Scaling protection and restoration of natural infrastructure to reduce flood impacts and enhance resilience

By

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ABSTRACT

Restoring natural infrastructure offers much promise as a means to reduce both flood hazard and exposure to complement and supplement other flood damage reduction strategies. Interest increased in flood risk reduction methods using natural and nature-based features, in part, because of increased recognition that such could provide both flood risk reduction and other benefits, such as water quality uplift, community recreational space, and fish and wildlife habitat. Recent flood disasters and the rising costs of disaster response and recovery have triggered policy shifts toward economically efficient investments that enhance greater community resilience. While natural infrastructure is becoming more widely recognized as a tactic for building community and ecological resilience to erosion and flooding, it remains underutilized. Actions to aid consideration of natural infrastructure and scale up its use are presented.

ADDITIONAL KEYWORDS: Flood resilience, natural infrastructure, ecosystem functions, risk reduction.

Urban, industrial, and agricultural expansion into riparian and coastal floodplains occurring concurrently with aging and inadequate infrastructure networks has amplified our vulnerability to floods. As a result, the cost of storm events is rising; from 2015 through 2018, the United States experienced eight flooding disasters that each exceeded $1 billion and collectively cost $25 billion (NCEI 2019). Buchanan *et al.* (2017) estimated, based on probabilistic relative sea level projections and fixed storm frequency, a 40-fold increase in the expected annual number of local 100-year floods for U.S. coastal locations by 2050. Climatology-hydrodynamic modeling that takes into account both sea level rise and changes in tropical cyclones frequency and intensity, found that the historical 100-year flood level would occur annually in the northeast and mid-Atlantic states and every 1-30 years in southeast Atlantic and Gulf of Mexico regions in the late 21st century (Marsooli *et al.* 2019).

Reducing the damages from flooding requires managing the hazard (i.e. flood waters), reducing exposure (i.e. people and infrastructure present in flood hazard areas) and lowering vulnerability (susceptibility to the damaging effects of a hazard). Reducing flood risk by relying on traditional flood "control" structures, building codes, and insurance has met with mixed success at best as demonstrated by the devastation and economic impact of significant flooding in areas beyond identified 100-year floodplains (e.g. widespread winter flooding in the Midwest, 2015; Baton Rouge, 2016; and Houston, 2017) and repetitive flooding events of known flood hazard areas (e.g. Princeville and Kingston, North Carolina; Des Moines, Iowa; and Ellicott City, Maryland). The nation's approach to flood risk is insufficient and can be improved. Given increasing flood risk, the nation needs to adopt a far more concerted and multifaceted approach that simultaneously addresses hazard, exposure, and vulnerability to reduce the socio-economic impacts of floods and improve resiliency when floods do occur.

Restoring natural infrastructure may be the key missing tactic for reducing both flood hazard and exposure to complement and supplement other flood damage reduction approaches. (For simplicity, this paper includes natural features, nature-based processes, and green infrastructure under the rubric of "natural infrastructure"). Along the nation's seaboard, development, leveed rivers, declining water quality, and erosion from rapidly rising seas led to deterioration and loss of features including marshes, mangroves, barrier islands, dunes, and reefs (see Alexander *et al.* 2012, Feagin *et al.* 2005, Polidoro *et al.* 2010, Dahl 2011, NOAA 2017 for information on causes and trends of habitat loss). Habitat deterioration and loss means loss of key ecosystem services. Losing these "first lines of defense" has increased exposure to riparian floods and coastal waves, storm surge, and king tide flooding. Therefore, reversing habitat loss by restoring natural infrastructure is a way to reduce the effects of flood-intensifying conditions associated with climate change (e.g. more intense precipitation, higher waves, accelerated coastal erosion) and mitigate effects of expanded urbanization of floodplains (see Figure 1). Protecting and restoring natural infrastructure can lessen the human impacts on hydrology and the environment by combatting erosion, promoting water storage and infiltration, attenuating flood peaks, dampening wave heights and dissipating wave energy (NAS 2014; Spalding *et al.* 2014; Cunniff and Schwartz 2015; and Nilsson *et al.* 2018) and thus reduce flood damages. Natural infrastructure also offers other advantages, such as recreational space, water quality improvement, and fish and wildlife habitat to yield solutions that improve community quality of life on a daily basis and not just when a storm occurs.

NATURAL INFRASTRUCTURE FUNCTIONS

Flood height is one of the most critical determinants of the economic cost of a flood (Williams *et al.* 2012) and inches can make a big difference; therefore, natural infrastructure techniques that aid holding water on lands upstream of developed areas or on less-developed floodplains can reduce flood damages. Well-managed forests and agricultural land using sustainable practices, such as cover crops, can absorb more precipitation and slow surface flow to reduce downstream flood height and flood speed (Nilsson *et al.* 2018). This is due to several factors: areas with greater foliar cover and leaf litter cover intercept and slow precipitation hitting the soil, reducing the rate of overland flow, reducing erosion, and together with healthy soils increas-

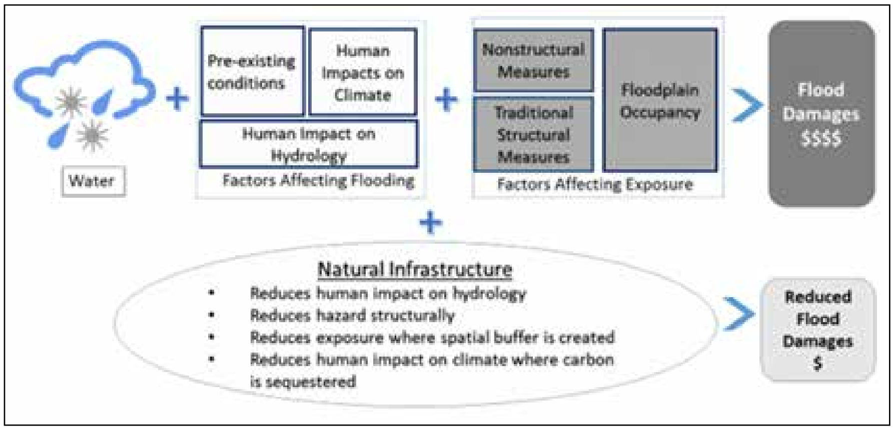


Figure 1. Natural Infrastructure's contributions to flood damage reduction. (adapted from Pielke and Downton 2000).

ing percolation of water to reduce runoff and attenuate flood peaks (see Figure 2). Coastal and floodplain wetlands can store water and slow its advance (Bridges *et al.* 2015). Mangroves and reefs can attenuate coastal wave energy — reducing its power — and reduce the inland advance of tidal waves and storm surge (Guannel *et al.* 2016). Dunes provide physical buffers to erosive waves and reduce storm surge penetration (Bridges *et al.* 2015).

Restoring natural *processes* is another way to reduce hazard and thus reduce risk. Louisiana's 2017 Coastal Master Plan (CPRA 2017) includes sediment diversions to reconnect the sediment-laden Mississippi River to its sediment-starved deltaic wetlands to combat erosion, subsidence and sea level rise and rebuild wetlands to serve as buffers for human communities. Likewise, urban areas, such as Philadelphia and Washington, DC, are employing nature-based solutions (called "green infrastructure") to slow, capture, and cleanse urban stormwater.

Less often recognized is that protecting and restoring natural infrastructure also reduces *vulnerability* by avoiding development in high flood hazard areas in the first place or through changing land use and creating space to restore naturally protective features and ecosystems. Furthermore, restoring some types of natural infrastructure — forests, wetlands, mangroves, and oyster reefs — may increase carbon sequestration to contribute to slowing the rate of sea level rise and intense precipitation (NAS 2019).

A GROWING ACCEPTANCE OF NATURAL INFRASTRUCTURE

Organizations across the U.S. have begun promoting natural infrastructure as a viable, even preferred, tool for addressing flooding and rising seas. The Association of State Floodplain Managers (ASFPM), comprised of professionals in various aspects of flooding, flood hazard reduction, and floodplain management, has long advocated for natural and beneficial uses of floodplains (ASFPM 2008). In partnership with other professional and non-governmental organizations, ASFPM helped expand awareness and acceptance of how protecting and restoring natural infrastructure enhances resilience to flooding (see for example, www.nrcsolutions.org and https://www.floods.org/n-news-hottopics/article.asp?id=460).

Environmental nongovernmental organizations (E-NGOs) were quick to recognize natural infrastructure as a means both to address erosion, habitat loss, and water quality issues and to engage citizens concerned about increased flooding risks and climate change. A coalition of E-NGOs — Environmental Defense Fund, National Audubon Society, National Wildlife Federation, Restore or Retreat, the Lake Pontchartrain Basin Foundation, and the Coalition to Restore Coastal Louisiana — coalesced around restoring the Mississippi River's deltaic wetlands, barrier islands, and oyster reefs as key strategies to combat land loss in Louisiana and mitigate increased risk of damaging storms. Restore America's Estuaries, North Carolina Coastal Federation, Wetlands Watch, and Chesapeake Bay Foundation have been advocating for "living shorelines" as an alternative to hardened shoreline structures, such as bulkheads, to address erosion concerns and water quality for over a decade. By slowing waves and reducing erosion, living shorelines reduce exposure to floods. The Nature Conservancy developed tools to advance incorporation of natural infrastructure into community flood risk reduction practice; their science, analytical and decision support tools, and partnerships have significantly advanced interest in and use of natural infrastructure to address current and future challenges due to coastal flooding (see www.coastalresiliency.org/project/ten-year), riparian and urban storm water flooding (see www.nrcsolutions.org). Numerous other E-NGOs have advanced natural infrastructure projects for flood risk reduction across the nation.

Studies grounded in science and economics complemented by advocacy efforts led to states taking actions to encourage consideration of natural infrastructure solutions. Louisiana's 2012 Coastal Master Plan (CPRA 2012) was perhaps the first planning effort in the nation to integrate the dual goals of coastal protection and coastal habitat restoration; subsequent updates of the plan and annual spending demonstrate the state's clear commitment to restoration of barrier islands and coastal wetlands to reduce storm damage. After a Restore America's Estuaries (2015) report identified policy barriers to implementing living shoreline solution, several states — including Maryland, Virginia, and North Carolina — enacted policies to put this nature-based option on equal footing with structural solutions like bulkheads and revetments, and, in some cases, make living shorelines preferential to hardscape approaches. (The U.S. Army Corps of Engineers (USACE) subsequently issued Nationwide Permit 54 in 2017 to put small living shoreline solutions on more equal footing with small bulkhead projects in terms of permit costs and processing times.) In 2015, California published a study (CSCC 2015) proposing natural infrastructure approaches to address sea level rise in San Francisco Bay and issued Executive Order (EO) B-30-15 on 29 April 2015 (https://www.ca.gov/archive/gov39/2015/04/29/news18938/). This EO, directing state agencies to incorporate climate considerations in all planning and investment decisions, specifically mentioned prioritizing actions that utilize natural and green infrastructure solutions and enhance and protect natural resources.

Federal policy has long recognized the dual goals of flood risk reduction and conservation of floodplain habitat; EO11988, Floodplain Management (https://www.fema.gov/executive-order-11988-floodplain-management) established these goals in 1977 and it is still in effect in 2019. However, explicit recognition of the environmental services provided by protecting and restoring natural infrastructure is a more recent phenomenon. The Federal Emergency Management Administration (FEMA) can fund restoration of natural infrastructure such as protective dunes and beaches damaged by storms. FEMA has also long credited creation of open space in floodplains under the NFIP's Community Rating System (CRS). It was not until 2014, when FEMA updated its Benefit Cost Analysis Tool (https://www.fema.gov/media-library/assets/documents/128334) — used for documenting a proposed hazard mitigation project's positive benefit-to-cost ratio — that benefits from ecosystem services began to be included. Then, in a 2015 fact sheet, FEMA explicitly recognized that natural infrastructure can be a means to mitigate flood hazards when it called out that projects involving natural infrastructure would need to demonstrate a project is cost effective and provides risk reduction benefits as well as meet other FEMA requirements (FEMA 2015). The Environmental Protection Agency (EPA) has for well over a decade advanced consideration of green infrastructure for improving urban storm water quality and reducing the demand on urban stormwater collection and treatment systems (Mell 2017).

But Superstorm Sandy in 2012 may have been the real turning point in broad federal agency support for natural infrastructure solutions as part of a broader recognition of the need to improve resilience to storms (and other shocks and stressors to human systems and the environment). With numerous Department of the Interior (DOI) assets affected by the storm, Congress' Sandy Relief appropriation enabled DOI to work with the National Fish and Wildlife Foundation (NFWF) to issue grants for projects to restore natural infrastructure and reduce flooding threats. Monitoring to assess the effectiveness of beach, dune, living shoreline and other wetland projects continued for several years after the storm (NFWF 2017). As part of its post-Sandy responsibilities, the U.S. Army Corps of Engineers (USACE) prepared the North Atlantic Comprehensive Study (USACE 2015) that presented risk management strategies for coastal communities; initially embedded in the draft report as an Appendix but subsequently issued as a "related document," the Corps addressed the use of nature and nature-based features for coastal resilience (see Bridges *et al.* 2015). Also emerging as a result of unspent Superstorm Sandy disaster funds, was Housing and Urban Development's National Resilience Design Competition which led to the Rebuild by Design initiative; many of the projects pursued included natural infrastructure elements. National Oceanographic and Atmospheric Administration's (NOAA) policy framework for coastal resilience provided a launching point for the agency's strong support of natural infrastructure (Sutton-Grier *et al.* 2015). NOAA fisheries, digital coast, and coastal management and other offices now promote natural infrastructure to build resilience of coastal communities, livelihoods, and habitats — offering fact sheets, information on economic benefits, grant funding, podcasts, and highlighting projects restoring natural infrastructure (https://coast.noaa.gov/digitalcoast/topics/green-infrastructure.html). By 2016, other federal agencies, such as the Federal Highway Administration had started exploring natural infrastructure solutions to protect coastal roads (e.g. DOT 2018a, DOT 2018b).

While USACE products and USACE-organized or -led efforts — such as Systems Approach to Geomorphic Engineering (http://sagecoast.org/info/activities.html) and Engineering with Nature (https://ewn.el.erdc.dren.mil/) — contributed significantly to expanding awareness and consideration of natural infrastructure solutions, securing support for funding projects involving wetlands to reduce flooding and storm impacts under USACE storm and flood protection authorities has proven challenging (e.g. Jamaica Bay, New York; Hamilton City, California). Congress tried to address this concern when it directed the USACE to "consider use of natural infrastructure, alone or in conjunction with traditional infrastructure, where practicable for flood risk management or hurricane and storm damage reduction projects" in Section 1149 of the Water Resources Development Act of 2018. To date, this direction appears to have had little effect.

SCALING UP USE OF NATURAL INFRASTRUCTURE SOLUTIONS

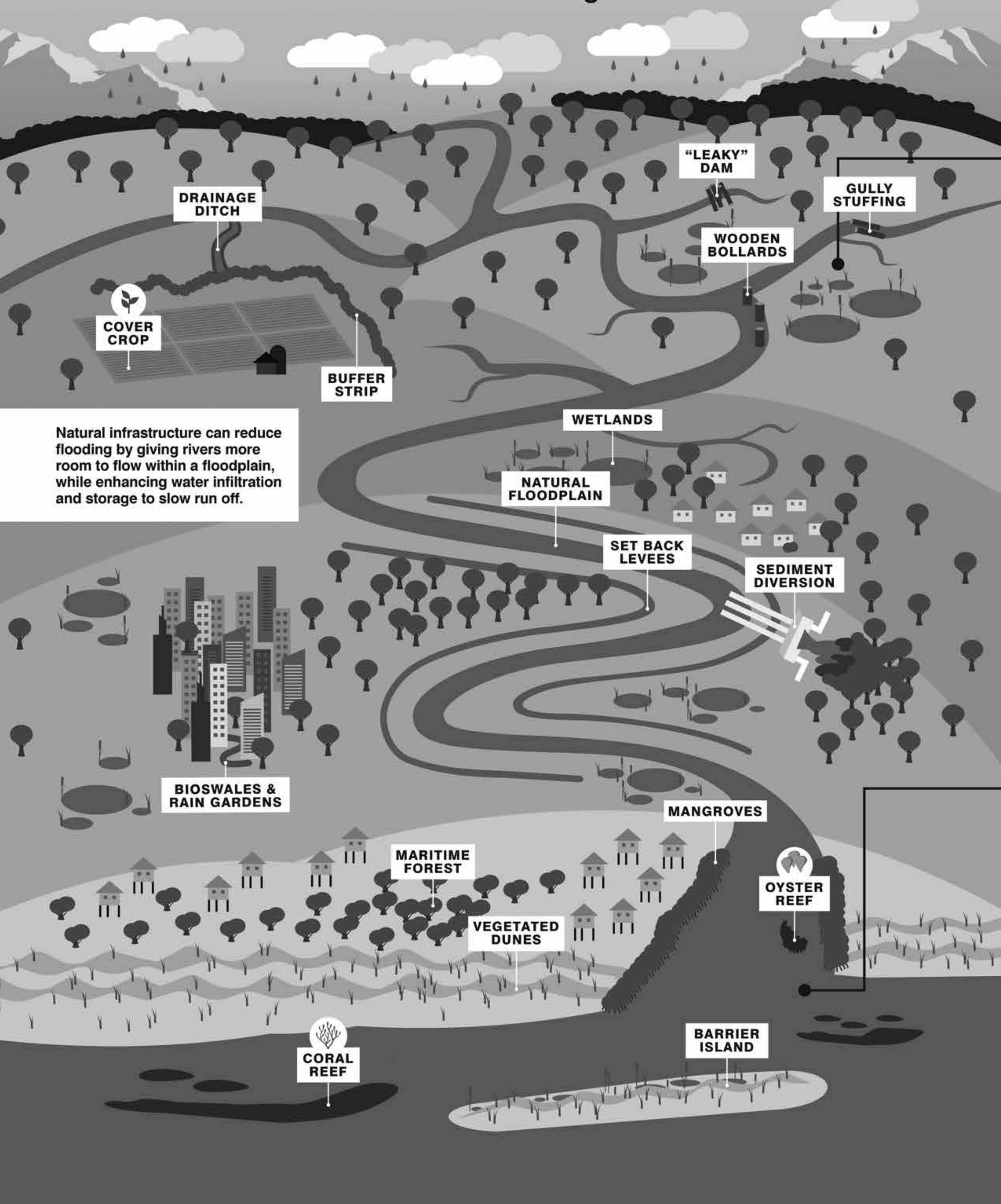
Interest in and implementation of flood resilience projects using natural infrastructure appears to be expanding as evidenced by the number of publications about natural infrastructure providing some flood and risk reduction benefits (Figure 3). Given increased risk of flooding due to climate change, enhancing community and ecological resilience by reproducing successful natural infrastructure projects necessitates implementation at a speed and scale not yet achieved. Achieving scale will require better governance and creating new notions of adequate flood risk reduction practice.

Political leadership, from the local to state level, is especially important to create a unified vision and launch new initiatives and maintain momentum; the focus, however, must be on sustaining implementation of resilience to transcend administrations and ensure meaningful progress (USCA 2018). Establishing effective governance bodies, appropriately scaled to the issues and involving the key agencies having a role in implementing solutions, offers significant opportunities to address the myriad physical and social factors contributing to flood risk (NAS 1999). Extending the geographic purview of governing bodies and aligning and shifting agency priorities serves to enhance interdisciplinary cooperation, remove boundaries, increase ownership over problems, and leverage funding. Historically, an overly local focus on flooding has resulted in structural solutions involving rapid shunting of water downstream increasing flooding in out-of-jurisdiction communities (e.g. levee "wars" on the Mississippi River). Watershed or regional governance bodies facilitate solutions that work for multiple jurisdictions. Louisiana created its Coastal Protection and Restoration Authority, integrating elements of the Department of Natural Resources, the Department of Transportation and Development and other state agencies to "develop, implement, and enforce a comprehensive coastal protection and restoration master plan" (CPRA 2017).

Effective governance will also facilitate more effective community level master planning by aiding integration of myriad separate community plans (e.g. emergency management, natural resource management, transportation, economic development, *et al.*) to align agency policies and practices to make flood-risk informed decisions that reduce risk (Berke *et al.* 2019). These approaches

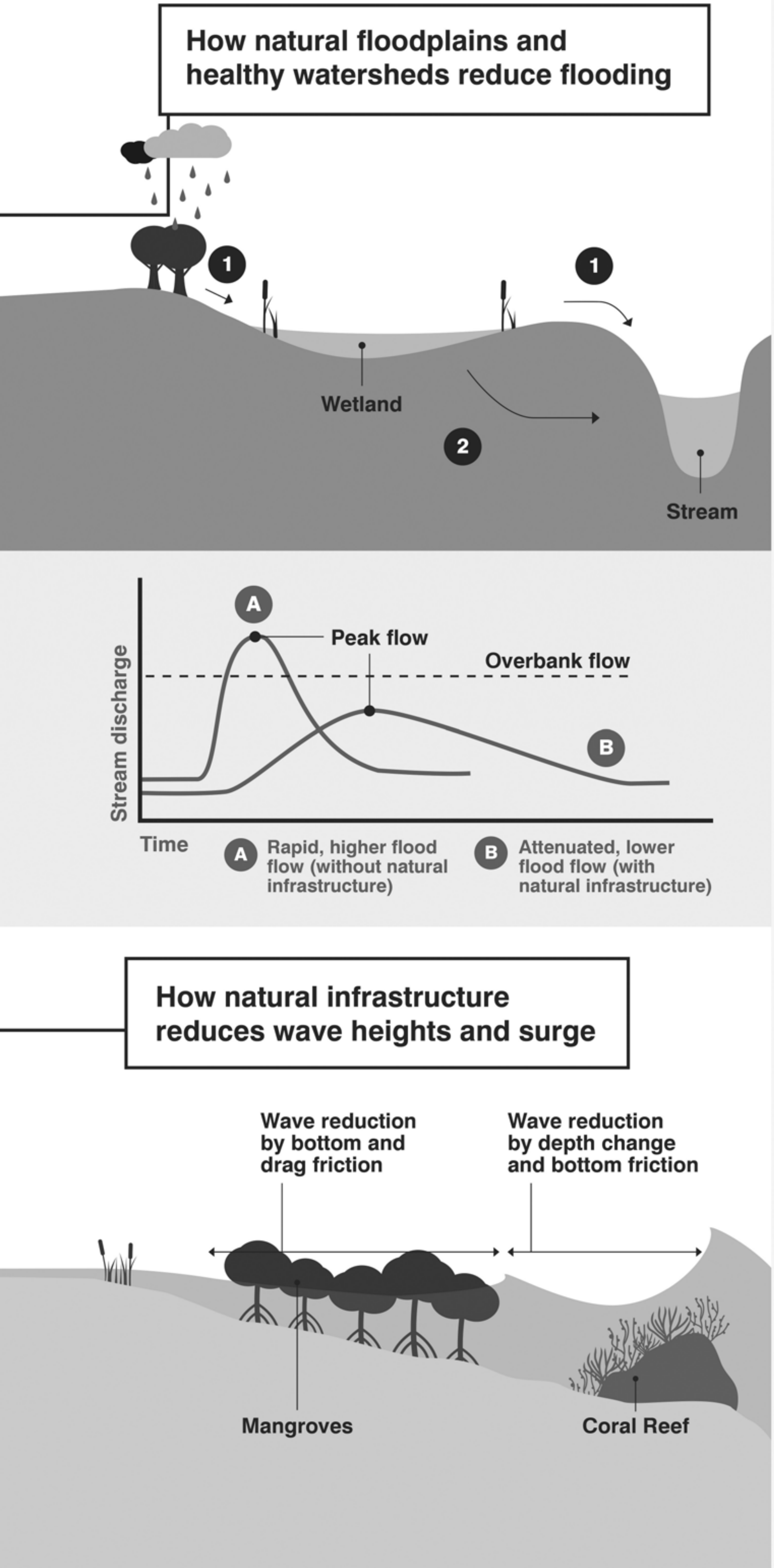
Figure 2.

How natural infrastructure reduces flooding



Natural infrastructure can reduce flooding by giving rivers more room to flow within a floodplain, while enhancing water infiltration and storage to slow run off.

Figure 2.



Natural Infrastructure Examples and Benefits

Barrier Islands: offshore sand islands that absorb wave energy to reduce erosion.

Bioswales and rain gardens: low-lying vegetated areas that slow and cleanse urban runoff.

Cover crops: planted agricultural fields to increase soil permeability and slow surface runoff.

Curved drainage ditch: meandering agricultural drainage ditch that mimics small streams to slow velocity of water and support growth of wetlands.

Double U drainage ditch: a two-tiered drainage ditch that captures sediment, removes nutrients and supports wetland growth.

Floodplain restoration: Restoration approach that puts the stream channel and floodplain at or near historical elevations and locations, benefitting water quality, increasing absorption and providing wildlife habitat.

Gully stuffing: logs and woody debris placed in ditches, gullies or channels to slow the flow of water and trap sediment.

Leaky dams: woody debris placed across a stream or channel that allows fish passage, provides habitat, and disperses and slows flow of water

Mangroves: coastal shrubs/trees with dense roots and stems that reduce wave energy and height, trap storm debris and slow inland transfer of water.

Maritime forests: dense coastal vegetation that reduces wind and wave energy and captures debris to buffer inland areas from storm damages.

Oyster, shellfish, and coral reefs: function like submerged breakwaters to buffer coastal areas from waves and reduce erosion, while oyster and shellfish reefs improve water quality.

Sediment Diversion: strategically placed and managed structures that reconnect rivers to wetlands and deliver sediment, freshwater and nutrients to build and maintain coastal land.

Set-back levees: levees built well beyond the river to allow natural floodplain flooding and store water, slow stream velocity, and reduce downstream flood height.

Vegetated Dunes: vegetated mounds or ridges adjacent to beaches or on barrier islands that trap and stabilize sand and absorb storm surge and waves.

Wetlands: act as sponges by slowing and absorbing water to reduce flood heights and storm surge velocity and height.

Wood bollards: wooden structures or tree stumps placed in streams to decrease stream velocity near river banks and reduce erosion of banks.

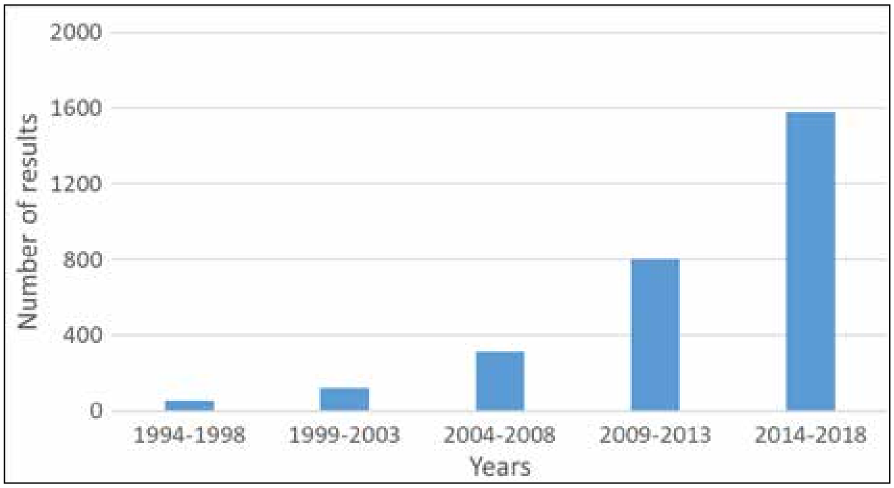


Figure 3: Publications including "natural infrastructure" and other terms over time. Figure 3 is derived from a Google Scholar query on 15 February 2019 using the exact phrase "natural infrastructure" and at least one of the following words/phrases included anywhere in the article: flood, storm, risk, reduction, nature based, coastal, green infrastructure, urban runoff (patents were excluded from the search). Five articles appeared in the period between 1989 and 1993, but were excluded as they did not include other terms associated with flood risk reduction. While it is possible that some of the articles found in this query are not full matches, this histogram likely reflects the overall expansion in interest in natural infrastructure.

overcome agency's narrow missions and authorities that make planning and implementing multi-objective projects, like those that include natural infrastructure, harder to realize. The result realized from establishing a clear vision for improving resilience to flooding and aligning agencies and plans to support that vision, is risk-informed decision-making that addresses hazards, exposure and vulnerability, improves environmental conditions, and advances resilience.

Practices that enhance governance and can improve consideration of natural infrastructure are provided below:

Adopt policy models to reduce risk and build resilience

Several new policy models have emerged to reduce flood damages more effectively:

- The European Union established a Green Infrastructure policy in 2013 that encourages spatial planning and recognizes the value of the natural infrastructure in delivering a wide variety of benefits to society, including adapting to (and mitigating) climate change (Slätmo *et al.* 2019). Well known programs, such as the United Kingdom's program of "Making Space for Water" (HM Government 2008) and Netherland's "Room for the River" (Rijkswaterstaat 2016), emphasize spatial approaches. These programs focus on modifying the event, such as increasing channel and floodplain capacity to accommodate peak river discharges and modifying vulnerability by moving humans and infrastructure out of high hazard areas. While technically increasing channel capacity and restoring open space to floodplains are not new concepts, the successful implementation of projects involving large scale buyouts and relocation of people and infrastructure and the use of nature-based features has elevated attention to these approaches. Whereas the EU's green infrastructure policy emphasizes restoration of ecological networks and the conservation and restoration of open green space (Slätmo *et al.* 2019).

- The "Living with Water" model reflects greater acceptance of sea level rise and flooding events by designing and constructing communities, infrastructure, and homes to cope with and even embrace water as an asset (for example, see the "Structures of Coastal Resilience" initiative (http://structuresofcoastalresilience.org/) led by Guy Nordenson, Julia Chapman, Enrique Ramirez, and Elizabeth Hodges.

- The "Building with Nature" approach takes advantage of ecosystem functions to reduce costs, restore lost functions, and create new ecosystem services (e.g. food supplies or recreational space) and may be especially effective for coping with the gradual changes associated with sea level rise (Slobbe *et al.* 2013).

- The "Ecosystem-based Disaster Risk Reduction" model (referred to as ECO-DRR), recognized in the United Nations' Sendai Framework for Disaster Risk Reduction adopted in 2015 (https://www.unisdr.org/we/coordinate/sendai-framework), incorporates protecting and restoring natural infrastructure as an effective component of disaster risk reduction and climate change adaptation. This is because it is widely recognized that poorly vegetated and denuded areas, compacted soils, and filled wetlands aggravate flood disasters by increasing erosion, runoff and debris (Sudmeier-Rieux *et al.* 2006). It stands that protecting and restoring natural infrastructure will lessen the risk of disasters and reduce their impact when they do occur; in these and other ways, natural infrastructure enhances community resilience to disasters.

These new policies and practices were motivated, in some part, by a growing awareness that current approaches were proving inadequate because damaging floods were increasing, and by concerns over the lack of economic and environmental sustainability of the traditional "hard" engineering approaches (Adger *et al.* 2005; Kamphuis 2006; Spalding *et al.* 2014; and Airoldi *et al.* 2005). Likewise, new means to account for ecosystem services are helping communities recognize the myriad advantages provided by natural infrastructure.

Implement refined community engagement

Stakeholder engagement and management are necessary to move projects forward with any alacrity. Both are necessary to achieve a reasonable consensus around a plan or project. Effective stakeholder engagement processes for flood damage reduction projects typically start by build understanding of risks and soliciting ideas on needs, desires and priorities for reducing hazard, exposure and vulnerability. The Dutch Dialogue™ process (see http://plus.usgbc.org/dutch-dialogues/) used in New Orleans, Louisiana, Charleston, South Carolina, and Hampton Roads, Virginia, follows these tenets while joining technical professionals together with citizens to develop ideas.

Superior stakeholder engagement will develop a cadre of thought leaders and project support able to sustain political support that transcends political appointments. Collective ownership in projects can lead to the longer-term benefits when effective local organizational frameworks develop to yield improved disaster response, recovery and resilience.

For efforts where natural infrastructure might be part of the solution set, meaningful public engagement it is especially important as stakeholders may be less familiar with natural infrastructure functions, tradeoffs, and attributes. Furthermore, engaging a broad base of stakeholders may increase the probability that projects are designed to achieve multiple objectives including natural resource recovery, environmental quality, recreational space, economic development, and flood damage reduction.

Apply systems analysis

Flood risk reduction intrinsically includes consideration of natural, social and governance systems and lends itself to a systems approach of problem analysis. System approaches look beyond immediate events or local problems to identify patterns and relationships (Leveson 2011). Such analysis expands perspectives on causes and solutions. For flood risk reduction, systems analysis involves consideration of the dynamic interactions of physical, ecological, and relevant cultural environments. Analyses rooted in systems thinking have multidisciplinary inputs and reveal root contributors to flooding risk. By considering the economic, social, and environmental aspects of a system, this approach should promote development of solutions that create added value by identifying solutions meeting multiple diverse needs and providing an array of benefits. A systems approach promotes diverse near- and long-term benefits of natural infrastructure. Done well, it will identify and help avoid unacceptable impacts and unintended consequences from actions taken. As a result, systems analysis typically yields better understanding that leads to more effective, multi-functional solutions that include natural infrastructure and provide value to both people and nature and can achieve and sustain broad stakeholder support.

Use spatial data and trend analysis

Among the challenges to the implementation of natural infrastructure solutions is determining the location(s) in the landscape where they will have the most impact in reducing flood damages. Systems analysis supported by mapping, modeling, and trend analyses can reveal where natural infrastructure tactics may be appropriate for providing extra layers of defense against floods and rising seas. In response to a flood risk assessment and its formal "bad" ecological classification of the Eddleson River, the Scotland Environment Protection Agency assessed the effectiveness of specific types of natural infrastructure to reduce flood risk and improve ecological status. They employed detailed studies of interventions, using a "Before-After, Control-Impact" study design, and assessed the impact of restoration on flood risk and habitats at a whole catchment scale (Spray 2016). With a suite of natural infrastructure solutions in place, they plan to monitor the watershed and river during the next large precipitation event (Chris Spray, pers. comm 2019) to document the effectiveness of the natural infrastructure solutions in altering run off amounts and timing.

Guerrero *et al.* (2018) suggests use of "hydromorphological landscape units" to create spatial visualizations that aid initial planning and provide an easier basis for communication with stakeholders and decision-makers; such would be subsequently supplemented with more detailed hydrological, hydraulic, socioeconomic, and ecological data.

Time series maps are especially helpful to reveal geomorphic changes (subsidence, sea level rise, current and likely areas of erosion), land use and habitat changes, flooding patterns, and population density, and socio-economic factors. Time series maps should be able to highlight changes such as lowered soil permeability that may be intensifying flooding. High-resolution LIDAR maps, like those developed by North Carolina (https://sdd.nc.gov/sdd/DataDownload.aspx) that show relatively small changes in elevation should be helpful in identifying where natural storage capacity exists and where nature-based techniques such as intentional woody debris in streams, gullies, or floodplains could be used to slow, retain, or direct water flow to reduce flood damages.

Mapping analyses of structural damage, property values, social vulnerability, and population density shifts such as done by Diakakis *et al.* (2017), Bernstein *et al.* (2019), Bergstrand *et al.* (2015), and Hauer (2017), respectively, may reveal alignments between emerging needs and opportunities for broadening floodplains and restoring their natural beneficial functions.

Spatial analysis may also be able to identify where dam removal or design and operation updates to restore or mimic nature-based processes could restore sediment flows critical for beaches and wetlands to keep pace with sea level rise.

Choose adaptive management

Adaptive management is an iterative decision-making process that reduces uncertainties over time to improve project planning and outcomes. Adaptive management provides the structure needed to proceed with project implementation based on current understanding, and then monitors and assesses project performance over time to identify adaptive actions that may be needed to address unanticipated outcomes (Murray and Marmorek 2003). Adaptive management of natural infrastructure projects would provide a science-based approach to try new tactics and new techniques, facilitate data collection and analysis and provide a "safety valve" for engineers and decision-makers uncomfortable with uncertainty over performance outcomes.

Facilitate rapid information dispersal

In 2014, NAS recognized the value of natural infrastructure but reflected the need for greater quantification of risk reduction benefits (NAS 2014). A rapidly expanding body of literature is documenting natural infrastructure benefits, in ways meaningful to engineers and economists (e.g. Gittman *et al.* 2014, Bridges *et al.* 2015, Narayan *et al.* 2016, Watson *et al.* 2016, and Narayan *et al.* 2017; Cunniff and Schwartz 2015, provides a literature review of engineering performance of coastal natural infrastructure.) Decades, even centuries, of experience back traditionally engineered structures for flood risk reduction. Therefore, accelerating understanding of natural infrastructure necessitates building more projects complemented with rigorous documentation of project conditions, designs, construction practices, maintenance, and performance under various conditions. To these ends, the USACE is leading an international group of experts to publish (planned release in 2020) a best practices planning and design guidance book that builds upon successful coastal natural infrastructure projects. Detailed field performance information is crucial for understanding the limits of natural infrastructure and will demonstrate how natural infrastructure can best be integrated with other means to reducing flood risk.

Broad participation in a single database that gathers and allows analysis of detailed project design, construction and maintenance information relevant to engineering (expected and realized performance), ecology (expected and realized habitat values and ecosystem services) and economics (costs, expected return on investment, realized benefits, etc.) would accelerate learning, lead to improved designs, and expand acceptance of natural infrastructure solutions. Fourteen databases collect information on coastal natural infrastructure projects implemented for shore protection or habitat restoration (https://livingshorelinesacademy.org/index.php/projects-databases, accessed 5 February 2019). Some provide project specifications, none present meaningful post-construction performance information.

Use new technologies

Given the high resolution now possible with modeling and imagery, crowd sourcing, systems of interrelated computing and devices, and broad public access to information, communities now have far more powerful new ways to effectively analyze, plan for, and respond to resilience challenges and figure out what types of natural infrastructure will work best, where, and under what conditions.

Advances in numerical modeling are helping to assess the combined effects of precipitation, riparian flooding, tides, and storm surges to yield more informative assessments of risk. Models can now be used to evaluate the benefits of nature-based infrastructure in reducing flooding risk as demonstrated by Risk Management Solutions, which has developed high resolution models which were used to calculate how coastal wetlands reduced flood impacts during Super Storm Sandy (Narayan *et al.* 2017). High-resolution modeling can help communities evaluate alternative approaches by helping to quantify the benefits of preserving and expanding natural infrastructure.

Drone technology is enhancing the scale of imagery available and is especially well suited for rapidly collecting data on constantly evolving coastal and riparian conditions at relatively low cost.

While many satellites capture rich local imagery every three to five days, processing these data remains costly, time-consuming and requires extensive expertise. Recent advances in machine learning offer new opportunities to develop estimates of flood risk (Mojaddadi *et al.* 2017). It may be possible to interpret and refine the scale of data to make it even more meaningful at the local level (Keshtkar *et al.* 2017).

Lower cost current and locally relevant data will be especially important for under-resourced communities that would otherwise not have the ability to collect, monitor and interpret data critical to emerging flood threats. Small cities, towns and rural areas, in particular, need efficient, data-driven and actionable methods for understanding interactions between current natural and physical infrastructure and future flood risk. Often having limited local government service delivery and planning capacity (ICMA 2010), they face greater challenges associated with acquiring data and making timely, informed decisions to reduce their flood risks in ways that strengthen their economy, protect valued local assets and build environmental resilience. Currently these areas often rely on federal government maps — such as FEMA National Flood Insurance Rate Maps (FIRM) intended primarily for determining insurance rates and not updated frequently. However, higher-resolution maps currently being produced by NOAA and partners should soon be available on the Digital Coast website (https://coast.noaa.gov/digitalcoast/) for meaningful flood management) to aid community decision making.

Private companies are offering networked water sensing services and communities are trying them to detect location and intensity of precipitation and track surface flows to facilitate manipulation of distributed water storage and to time releases to reduce flood peaks (e.g. see https://sensus.com/smart-water-network/ and https://optirtc.com/products/). Placed by natural and built infrastructure these hyperlocal networks of sensors could cooperatively operate to identify to reduce flood risk.

Remote sensing and hyperlocal sensor networks coupled with machine learning offer considerable potential to increase the capacity and capabilities to reduce flood damages by helping to:

- Explore the connection between historic, current and projected flooded areas and historic land use change;
- Show where restoration of natural areas could reduce runoff and/or attenuate floods to reduce flood damages;
- Prioritize natural areas for protection or restoration based on location relevant to reducing flood hazards;
- Integrate natural infrastructure solutions to complement traditionally engineered water management;
- Measure performance of changes in land use and restoration of natural infrastructure, especially if combined with precipitation data, river and tide gauges, and post-event flood depth data;
- Alert planners when identified thresholds are being approached (such as when shifts in impervious cover or wetlands loss markedly increases downstream flooding); and
- Improve early flood warning systems.

Just as important, remote sensing supported by machine learning and sensor systems can enhance the visual story telling capacity of a community floodplain manager by providing powerful information to elected officials and the public about flood hazards and how land use and environmental change will affect flood risk to the human and natural community.

Seek compensation for risk-reduction services

The concept of payment for ecosystem services is gaining increasing traction as a means to compensate actors for the societal benefits of their actions (Reed et al. 2017). Communities can look to other localities that have implemented payment for ecosystem service transactions that minimize surface run off or reduce flood risks (for example, Somerset, United Kingdom (https://www.fwi.co.uk/news/environment/somerset-farmers-paid-to-help-reduce-flood-risk) and South Florida Water Management District's Dispersed Water Management Program (https://apps.sfwmd.gov/webapps//publicMeetings/viewFile/19693).

Where natural infrastructure is protected or restored, it can be possible to obtain financial benefits, in addition to flood risk reduction benefits. Under the NFIP's Community Rating System (CRS) program, participating communities can obtain points for engaging in flood management activities that go beyond the NFIP's minimum standards to receive insurance premium discounts up to 45% for their citizens (FEMA 2017). These activities include mapping and regulation activities that preserve and protect open spaces and natural floodplains and other flood damage reduction activities (such as enforcing standards, managing stormwater, creating a floodplain management plan, relocating or retrofitting structures and maintaining drainage systems). Many coastal communities fail to account for existing natural infrastructure when seeking CRS rating updates, so in response, The Nature Conservancy created the CRS Explorer (https://coastalresilience.org/project/community-rating-system-explorer/) to help communities identify areas that are eligible for CRS's Open Space Preservation credits. In addition, ASFPM designed its Green Guide explicitly to help communities capture points from natural infrastructure projects (ASFPM 2018). Where clear evidence of flood reduction benefits from restoring natural infrastructure exists, it should secure points for flood damage reduction actions to obtain improved CRS ratings.

Communities that plan and implement actions to reduce the impact of storms and climate change may benefit financially in another, less direct but important way — lower interest rates for municipal bonds. Moody's Investors Service (2017) issued a report linking credit worthiness to climate adaptation indicating that their evaluations for credit worthiness took climate threats and adaptation measures into account. Moody's indicated analysts would be considering community emergency response and climate adaptation plans as part of their evaluation. By including natural infrastructure to both lower vulnerability and flood hazard, communities are enhancing their ability to recover from climate shocks which should help them secure good ratings.

In the future, insurers of municipalities and industries may be better equipped to analyze and acknowledge the contribution of natural infrastructure to lowered damages from floods and storms. Narayan *et al.* (2017) used high resolution models provided by Risk Management Solutions to estimate that coastal wetlands reduced flood heights and avoided losses of more than $625 million from super storm Sandy. As risk modeling gets increasingly refined, insurers will be better equipped to recognize where integrating natural infrastructure safeguards their investments by reducing flood damages; reduced risk of damages can translate to lowered insurance rates.

Expand funding and financing options

Communities across the nation will need additional resources to address evolving flood risk in a cost-effective manner. Currently federal sources of funding for natural infrastructure can come from the USACE, FEMA, NOAA, DOI, and EPA. E-NGOs, many with philanthropic or corporate support, provide funding for planning and implementing natural infrastructure projects (Carter *et al.* 2018). Louisiana, due to its ongoing coast-wide land loss, has been using oil and gas revenues and several funds associated with the Deepwater Horizon oil spill to fund implementation of its comprehensive master plan for protecting and restoring coast (see CPRA 2019). (Louisiana has also explored performance-based contracting to ascertain whether such would result in lowered costs in effect expanding available funding.) Some private companies have implemented natural infrastructure projects to protect their assets (Dow *et al.* 2013).

The financial sector offers greater opportunities to expand investment in natural infrastructure projects or accelerate project implementation. A new tool, environmental impact bonds (EIBs) offers some promise. These pay-for-performance bonds, already in use to attract private investment in social programs, can be designed for flood risk reduction and resilience projects. The District of Columbia's Water and Sewer Authority implemented the nation's first EIB funding wetlands creation to address storm water runoff and combine sewer overflow challenges in September 2016 (http://www.quantifiedventures.com/dc-water/). Environmental Defense Fund and Quantified Ventures (EDF and QV 2018) proposed that an environmental impact bond could finance restoration of wetlands in Louisiana to speed implementation of projects that improve coastal resilience. In both of these models, private investors buy bonds from a public entity interested in financing flood risk reduction and payback is conditional on the projects' performance. In the proposed Louisiana EIB, if a wetland restoration project exceeds a defined performance level, industries or other beneficiaries of the enhanced protection from erosion and floods would provide the performance payment shared by investors and the contractor building the project (Herrera *et al.* 2019). EIBs could facilitate more investment in natural infrastructure solutions because they can generate a return to investors and help investors meet corporate sustainable development goals. Because they are performance-based, they also provide a means to secure financial participation of those that directly benefit from project's ecosystem services (EDF and QV 2018).

Any entity with bonding authority can pursue design and implementation of an EIB. To expand use of EIBs as a natural infrastructure financing mechanism, data are needed to attract private investment by defining probabilities that performance will be met or exceeded. Similarly, rapid, low cost methods to establish whether performance has been exceeded will keep transaction costs low to make these bonds more attractive.

New risk reduction service valuation studies, such as Reguero *et al.* (2019), that document benefits derived from protecting and maintaining coastal natural infrastructure are aiding development of new risk finance and insurance strategies such as resilience bonds. One recent example is the purchase by Quintana Roo, Mexico, of insurance for the Mesoamerican reef that protects coastal homes and businesses from erosion and storm surge and is critical to the local tourism economy. Organizations, such as the Coalition for Private Investment in Conservation (http://cpicfinance.com), Conservation Finance Network (https://www.conservationfinancenetwork.org), and Global Impact Investing Network (https://thegiin.org), are helping to share models of new transactions to expand investment opportunities.

CONCLUSION

Several existing approaches used in the United States could be enhanced to reduce the risk of flood damage that will only increase with climate change. Adapting to the new, more severe realities of increased flood hazard and exposure due to climate change will necessitate an unprecedented level of involvement, cooperation, and accountability from every facet of society – individuals, businesses, industries, communities, nongovernmental organizations, local, state, tribal, and federal government agencies. Building resilience to increasing flood risk will be a complex task, requiring hazard, exposure, and vulnerability issues to be fully and simultaneously addressed. Realizing rapid and sustained success at flood damage reduction will entail better synthesis of engineering, ecological and social information; consensus building; and distributed responsibility in implementation.

Communities that implement measures to protect and restore natural infrastructure functions are managing their flood hazard by decreasing erosion, lowering peak discharge, and/or reducing storm surge. They are also reducing exposure where habitat replaces vulnerable homes and businesses. The result will yield safer, more resilient communities and should result in strategies that include restoration and protection of natural infrastructure that enhances both human and natural community's resilience to climate change.

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