam undermined the structure of the adjacent brick mill, which could have led to a catastrophic collapse of a portion of the mill into the river, aggravating water control, flooding, and increasing jeopardy to the natural resources. Catastrophic failure of the dam would likely have resulted in damage to the CT Rt. 149 bridge, which is about 75 feet downstream of the dam, and would most likely have resulted in the scouring, undermining, and collapse of the Papermill Road bridge about 500 feet upstream of the dam (R. O. Bennett, *personal communication* and photo credit).

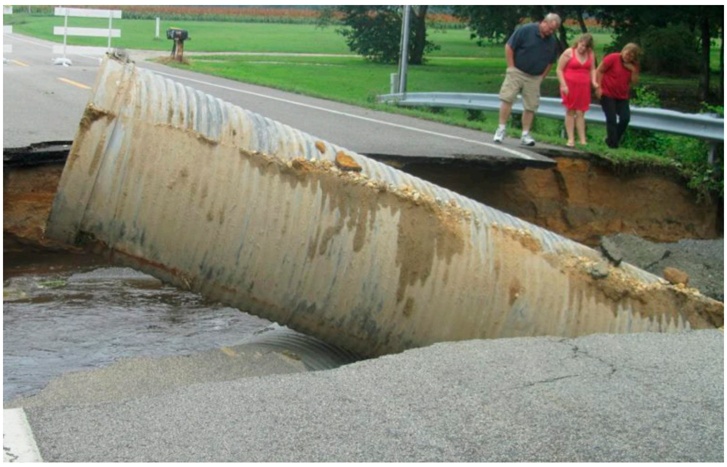
Over the last two decades, the need for investment in NNBI along U.S. coastlines has become increasingly apparent. Failure of deteriorating and outdated coastal built infrastructure, such as seawalls and levees, and the degradation and loss of natural infrastructure, such as coastal dunes and wetlands, have contributed to the loss of life and property caused by large, powerful coastal storms (e.g., Hurricane Katrina in 2005, [10]; Hurricane Sandy in 2012, [23]; Hurricane Harvey in 2017). These disasters provide "windows of opportunity" to assess opportunities for improvements in infrastructure design [24]. The lessons learned from these events also suggest that investment in NNBI solutions has the potential to reduce coastal erosion, limit damage to public and private properties, and prevent flooding of coastal communities.

2. Building Better Coastal Infrastructure

Natural coastal infrastructure, including beaches, dunes, oyster and coral reefs, seagrass beds, and marshes, can reduce wave energy, coastal erosion, and flood hazards [14,17,25–28]. For example, insurance industry models estimate that wetlands have saved more than $625 million in avoided flooding damages and that communities behind marshes experienced 20% less property loss during Hurricane Sandy [29]. There are also numerous opportunities to combine built and natural infrastructure in hybrid NNBI designs to provide additional storm erosion and flooding risk reduction, as well as the additional co-benefits that built infrastructure typically fails to deliver. Coastal NNBI co-benefits include the creation of habitats for commercially and recreationally valuable fishes, maintenance and enhancement of biodiversity, improved aesthetics and access to "nature" that can increase tourism and recreation, and improved water quality, with estimated benefits valued at over $100 billion annually [7,14,20,25,30]. Citywide Rebuild by Design© projects [31] and innovative urban flood management approaches that use novel engineering designs to mimic and restore natural landscapes are being used to improve flood resilience in New York, Bangladesh, and cities throughout the Netherlands [32]. Additional examples of the use of NNBI include site-specific "living shorelines" for erosion protection of waterfront properties (Figure 2, [33,34]), and stream-design culverts to restore natural tidal flow and reduce flood damage to roads and adjacent properties (Figure 3; [35]).

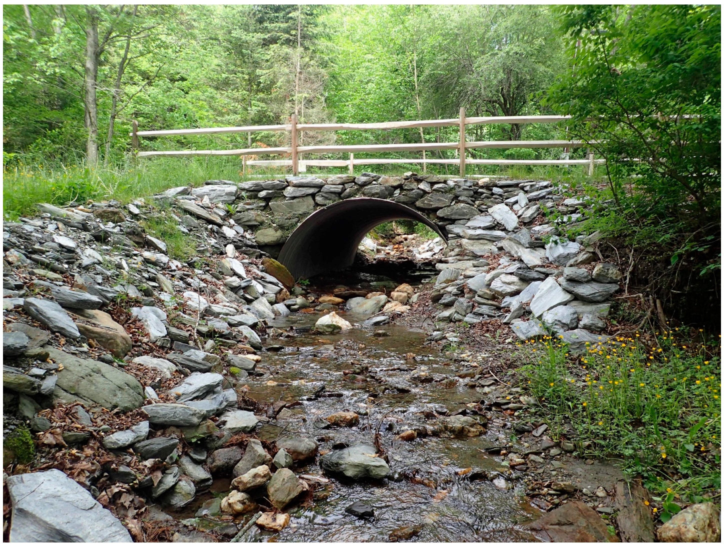
Infrastructure Type[a]	Installation Cost[b]	Annual Maintenance/ Repair Cost[b]	Annual Water Quality & Fish Production Value[c]
Built (seawall/bulkhead)	\$6,500 - \$9,800 m^{-1}	\$0 - \$1,710 $m^{-1}yr^{-1}$	\$0 $m^{-2}yr^{-2}$
NNBI (natural/living shoreline)	\$0 - \$6,562 m^{-1}	\$0 - \$328 $m^{-1}yr^{-1}$	\$1 - \$7 $m^{-2}yr^{-2}$

Figure 2. Comparison of costs and benefits of using built and natural or nature-based infrastructure for coastal protection. [a] Installation and maintenance costs for seawalls/bulkheads and natural and living shorelines from Chapter 8 of the National Park Service Coastal Adaptation Strategies Handbook [33]; [b] Seawall installation costs can be as high as \$32,800 per meter but the range is typically \$6500–\$9800 per meter. Maintenance and repair costs were converted to annual costs assuming a 50-year lifespan and do not include projects that involved complete structure replacement [33]; [c] Ecosystem service values per square meter (m^2) of oyster and salt marsh habitat components of living shorelines for the services of fish production and water quality [25,30]. Photo credit: R. K. Gittman.



(**A**)

Figure 3. *Cont.*



(B)

Figure 3. Using stream simulation design to restore habitat and reduce hazard risks. During Hurricane Irene more than 1000 traditional culverts (**A**) were damaged or destroyed by flooding, while damages to road-stream crossings constructed using stream simulation design were avoided (**B**); Stream simulation design mimics a stream or river's natural channel structure, sediment characteristics, water velocity and depth, and resting areas for aquatic organisms allowing for passage of aquatic organisms, debris, and water during various flow conditions including 100-year flood events. Although the initial installation cost can be higher than a traditional culvert, the cost of stream simulation designed road-stream crossings is offset in the long term via reduced maintenance and/or replacement costs associated with failures during storm events [14]. Photo credits: USFWS.

The decision to use traditional built over natural or nature-based infrastructure can often be based on short-term construction/installation costs without incorporating long-term maintenance and repair costs or the co-benefits associated with NNBI [14,27,33,35–37]. In addition, built infrastructure, such as seawalls, levees, and culverts, often incurs emergency repair and replacement (ER) costs, sometimes multiple times over its lifetime, and ER costs are generally higher than normal repair and replacement costs [10,33,35,37]. Moreover, built infrastructure is strongest the day it is built but often grows weaker with time and can require more maintenance expenditures than NNBI (Figure 2, [33,35,37,38]). NNBI, on the other hand, can strengthen with time, reduce the cost of construction and maintenance, and lengthen the lifetime of the built infrastructure [3,14,36]. Thus, investments today in NNBI can pay dividends well into the future by reducing the need for continued investment.

3. Opportunities to Invest in Coastal NNBI

The inclusion of coastal NNBI as a component of an investment strategy to update America's infrastructure, support the U.S. economy, and protect coastal communities is paramount. There will always be a need for built infrastructure as U.S. coasts are expected to see a continued increase in population and development; however, coastal communities will benefit most from policies that prioritize the inclusion of NNBI options into coastal infrastructure planning, upgrades, and investments [3,14,17,39]. The U.S. has made significant progress in some infrastructure sectors over the past two decades—especially in stormwater and sewer infrastructure and in green building design and standards—by integrating natural or nature-based hybrid solutions. For example, as part of the Executive Order 13693, "Planning for Federal Sustainability in the Next Decade," federal agencies are required to install "appropriate green infrastructure features on federally owned property to help with stormwater and wastewater management." Another recent example of prioritization of NNBI investment is the 2016 Water Infrastructure Improvements for the Nation (WIIN) Act, which specifically recommends that the U.S. Army Corps of Engineers (USACE) use NNBI, including wetland restoration and dam rehabilitation and removal, to enhance coastal resilience and reduce flood risks [3,36]. Despite these recent advances, coastal communities in the U.S. are still vulnerable to flooding and erosion associated with major coastal storms, extreme precipitation events, and rising sea levels, as was recently demonstrated by the catastrophic flooding and property damage caused by Hurricanes Harvey, Irma, and Maria in 2017 [40–42]. There is an opportunity now to incorporate NNBI along with built infrastructure as we work to make coastal communities more resilient.

Funding of coastal infrastructure projects, built and nature-based, is always challenging and consequently requires commitment from multiple levels of governance. Notably, municipal, state, and federal branches of the U.S. government have already begun using incentives effectively to promote the adoption of NNBI, while also saving money. For example, FEMA's Community Rating System (CRS) provides 5–45% discounts on insurance premiums in communities that take some combination of risk-reducing actions, including the preservation of natural areas in high flood-risk areas [36]. The CRS program could further incentivize investments in NNBI by awarding more risk-reduction points to communities that use NNBI to reduce flood risk. Additionally, green bonds, which are currently used in the state of Massachusetts to acquire and conserve land, and infrastructure banks, which are used by 32 states for transportation infrastructure, could also be used to fund NNBI projects [36]. Thus, although there remains a significant need for policies and funding mechanisms to facilitate the inclusion of NNBI alternatives for infrastructure projects, good example programs and funding mechanisms exist that could be used to support additional investment in NNBI. What is needed is commitment and, in some cases, policy changes at all levels of government to support NNBI investments as part of increased infrastructure investments.

Bipartisan support in the U.S. Congress for recent infrastructure bills, such as the 2016 WIIN Act, and the proclaimed prioritization of infrastructure investment by the current U.S. President demonstrate an opportunity to capitalize on this momentum and to prioritize investments in NNBI in forthcoming legislation. This bipartisan support stems in part from the current dilapidated state of much of the nation's infrastructure, which consequently impacts Americans on a regular basis [1]. The WIIN Act, which passed with greater than a two-thirds majority in both chambers, demonstrates strong support for the role of NNBI in our nation's infrastructure system. However, action by the federal government is not the only option for increasing investment in NNBI.

State and local levels of government can aid in facilitating the adoption of NNBI in infrastructure investments. For example, Maryland has been leading in promoting living shorelines with the passage of the Living Shorelines Protection Act in 2008. In this policy, the default for shoreline protection is to use an NNBI living shoreline option unless a property owner can demonstrate they need to put in a built feature such as a bulkhead instead. Another example of state investment in natural infrastructure restoration is the Massachusetts Department of Ecological Restoration (MA DER) promotion of dam removal. Since 2005, MA DER has removed over 40 dams, with the priority being the removal of aging dams that could fail and are no longer needed [43]. Post-superstorm Sandy, New York City (NYC) is considering using vegetated berms and converting current built infrastructure to open green space to reduce flood risk as part of "The East Side Coastal Resiliency Project" [44]. Other major U.S. cities, including Boston and San Francisco, are partnering with Rebuild by Design© to develop citywide plans to improve resiliency to climate change, which include restoration and implementation of NNBI [31].

In addition to public investment in NNBI, there is likely a role for private investment in NNBI as well. International companies value the associated societal and ecological benefits that accompany NNBI. For instance, an industry-led white paper by The Dow Chemical Company, Shell, Swiss Re, and Unilever evaluated the use of natural infrastructure and concluded that it is an essential component of business solutions to increase the resilience of business operations [45]. To attain more resilient company facilities, the report emphasized opportunities to rejuvenate or replace aging built infrastructure with NNBI solutions where environmentally stressed areas would receive co-benefits such as better land management, flood and erosion protection, and enhanced biodiversity. The use of

NNBI was determined to be more cost effective than traditional built infrastructure, to provide new opportunities for stakeholder engagement, and to benefit business, communities and the environment. Given that the demand for infrastructure spending far outstrips the public's appetite for government spending, with drinking water infrastructure updates requiring an estimated $1 trillion [1], innovative solutions that engage private sector buy-ins are essential. For example, public-private partnerships could be used to leverage public spending with private support to implement natural infrastructure projects that also benefit industry [36,45].

4. Challenges to Implementing NNBI Solutions

Importantly, there is no "one-size fits all" solution for infrastructure improvements. All infrastructure projects need to be designed to address the needs of each community or site. Despite the potential socio-ecological benefits of integrating NNBI into our current and future coastal infrastructure, uncertainties still remain about the long-term performance of NNBI as the climate changes and how best to design and use NNBI for coastal storm damage and flood protection [3,16]. An understanding of the site-specific environmental conditions that are necessary for the natural infrastructure to match the projected rates of sea level rise has improved, such as sufficient sediment to support salt marshes and the optimum tidal height for the placement of intertidal oyster reefs [19,46–48]. Yet, translation of this information into broad guidance for the design and siting of NNBI has only recently been attempted [3,49]. Further, the development of easily interpreted, universal metrics for measuring short- and long-term NNBI performance, such as the universal metrics developed for restored oyster reefs, will be critical to the widespread adoption of NNBI strategies [50]. Additionally, there is a need to monitor NNBI projects during and after storm events to assess performance under extreme conditions [34,37]. Finally, the use and refinement of existing national or regional socio-ecological indices, such as the Coastal Vulnerability Index [51] and Coastal Hazard Index [17], and the development of new indices could allow for more efficient, cost-effective, and appropriate siting of NNBI [14,17]. These efforts will help to demonstrate the effectiveness of NNBI and to reduce uncertainty about the role of NNBI in coastal resilience efforts.

While NNBI has great potential to protect coastal communities and ecosystems, many barriers currently limit its potential. For instance, NNBI approaches often do not conform to current permit and zoning regulations. USACE permitting of bulkheads and living shorelines is just one example of where U.S. federal and state regulations have historically inhibited and even discouraged the use of NNBI in preference of traditional built infrastructure, despite the clear socio-ecological benefits of NNBI [9,14,20]. However, USACE has made progress towards addressing this challenge: in March 2017, it implemented Nationwide Permit 54 for living shorelines [52], which will hopefully facilitate the implementation of NNBI shoreline projects. Other policy barriers remain, however, which limit the opportunities for infrastructure to maximize return on investment. For example, in some cases, particularly after a disaster, communities are not able to upgrade infrastructure to enhance their community's resilience to future disasters. Under the Public Assistance Program from the Federal Emergency Management Agency (FEMA), funding is available to rebuild a structure to its pre-disaster condition but not to upgrade it, or funding is insufficient to cover the cost of upgrades [10,35]. Unfortunately, this approach can be less cost efficient, lead to additional maintenance costs, and increase the risk of future failures [35]. Thus, it is critical that policymakers update agency guidance and regulations to broadly enable communities to design NNBI that will last longer and function better than the existing built infrastructure.

5. Conclusions

A changing climate coupled with increasing levels of natural hazards has exacerbated the risks associated with aging built infrastructure and reduced the life expectancy of existing and future built structures along coastlines. Investing in NNBI designs that are more resilient to disasters provides greater protection to coastal communities, while also being cheaper to maintain over the long term.

This investment equates to good stewardship of taxpayer dollars. Furthermore, investments in coastal NNBI will benefit society by providing cost-effective strategies to protect coastal communities, as well as provide many co-benefits not provided by traditional built infrastructure. Although challenges remain in implementing coastal NNBI, including the gathering of data on long-term performance, developing appropriate NNBI siting guidance, and overcoming obstacles with permits, the return on investment from coastal natural and nature-based infrastructure to society is expected to be high [3,14,17,39]. Now is the time to invest in coastal infrastructure that has the capacity to meet societal needs in the face of environmental change.

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