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Advancing disaster risk reduction through the integration of science, design, and policy into eco-engineering and several global resource management processes

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ABSTRACT

By the later part of the 21st Century, our planet will be faced with compelling climatic circumstances requiring tradeoffs to maintain viable environmental conditions and standards of living. The prognosis for people near coastlines and waterways is particularly dire without decisive actions that capitalize on shared strengths such as ecosystems. One clear opportunity is the regenerative services and co-benefits of natural infrastructure that reduce the impacts of environmental disasters as magnified by climatic change. Certainly, nature-based solutions are increasingly being viewed as critical actions to reduce societal risk. However, to advance the use of natural infrastructure through eco-engineering, there is a need to clarify the science regarding risk reduction effectiveness, develop agreeable principles, standards, and designs, and grow a demonstration site network responsive to circumstances faced by communities around the globe. In addition, there is a need to consider the legal, policy, and regulatory obstacles and opportunities for natural infrastructure within local to national contexts (i.e., science-based building codes, architectural design criteria, incentive policies, etc.). Ultimately, the integration of science, designs, and policy coupled with installation within several global resource management processes (IWRM, ICZM, etc.) will help establish eco-engineering standards. Supportive coastal, river, and urban examples from around the world are used to illustrate the current state of knowledge, model this integration of science, design, and policy, serve as initial "benchmark site", and finally help define guiding principles for the emerging field of eco-engineering.

1. Introduction

The planet will be faced with environmental and climatic circumstances requiring tradeoffs by the latter part of the 21st century. Economic losses from environmental disasters globally (1970–2013) topped $2.8 trillion with $484 billion due to extreme weather and flooding [1]. Flood losses in 2005 for the 136 largest cities worldwide was estimated at $6 billion with projected escalation up to $1 trillion per year by 2050 with sea level rise and land subsidence [2]. In 2010, the world's gross domestic product exposed to tropical cyclones was 4.47 percent, representing more than US$1.9 trillion [3]. This level of exposure is most pronounced in coastal zones where development continues largely irrespective of future climate projections [4–6]. Despite these alarming trends and forecasts, communities continue to discount disaster risk when making development and redevelopment decisions [7].

The prognosis for people near water across complex urban to rural landscapes is particularly dire. For example, as sea level rises, tropical cyclones will pose a greater risk of extreme flooding in the coastal zones, which would inflict the greatest damages on highly populated shorelines [5]. Meanwhile, it is projected that coastal growth in population and development will outpace progress in risk reduction [8]. To counter this prognosis, communities globally require measures to manage and reduce risks to people and property. Consequently, there is heightened demand for the use of ecosystems to help avoid this mounting, global risk due to natural disasters and climate change through greater community resilience

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building. Resilience, as considered in this paper is defined as "the capacity of (…) systems to cope with a hazardous event or trend or disturbance, responding or reorganizing in ways that maintain their essential function, identity and structure, while also maintaining the capacity for adaptation, learning and transformation" [9].

Nature-based solutions is a concept used "to promote nature as a means for providing solutions to climate mitigation and adaptation challenges" [10,11]. The integration and use of ecosystems or natural infrastructure (e.g. floodplains, salt marsh, mangroves, etc.) that capitalize on or mimic natural processes, or work in tandem with traditional, man-made structural approaches to address hazards and their impacts is referred to herein as eco-engineering. Communities along rivers or coasts, large or small, rural or urban, can integrate and use natural infrastructure through eco-engineering in local planning, zoning, regulations, and built projects to help reduce their exposure to flood and erosion impacts. In addition, frameworks, goals, funding instruments, and partnership can support the use of nature-based solutions. Recent advances that are helping to accelerate the integration of natural infrastructure via eco-engineering include the United Nations Framework Convention on Climate Change and Paris Agreement [12], Sendai Framework for Disaster Risk Reduction (SFDRR) [7,13], Sustainable Development Goals [14], World Bank's Adaptation Fund, and the Partnership for Environmental and Disaster Risk Reduction [15,16]. This uptake requires even greater attention to defining the science, design and policy as well as guidance and standards related to using ecosystems to reduce risk.

The current global need for investments in infrastructure presents an immediate opportunity for incorporating guidance and standard for natural infrastructure into engineered approaches (i.e., eco-engineering). Estimates by the Organization for Economic Cooperation and Development [17] suggest that $189 trillion in infrastructure investments will be required globally, by 2030. An estimated $3.6 trillion by 2020 is needed for infrastructure to meet adequate standards in the United States [18]. Public-private partnerships, therefore, offer opportunities for dialogue on the capacity of natural infrastructure to reduce the financing requirements of projected infrastructure costs. Eco-engineering hence is viewed as a critical asset to help reduce risk to society from disasters and climate change [15,19]. This is also acknowledged through the SFDRR via selected indicators used to monitor progress for "green infrastructure" - including "direct economic loss resulting from damaged or destroyed critical infrastructure attributed to disasters" and the "number of other destroyed or damaged critical infrastructure units and facilities attributed to disasters" [7]. The protective and regenerative services and co-benefits provided by coastal ecosystems, when recognized, can and are starting to be integrated into comprehensive risk management planning and resilience actions [20–22]. These recent advancements are supported by a growing body of scientific evidence that coastal habitats such as mangroves [20,22], coral reefs [23], salt marshes [24,25], and oyster reefs [26,27] can reduce the impacts of extreme weather events, storm surge, and flooding. Most compelling however, is that private and public sectors are beginning to prove that coastal habitats are in fact cost-effective defenses [28,29] that further warrant incorporation within traditional infrastructure investments. For example, partnerships with the insurance sector applied flood and loss models to estimate that marsh wetlands in the northeastern U.S. to show avoided damages over $625 million for Hurricane Sandy [30]. This resonates in watershed management applications where ecosystems such as floodplain forest and wetlands, public amenities (i.e. parks, recreation fields, open space), and agricultural lands are critical assets that reduce downstream flooding risks to urban centers and existing infrastructure situated along major rivers and receiving estuaries [31].

The science, management and economic advantages of eco-engineering are evident, however there remains a need for further definition, designing, calibrating, and monitoring in coastal, watershed, and urban circumstances and at various scales and geographies. In addition, there is a need to create equivalencies and assurances on the utility of natural infrastructure. To enable a legitimate comparison and eventual adoption of eco-engineering alongside or integrated with typical engineered approaches, a great deal of multi- and trans-disciplinary collaboration is required. The incorporation of ecosystem dynamics and characteristics into regulatory guidance and standards is an immediate goal. The longer-term outcome is the universal acceptance of eco-engineering as a viable alternative to traditional engineering during the first half of the 21st century.

The following paper will provide (1) an overview of eco-engineering origins and principles, (2) a basis of risk and current status of risk reduction criteria (models and flowcharts), (3) consideration of current challenges/limitations to advancing eco-engineering applications, (4) assessment of opportunities to interject eco-engineering approaches, principles, and standards into several globally recognized resource management processes (Integrated Water Resource Management (IWRM), Integrated Coastal Zone Management (ICZM), and other risk reduction processes – in accord with Sendai's priorities for action and guiding principles), and (5) provision of overarching recommendations to advance eco-engineering. These objectives will be illustrated by supportive examples that utilize eco-engineering in a watershed/water resource project for IWRM, coastal project for ICZM, and an urban-based, risk reduction process and project. The examples will showcase current limitations and opportunities for integrating services and co-benefits of eco-engineering into several globally recognized global resource management processes. The limited considerations of risk reducing actions in global processes such as IWRM and ICZM can be remedied via recommendations provided herein.

2. Overview of eco-engineering origins and principles

2.1. Ecosystems defined

To properly conceptualize and implement eco-engineering as well as maintain natural infrastructure for disaster risk reduction and climate change adaptation, there is a need to define ecosystem complexities. Ecosystems are essentially integrated and dependent systems that sustain life. They are in fact living systems which is a critical consideration for eco-engineering. Ecosystems also exist and operate at various interconnected scales from the local embayment to an entire estuary and coastline (Fig. 1). Critically, ecosystems shift and adapt (or regenerate) to a diverse array of external and internal forces over time. Humans are integral parts of ecosystems [32].

2.2. Ecosystem-based approaches

As an early conceptual step, ecosystem-based adaptation (EbA) was advanced and defined as "the use of biodiversity and ecosystem services to help people adapt to the adverse effects of climate change" [33]. Ecosystems offer communities a broad portfolio of services and specific features that can help them adapt to hazards and reduce risk. Estimating the provision of services in management plans offers a systematic way to incorporate biogeophysical and socioeconomic information as well as the views of stakeholders in the policy and management process, for successful ecosystem-based management and adaptation [19,34]. More recently, the concept of Ecosystem-Based Disaster Risk Reduction emerged (Eco-DRR; see e.g. [35]) as a proposal to link DRR objectives with services and co-benefits of ecosystems. In 2016, a combination of Eco-DRR with Climate Change Adaptation (CCA) to foster closer alignment emerged as Eco-DRR and CCA (Eco-DRR/CCA [36]). Eco-DRR/CCA was defined as "the sustainable management, conservation, and restoration of ecosystems to reduce disaster risk and adapt to the consequences of climate change, with the aim of achieving sustainable and resilience development" [36]. The key connection between EbA, Eco-DRR, and Eco-DRR/CCA (as well as "nature-based solutions" [10,11]) being the agreement on the risk reduction capacity of ecosystems that improves resilience and adaptation for people.

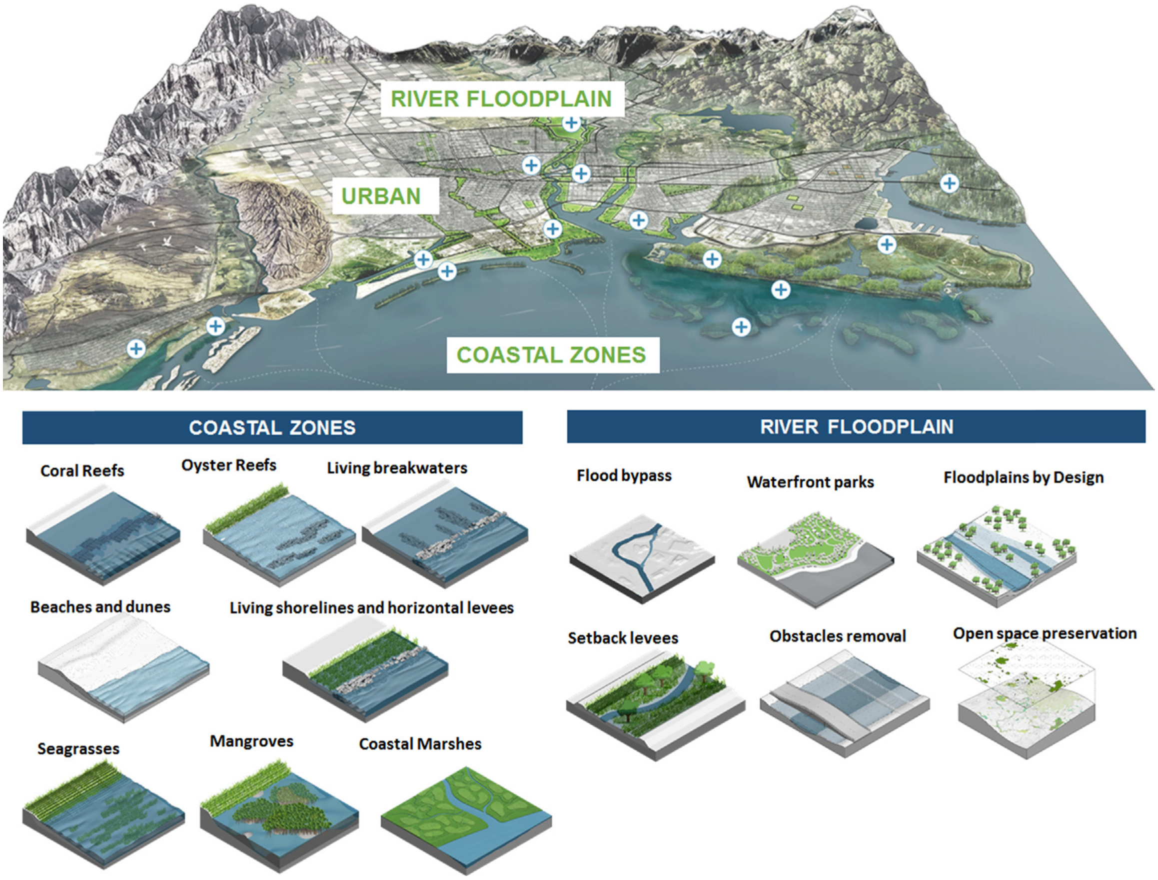

Fig. 1. Illustration depicting the diversity and location of ecosystems and eco-engineering approaches across coastal, riverine, and urban landscapes. The "+" signs indicate location of typologies presented. Adapted from www.nrcsolutions.org and used with permission (Sasaki Associates & The Nature Conservancy).

2.3. *Ecosystem characteristics as protective natural infrastructure*

Certain characteristics of ecosystems influence how they reduce risk. Ecosystems, large and small, are driven by dynamic and ever changing climatic and physical forces that may include waves, wind, rain, storms, drought, heat, slope, and geology. In most ecosystems, it is the unique combinations of these forces (at various magnitudes) that define current and future form and function. For example, the elevation and drainage of a naturally occurring salt marsh is determined by tidal amplitude, sediment composition as well as precipitation events that carry upstream sediment to marshes in deltaic systems (i.e., Mississippi or Rhine River Deltas).

The future form of ecosystems is uncertain. Ecosystems can and are adapting to ever changing conditions, be it from natural forces and/or anthropogenic disturbances. In addition, ecosystems generally require a large amount of space and often cannot be forced to perform in locations as determined by project scopes, regardless of design prowess and engineering capabilities. Finally, ecosystems are dynamic and often react in non-conforming, non-linear ways in response to site conditions and forces. In contrast, other engineering approaches in coastal, riverine, and urban locations that use hard, static structures against specific forces (waves, wind, precipitation) are singular in purpose with specific design life and predictable reactions to stress (even if failure has often occurred). A balance between form and function with careful considerations of limitations is needed to truly integrate ecosystems and engineering and design (i.e., eco-engineering) across coastal, riverine, and urban landscapes, as represented in Figs. 1 and 2.

In **coastal areas**, the protective services provided by ecosystems such as, reefs, tidal wetlands, and coastal vegetation, are diverse [e.g. 22,24,37,38,39,40,41,42], as they:

- Buffer the effects of storms, including extreme sea levels through the attenuation of waves and surges;
- Reduce wave energy and associated shoreline erosion, in turn reducing economic and property loss;
- Reduce stormwater flow rates into receiving waters;
- Build land by generating and trapping of sediments, and stabilize the shoreline by influencing wave energy and hydrodynamic circulation;
- Allow cross and long-shore natural sediment movement; Improve water quality in bays and estuaries by filtering pollutants (e.g. wetlands);
- Can self-adapt to changes such as sea level rise;
- Trap carbon to help mitigate climate change;
- Create and connect diverse habitats for fish and wildlife, including valuable fisheries thus sustaining livelihoods locally and beyond;
- Provide recreation, aesthetic, and cultural values.

Floodplains are areas of land adjacent to waterways that stretch from channel banks to the base of the enclosing valley walls and experience flooding during periods of high riverine discharge [43]. They include the floodway: the stream channel and adjacent areas that actively carry flood flows downstream; and the flood fringe: the areas inundated by the flood, but are not subjected to high velocity currents. Effectively, a floodplain is an area near a river or a stream that floods when the water level reaches flood stage. Floodplains can support particularly rich ecosystems, both in quantity and diversity. Floodplain provides a wide range of services including water flow and flood regulation that are largely determined by the connectivity between water body and floodplain, which can be hampered by development and infrastructures. Reduced connectivity between river beds, river channels and floodplains is often related to reduced flood-protection and

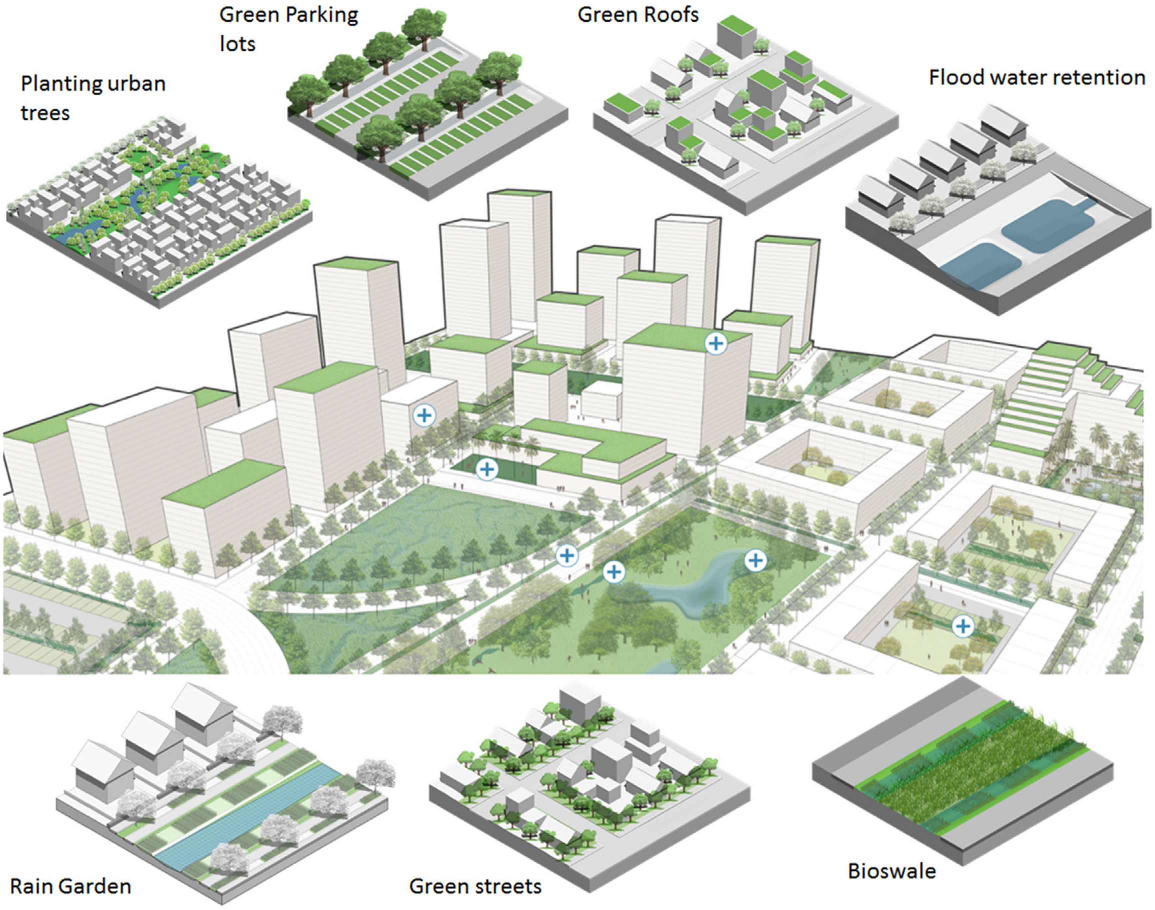

Fig. 2. Urban landscape eco-engineering typologies. Through vegetation and flood water alleviation systems, air temperatures can be reduced, flood flow facilitated, and excess of flood water stored and infiltrated. The "+" signs indicate location of typologies presented. Adapted from www.nrcsolutions.org and used with permission (Sasaki Associates & The Nature Conservancy).

increase losses.

Although these areas are highly susceptible to flooding, human settlements have been built historically on floodplains due to access to water, fertile soils for agricultural production, cheap transportation and ease of development on flat land. Floodplains are some of the most valuable places on the globe, both for people and wildlife. Fertile soils deposited by rivers make these areas extremely productive for agriculture. Within these areas, fish and wildlife thrive, benefiting important commercial and recreational industries, too. This explains why in the past centuries humankind has encroached on these rivers and deprived them from large parts of their floodplains.

Floodplains provide valuable services to people and larger ecosystems [44–47] summarized in the following categories.

- Flood Protection: Floodplains provide a river more room as it rises, thereby reducing pressure on manmade flood protection structures, like levees and dams.
- Improved Water Quality: Floodplains act as natural filters when inundated through removal of excess sediment and nutrients that can degrade water quality and increase treatment costs. Degradation of water quality due to the loss of floodplain habitat can be noted along smaller rivers and at-scale at large river basins, for example in hypoxic or "dead" zones downstream where little life exists due to excess nutrients carried by rivers.
- Recharged Aquifers: Outside of a river's main channel, water flow is slowed and has more time to infiltrate where it can replenish aquifers, which serve as a primary source of water for many communities and are critical for irrigation that grows much of the world's crops.
- Improved Wildlife Habitat: Floodplains are home to some of the most biologically rich habitats on the globe. They provide spawning grounds for fish and critical areas of rest and foraging for migrating waterfowl and birds.
- Recreational Use: Recreational activities such as fishing, hunting, camping, hiking, wildlife watching or boating come with the natural processes of rivers and healthy floodplains. These recreational activities are important economic activities in the United States and around the globe.

In **urban areas**, protective services are often limited due to prior land use policy and extensive development. The emphasis then is placed on restoring or enhancing ecosystems through eco-engineering to re-establish services and co-benefits (coastal and floodplain above) with additional focus on minimizing heat and air quality impacts on residents, public outdoor spaces, and building exteriors through urban tree canopy maintenance and enhancements (Fig. 2). Reduction of localized, precipitation-driven flooding is a key role of eco-engineered runoff capture and infiltration approaches widely referred to as stormwater gardens, bioswales, and/or rain gardens. Eco-engineering focused on facilitating stormwater runoff were introduced as sustainable urban drainage systems ('SUDS') at the end of the last century [48].

- Techniques that focus on retention of stormwater, such as retention basins, are often combined with green spaces, such as green roofs, artificial wetlands, infiltration trenches and grassed filter strips resulting in multiple purposed use of space. This also aids in groundwater recharge [49].
- In addition, the buffering from coastal and inland flooding of public

amenities and public or private structures along urban river banks, harbors, and open coastlines is a central focal point for urban eco-engineering applications.

- Unlike many coastal and floodplain locations, ecosystems services that enhance cultural, aesthetic, and recreational opportunities are highly valued in urban landscapes alongside protective functions.

3. Basis for risk reduction and status of criteria for eco-engineering

It is increasingly recognized and demanded that assessments of adaptation measures are based on risk analysis and science [50–53]. Loss and Damage and Analytical approaches [54] that quantify and assess risk can provide a rationale to make informed decisions on how to manage risks and quantify the effectiveness of measures to reduce them [49,55]. Furthermore, adaptation and climate risk assessment need to provide targeted policy information that address stakeholder's concerns [50,55]. This includes: (i) quantitative projections of long-term climate risks, (ii) define risk drivers, (iii) associated costs, and (iv) assess curative measures. Only economic, ecological and engineering frameworks that work on these principles can be used to make fiscally and socially responsible decisions about adaptation strategies by communities [52].

It is increasingly recognized that coastal and freshwater ecosystems from rural to urban settings can offer engineering performance and therefore reduce risk. However, to use ecosystems for risk reduction, it is necessary to quantitatively assess risk and the risk reduction potential of ecosystems in economic terms. Risk occurs at the intersection of climatic hazards and socio-economic exposure. Flood risk is therefore a function of probability, exposure and vulnerability [56]. In practice, risk is calculated as the probability that an event occurs (hazard), the reach of the flood extent (exposure), and the associated consequences (e.g. losses) (Fig. 3).

Risk analysis and science is well established for modeling of catastrophic events that project the effects of extreme events on people and assets. Risk is usually measured as the economic losses or damages associated to a certain probability, usually expressed through return periods (an estimate of the likelihood of an event, like extreme sea levels or a river discharge flow, which is usually based on historical data and represents the average recurrence interval over extended time periods). Nature-based risk reduction can be assessed under similar frameworks (e.g. Fig. 3) using different models and approaches [e.g. 57,58].

Fig. 3 provides a modeling framework to quantify risk. It involves sequential steps: (1) define the hazards (flooding, calculated from the action of waves and surges in coastal areas and rainfall and runoff in rivers), including the effect of the ecosystem on flooding (through physical characteristics such as friction, geometry, catchment capacity and retention, etc.), (2) define the exposure, i.e. people and assets in the flooded area; and (3) assess economic damages using damage curves that relate flooding properties (e.g. water depth) with the intensity of the damages. Assessing these risks for a scenario with (a) absence of natural infrastructure protection and (b) with the effect of natural infrastructure protection and/or eco-engineering options (see lower left diagram in the Fig. 3) provides a quantification of the protection ecosystems provide. A similar approach can be used to compare different scenarios and contributors to risk, for example the effect of climate change or changes in economic exposure (e.g. urbanization).

Proactive engineering applications that factor in the “difference” provided by the presence/absence of ecosystems serve as vehicles to justify the use of natural infrastructure using this flowchart. Further still, progressive applications should facilitate and enhance ecosystem co-benefits as reviewed above. Flowcharts of specific elements to address when assessing risk and risk reduction from ecosystems are instructive (Fig. 4). For coastal areas and floodplains, the models vary but their assessment framework is consistent and equally applicable, as represented in Fig. 4.

4. Current challenges and limitations to eco-engineering

Current engineering practices and practitioners require a higher level of confidence and certainty regarding the ability of natural infrastructure to reduce risk. As a response, ecological restoration efforts have over the last 20 years expanded to incorporate hazard mitigation as a priority (i.e. eco-engineering [61]). A recent synthesis [40] of sixty-nine coastal projects suggests that average wave height reduction ranges from 35% to 71% depending on habitat type and location (high/low energy coastline), such as coral reefs (70%), salt marshes (72%), mangroves (31%), and kelp beds (36%). Under non-storm conditions mangrove forests are highly effective at reducing waves by approximately 70% of nearshore height and eliminate scour of the mangrove bed [62]. Other studies have shown that mangrove forest width influences wave reduction; 13–66% over 100 m versus 50–100% over 500 m [63] due in large part to frictional drag within the water column by mangrove trunks and roots. The density, spacing, age, and size of trees, as well as the species of mangrove can also have a dramatic effect on

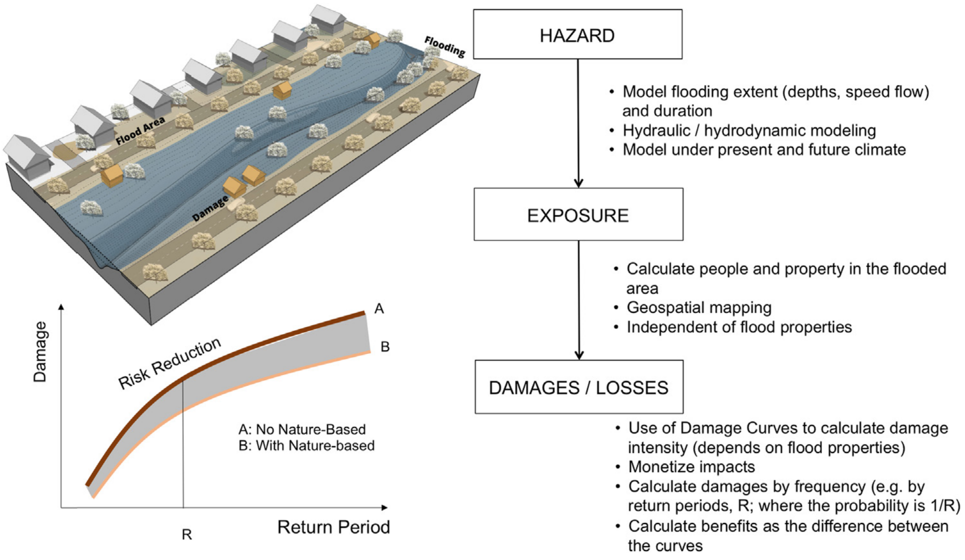

Fig. 3. Risk assessment and modeling framework with integrated considerations for natural infrastructure via risk reduction curves (Damage or Economic Loss versus Frequency) with and without protection and/or eco-engineering options (“No Nature-Based”; “With Nature-Based”). The flowchart shows how to quantify risk from the: (i) modeling of hazards (coastal and freshwater flooding), (ii) calculating the exposure of people and assets in the flood zone; and (iii) the calculation of damages and losses. Lower-left panel: the comparison between two scenarios: scenario A – with no nature-based options and scenario B – with the effect of nature-based options, provides a quantification (grey area in the lower left diagram) of the economic benefit of introducing these measures to reduce risk [52]. For example, a flood event with frequency 1-in-R years (i.e. where the return period is R, and the probability of 1/R), the difference between scenarios A and B, i.e. between the baseline risk and with nature-based option, represents the economic value the protection offered by that measure. The effect of this reduction (the risk reduction curves with and without nature-based solutions) needs to be modeled for each specific measure, site, and with the local settings (e.g. [58,59]), the curves in the diagram only represent sample curves for explanatory purposes. See [55,60] for additional information.

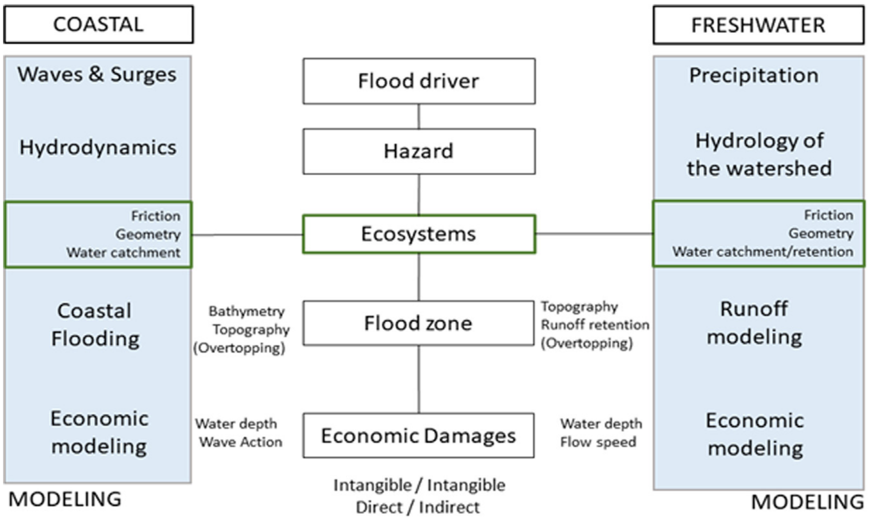

Fig. 4. Assessment of flooding risk and the role of coastal and freshwater ecosystems. The figure shows a general flowchart with steps to take for assessing economic damages and protection offered by coastal (left) and freshwater (right) ecosystems. The steps show the existing compatibilities based on an assessment framework depending on location and flood-driver for coastal and freshwater, respectively.

wave height reduction. Under storm surge conditions, there is a reduction of 4–48 cm per kilometer wide forest depending on hydrodynamics in front of and within the mangroves [63] which can have an impressive reduction in landward flooding extent to coastal property. Under tsunami conditions, mangrove can reduce flood depths by 5–30% over 200-meters or more wide forests however, wave heights above 4 m will decimate mangrove forests regardless of width [63]. Overall, there is no overwhelming evidence that mangrove forests can reduce significantly the impacts of big tsunami waves [64]. Under many of these scenarios, mangrove forests can decrease the flood level on the landward edge by at least 35% in the presence of both barrier and fringing reefs in coastal Belize [62].

In more temperate regions of the world, coastal salt marsh is a focal habitat when considering protective services and risk management. Under experimental conditions in a 300-meter wave flume with 40 m of transplanted natural marsh vegetation, wave attenuation was estimated by Moller et al. [25] at 60%. These authors also noted that despite the eventual damage to the vegetation the marsh substrate remained resistant to erosion suggesting that salt marsh is an important element for coastal risk reduction. In the Yangtze Estuary, China, waves ranging between < 0.1 and 1.5 m were effectively attenuated completely over a marsh width of 80 m except for the largest waves which required > 100 m [65]. For marshes in front of a dike in the Netherlands, van Loon-Steensma et al. [66] demonstrated that under storm conditions wave run up on the levee is reduced by 20–100%, depending on water depths and wave heights. These authors suggest that salt marsh when restored in front of a dike will reduce wave attack on the adjoining dike thus enhancing the overall risk reduction of an integrated, flood control system. In addition to salt marsh width, Yang et al. [65] also demonstrated an inverse correlation between plant height (*Spartina alterniflora* – tall and short form) and wave attenuation rates; the taller the vegetation the more wave attenuation. Based on these few studies the width, landscape position, and vegetation type are certainly an important design consideration for natural infrastructure projects involving salt marsh. While this empirical evidence demonstrates the capacity of natural infrastructure to reduce risk, the extent of comparable data currently curtails the ability to translate physical characteristics of these habitats into standards, criteria, and design parameters for engineering purposes; with the exception being coral reefs in high energy coastlines.

Additional challenges to the uptake of eco-engineering approaches and practices include more site specific, engineering considerations/concerns including the following (after [67]):

- Site suitability for physical environmental criteria such as amount of exposure, slope, and capacity to withstand loads of varying magnitudes and duration;
- Physical site characteristics and those of adjoining land uses. Neighboring properties with natural, undeveloped coasts will minimize wave energy deflection towards the natural infrastructure project site under consideration;
- A well-designed eco-engineering project must be durable and able to weather the wide range of storm events from higher frequency – lower energy to lower frequency – higher energy;
- To maximize a project's lifespan, maintenance and monitoring programs should be incorporated into their designs and approved plans;
- Functional lifespan – requires durability from event to event or during a sequence of changing events (i.e., thunderstorms, waves and high tide; ice; storms);
- Longevity – natural infrastructure project rarely have a 25-year lifespan; 10-15 years is more typical;
- Eco-engineering project design may need to integrate hard infrastructure elements (i.e., hybrid approaches). This type of application could extend the project's longevity from 15 to 25 years in some cases;
- Sustainable design of projects also requires an accounting of changing conditions such as increases in sea level rise and/or storm intensity over the projects intended life span (i.e., consideration 10 years – 2.5–5 cm of static sea level rise);
- Eco-engineering projects should look to achieve multiple objectives if possible such as native habitat and erosion prevention for immediate and nearby infrastructure and homes.

Additional challenges center on the fact that applications are still very scarce and tools limited [68], funding sources mostly restricted to traditional environmental protection and restoration rather than natural infrastructure funding [69], and regulatory and technical barriers persist broadly. The lack of standards and targeted guidelines are limiting a broader uptake. Case studies and supporting long-term monitoring are required to enhance confidence and comparability with standard engineering for coasts, floodplains, and urban landscapes.

5. Global/regional processes and supportive examples

An effective way to reduce these challenges/limitations and justify and legitimize the use of eco-engineering is by identifying interjection points within existing globally accepted land use/policy/management processes currently employed in coastal and watershed management (i.e. IWRM, ICZM). These processes are continuous and guide decisions surrounding coastal and watershed management. Usually, these

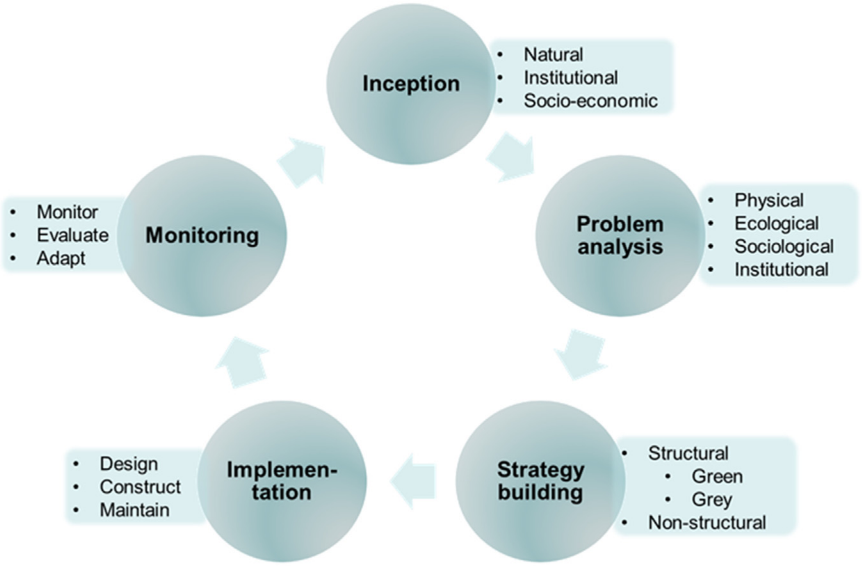

Fig. 5. General project phases for IWRM and ICZM projects based on general policy and planning cycles as integration points for eco-engineering principles and applications (modified after Sayers et al. [72]).

processes are complex including diverse stakeholders, are trans-sectoral, and focus on issues on large system scales that extend beyond political and legislative boundaries. The principal project phases identified in IWRM and ICZM are (Fig. 5):

1. Inception - entails defining the natural, social and institutional landscape;
2. Problem analyses - risk assessment with specific attention on physical, sociological and ecological elements of the system and preferably consider extensive time and spatial scales;
3. Strategy building - development of alternative strategies with measure(s) that consider structural and non-structural methods and combinations (green, grey, hybrid solutions);
4. Implementation - design, construction and maintenance;
5. Monitoring - evaluation to assess performance of measures.

Each of these phases offers opportunities to consider or reconsider eco-engineering integration (see Figs. 1 and 2) into land use/policy decisions; particularly at project onset (i.e. Inception) and during “Problem analyses” with specific attention given to natural, social and economic factors [70]. Importantly, both the “Inception” and “Strategy-building” phases can include developing a comparative financial assessment that includes eco-engineering alternatives along with project development and pace. Links between eco-engineering and IWRM and ICZM initiated by van Wesenbeeck et al. [71], are expanded here via examples across prominent coastal, floodplain, and urban landscape settings with an additional repository in Table 1.

5.1. Integrated water resource management process

A central driver of socio-economic growth and ecosystem integrity is water resources. The allocation, use, and return of this resource has been productively managed in most cases via the IWRM process which seeks to do so in a sustainable and equitable manner that minimizes demand conflicts. The three core principles of IWRM as described in a Global Water Project's report [70] are:

- Enabling appropriate policies, strategies and legislation for sustainable water resources development and management;
- Institutional framework through which the policies, strategies and legislation can be implemented; and
- Management instruments required for the implementation.

Despite the large number of tools and guidelines available through the IWRM process there are currently no comprehensive approach or examples that integrate resilience across diverse landscapes and hydrologic hazards within the context of applying eco-engineering. This type of consideration is critical to developing robust eco-engineering applications and principles. For example, in Europe, the remaining floodplains are viewed as important for nature conservation with required targets of 15 percent restoration of degraded ecosystems and their services by 2020 per the EU Biodiversity Strategy [73]. Since 2012, in Europe the 'Directive on the assessment and management of flood risks', better known as the 'Floods Directive', has become a new instrument to articulate flood risk reduction and align it with environmental and restoration goals. Sustainable flood risk management combines elements to reduce the exposure to flooding, lessen the vulnerability of people and property, execute sensible management of land and the environment, and improve preparedness and early warning for adverse events [73]. In Europe, proactive nature-based flood risk management not only meets objectives of the EU Floods Directive, but also the Water Framework Directive, and the Birds and Habitat Directives [73].

5.2. Integrated coastal zone management process

Integrated Coastal Zone Management refers to the holistic process of realizing a sustainable vision for coastal zones considering diverse stakeholder’ needs and values. It is based on strong understanding of the coastal ecosystem, including biophysical and ecological components, followed by defining strategies for dealing with long-term issues. Just like IWRM, ICZM is a circular process that needs to be evaluated as external conditions and system responses change. Per the European Commission “ICZM seeks, over the long-term, to balance environmental, economic, social, cultural and recreational objectives, all within the limits set by natural dynamics”. The need for coastal zone management typically arises where populations face problems with coastal erosion or flooding - often due to poor land use management and over development. There are four main goals of ICZM as identified by Thia-Eng [74]:

- Maintaining functional integrity of coastal resource systems;
- Reducing conflicts on resource use;
- Maintaining a healthy environment;
- Facilitating multi-sectoral development.

Table 1
Projects that integrate eco-engineering principles, standards, criteria, and policies. Graphic representation of eco-engineering application mentioned are presented in Figs. 1 and 2.

Project	Location	Objectives	Eco-Engineering Applications	S/C/P*	Reference
NY/NJ Shoreline Management	New York/New Jersey (USA)	Restore and enhance natural infrastructure to protect urbanized coastlines and watershed.	Beach/Dune - storm surge attenuation. Green Infrastructure - minimize localized flooding.	S/C/P	[101,102]
Louisiana Coastal Master Plan	Louisiana (USA)	Integration of natural infrastructure to protect coastal zone.	Salt Marsh - storm surge attenuation, sediment accretion.	S/C/P	[103–105]
Room for the River	Netherlands	Integrating natural infrastructure to protect riverine communities across multiple countries.	Floodplains - water retention, increased bank stability with vegetation, reduce dike overtopping, avoid erosion upstream, increase sediment deposition downstream.	S/C/P	[106–108]
Floodplain by Design - Washington	Washington state (USA)	Adjust water management to allow greater ecological functionality and risk reduction to property.	Floodplains - greater levee setbacks coupled with ecological restoration to connect floodplains with public recreation.	S/C/P	[47]
Belize Coastal Zone Management	Belize	Benefit/cost assessment of ecological services in risk reduction.	Coastal - economic benefits from ecosystems to risk reduction.	P	[21]
Monterrey Metropolitan Water Fund	Mexico	Cost analysis of risk reduction via floodplain restoration.	Floodplains - flood storage and diversion from downstream urban center.	C/P	[47]
Illinois River Managed Flood Storage Option Project	Illinois (USA)	Benefits of reduced flood peaks by opening selected levees.	Floodplains - flood storage/diversion via strategic levee opening.	C/P	[44]
Dockside Green	Victoria, BC (CAN)	Integrated energy and wastewater management.	Green infrastructure green roofs, rain gardens	S/C/P	[109]
Tucson Green Streets	Arizona (USA)	Integrated flood, stormwater, pedestrian friendly development	Green streets, bioswales, rain gardens	S/C/P	[110]
Grenville Artificial Reef Restoration	Grenada	Coral reef engineering for coastal protection	Coastal flooding and erosion control	S/C/P	[59]

- S/C/P = Standards, Criteria, Policies to enable eco-engineering.

These goals are rather broad and general but offer a good basis for working towards solutions and measures that integrate eco-engineering in ICZM, which are widely accepted and minimize conflicts with existing natural infrastructure.

Recently, guidance on using natural infrastructure to reduce risk was developed by the World Bank in collaboration with a wide-range of multidisciplinary partners [75]. This guidance makes use of IWRM and ICZM and offers a series of implementation steps and guidance via five principles that aim to accelerate and improve implementation the use of natural infrastructure to reduce risk (i.e., eco-engineering) [75].

5.3. *Eco-engineering supportive examples*

The following examples illustrate the use of eco-engineering via a watershed/water resource project for IWRM, a coastal project for ICZM, and an urban resilience project. The examples examine the current limitations and opportunities for integrating eco-engineering into several globally and regionally recognized resource management processes.

5.3.1. *Coastal*

5.3.1.1. Building with Nature Indonesia. Indonesian muddy coastlines, which are the more sheltered and gradual sloping coastlines (i.e., North coast of Java) are increasingly suffering from erosion and flooding [76]. This is mainly caused by alteration of river flows, removal of mangroves, and unsustainable management of groundwater resources. Extraction of large amounts of groundwater from deep wells (greater than 100 m) by industry, government buildings, and hotels causes rapid subsidence of coastal cities in Indonesia [77]. Conventional measures, such as seawalls and breakwaters, easily fail on the soft muddy soils and suffer from the rapid subsidence [78]. Hard infrastructure, such as seawalls with steep slopes, reflects waves thereby increasing bottom shear stresses, which create scour in front of the construction leading ultimately to the collapse of seawalls [79]. Attempts to restore the coastline through mangrove planting efforts often fail because elevation is too low and wave impact is too high. A pilot experiment along several kilometers of coastline was started with placing permeable brushwood dams that reduce wave energy but do not block sediment transport. Whereas many projects claim to use mangroves for flood risk reduction, this project is unique in that it started from a large-scale system perspective integrating coastal planning, watershed management, drinking water resources and community livelihoods. It followed steps for Integrated Coastal Zone Management in that it started with an inception phase to determine stakeholders, budgets and boundary conditions. Second, a situation analysis was carried out, specifically focusing on large scale system behavior, as the project embraced the “ridge to reef concept” and addressed both sediment and freshwater availability. Coastal construction of concrete seawalls is extremely expensive and technically challenging due to the presence of thick soft sediment layers in this area. Present hard structures that are constructed with low budgets show signs of failure after 1–2 years of implementation. Therefore, other measures that focus on stopping erosion and increasing sedimentation were considered as alternatives within ICZM. After assessment of the system and distinct measures, the project made an eco-engineering-based plan for design of permeable dams and adopted an adaptive approach where each year's design is adopted based on measurement results of previous years [80]. The project works to achieve clearly set targets at various scales routinely informed by monitoring, evaluation, management, and new designs as needed. Additionally, the local community is strongly involved in the design cycle and delivers input to new designs of dam locations. Further, field programs designed to optimize pond production for local aquaculture farmers also offer the communities a large-scale perspective on their own coastal system. This way, coastal measures to stabilize the coastline are combined with community programs to improve local incomes. Although systematic process steps are followed, implementation remains challenging. First, construction of permeable dams needs to be done by hand and achieving the right level of structural integrity therefore remains a challenge. Second, working with a cross-sectoral team needs constant communication and more intense collaboration than in project that follow conventional approaches.

5.3.2. Floodplains

Traditional flood risk management approaches seek to constrain watercourses by building dykes and hardening river banks to increase discharge capacity, dredging and building reservoirs, and artificial retention areas to store excess of flood water. During extreme flood stages the amount of damage can be catastrophic if engineered systems are overwhelmed and fail. Perversely, engineered flood-protection systems provide the perception of increased security. The areas behind a hard infrastructure (e.g. levees) are often highly developed, which has considerable economic and social consequences if the flood event is of a higher magnitude than the protection level (e.g. Hurricane Katrina and New Orleans). These protection measures may also have environmental impacts (e.g. water quality) that limit the capacity of the floodplain to provide ecosystem services.

In contrast, by reconnecting streams, rivers and natural storage areas and enhancing the capacity and quality of wetlands, river restoration increases the natural capacity to store flood water and ameliorate risk and damages. A network of natural and semi-natural areas designed and managed to deliver a wide range of ecosystems services also assists flood protection. Floodplain restoration is an important measure which gives more room to rivers, develops ecological beneficial hydrological regimes, and enhances floodplain and wetland habitats. Understanding flow discharge, sediment transport, and (large-scale) morphological behavior [45] is essential. Ideally, excess flood water is stored in naturally beneficial areas that also increase flood risk management options for communities responding to climate-related fluctuations in rainfall cycles and extreme weather patterns. In recent years, governments and managers of various rivers around the world have recognized these principles and proactively developed floodplain restoration projects for flood alleviation and restoration purposes, or both (i.e. eco-engineering).

The Floodplains by Design (FbD) project in Washington state (USA) is a comprehensive effort driven by broad watershed-scale, public-private partnerships to ensure better management of shared floodplain resource through the integration of flood hazard reduction, habitat protection and restoration, and improved water quality and outdoor recreation [47]. The FbD requires consideration of the dynamic connections and interactions of land and water through which a river flow (Inception (see Fig. 5)) and a modeling application (Problem Analyses) that maps ecosystem service values and trade-offs (Strategy Building) between conservation and development (Implementation and Monitoring).

A central concept of an FbD approach is that areas that flood most frequently (e.g. every one to five years) are most valuable for floodplains since they provide the most ecosystem services for people, but are most at risk of repetitive flood damages when developed. An FbD approach calls for these areas to be managed differently than other areas of the floodplains, following some key principles (modified from [47]):

- Natural Infrastructure Use Maximized – work with, not against, natural processes such as flooding frequency and extent (annual, 100 yrs., 100–500 yrs.) by incorporating floodplains, wetlands and open areas in management decisions. Some key tactics include:
    - Setback Levees: levees or berms constructed or moved farther from the river and ideally out of the annual and 100 yr. floodplain, thereby allowing rising rivers more room to adjust and flood yet provide protection during extreme flood events (100–500 yrs.).
    - Connected Floodplains: Connected or never “cut off” from the river by levees or other structures or “reconnected” by the removal or management of levees.

- Portfolio of Diverse Flood-Risk Management Techniques – tailor techniques to specific requirements of the watershed. In addition to dams and levees as well as setback levees and connected floodplains, such techniques can include floodways and flood bypasses, which are large-scale floodplain reconnections for storage and conveyance of water.
- Community Benefits Maximized – from initial identification of community needs/values, seek to enhance benefits of floodplains and rivers to local entities by improving access, safety and health of river systems through collaborative consideration of solutions; not only reducing flood risk but also improving habitat for fish and wildlife and water quality impacts at the source.
- Plan and Implement Resilient “Whole-River” Practices - dams, levees, floodways, natural areas, topography, croplands, existing and planned developments, and river uses – such as for recreation, municipal water supply, irrigation, and navigation – are all interrelated and must be managed as such.
- Mosaics of Accommodating Land Uses – a mosaic of diverse land uses that are both resilient to flooding and consistent with vibrant communities; tailor land use for the average frequency and duration of floods the area is subjected to.

These key FbD principles provide critical and discrete intersections with IWRM's three core principles [70]; particularly for sustainable water resource management and instruments for implementation; as well as with ICZM via Fig. 5. The following examples reinforce these principles and intersections.

The Calistoga Reach FbD project has helped dramatically reduce flood risk for the City of Orting, Washington state (USA) and surrounding community [81] by reconnecting side channels, moving 2.4 km of the levee back to more than double the width of the river, and installing log jams that add river complexity and shoreline protection. The project has also improved the habitat conditions. During a January storm in 2009, the Puyallup River in Washington was raging and crested at 479 m^3 per second (cms), and approximately 26,000 people were evacuated, which constitutes one of the largest evacuations in the State's history. The Puyallup River again crested above 453 cms on November 25th, 2014, after the redesign of the floodplain, with a result of only a handful of residents evacuated.

The Mollicy Farm Project in northern Louisiana (USA) is the largest floodplain restoration in the Mississippi River Basin to date [82]. Once a vast expanse of bottomland hardwood forest seasonally inundated by the floodwaters of the Ouachita River, the Mollicy Farms unit was separated from the river in the late 1960s and early 1970s by a 27-kilometer-long levee and converted to agriculture. In the 1990s, the Conservancy helped the U.S. Fish and Wildlife Service (FWS) acquire much of the Mollicy unit and add it to the national wildlife refuge. The FWS planted more than three million bald cypress, oak and ash trees and a host of other native species on almost 4450 ha of the refuge to restore the floodplain forest. The reconnection of the river and its floodplain was critical to the long-term health of the forest and aquatic life in the Ouachita River. Levee setbacks to help reconnect floodplain can bring multiple benefits and can also capitalize on opportunities during post storm recovery.

Other examples of these approaches have been implemented in the Danube River (Europe), Mississippi River (USA), Cauca River (Colombia) and the Rhine River (Germany) (see [83]). It is worth noting that river intervention work based on these key principles have also been shown to impact flow and sediment transport fields and induce larger dynamics of the riverbed [83], potentially affecting navigability. This is a factor to consider for management and reflects the multifaceted nature of watershed processes. However, it reinforces the principle of having a holistic view on interests, landscape, socioeconomics, and natural processes – which are also in alignment with core IWRM principles.

5.3.3. Urban

To meet UN sustainable development and SFDRR goals [7,12], urban centers will need to achieve a higher level of sustainability, "lived experience" (SDG 11), and resilience for an ever-increasing number of residents (Inception, Problem Analyses (Fig. 5)). Actions can include "resilient infilling" to increase density in lower risk areas by demarcating receiving zones from higher risk areas such as floodplains, low lying coastal areas, excessive heat islands, and settlements with reduced or compromised water supply (Strategy Building, Implementing, Monitoring (Fig. 5)). Prioritizing and fortifying stable, lower risk areas with adequate structures constructed using progressive building codes and supported by adaptable social networks with the resources to accommodate change is an ideal setting to advance urban resilience. These actions offer opportunities to integrate improvements to urban spaces using functional (and physical) aspects of ecosystems such as heat amelioration (urban tree canopy), flood retention (storm gardens, bioswales), and storm surge/flood protection (salt marsh, mangroves, reefs). What is lacking is not the generation of affirmative actions like these but a comprehensive process to strategically catalogue and plan for resilience in urban centers.

Unlike IWRM and ICZM where standardized principles, policies, and practices provide a process to intertwine adaptation to manage extreme events and climate change across complex social-ecological systems [21,84–86], urban centers present fundamental challenges to resilience planning and design [87]. Currently, there are limited examples [88] and no standardized process upon which resilience approaches can be integrated in urban centers [89]. Clearly, the challenges rest in the fact that urban centers are complex, interrelated, spatially-dependent systems developed over time in response to historic events and punctuated by periods of redesign/retrofit; given current local and global social-ecological demands [87,90,91]. The comprehensive utilization and application of eco-engineering practices for example across an interactive network of projects in urban centers are therefore limited [90,92,93]; particularly as it relates to extreme weather events accentuated by a changing climate.

To decipher the complexity of resilient urban systems in a comprehensive manner there is an engagement prerequisite. Engagement with local knowledge professionals (i.e. neighborhood representatives, pastors, employers, etc.) and other stakeholders that results in actions that straddle multiple planning sectors [see 47]. For example, a community-driven resilient building process [see 47,94] has been used in Bridgeport, Connecticut (USA) to comprehensively address the complexity and interdependence of urban systems and strategically prioritize eco-engineering within a post-industrial, mid-sized coastal city (pop. 144,000; size 50 km^2; 50th largest urban area in the USA). In 2011, a Community Resilience Building (CRB) workshop series (see www.communityresiliencebuilding.org) identified strengths and vulnerabilities, developed actions, and prioritized short and long-term resilience strategies for Bridgeport [see 94,95 for CRB process, approach, outcomes]. The CRB elevated awareness of ecosystem services such as flood retention and protection from extreme weather events at the neighborhood scale. One priority outcome was the identification of salt marsh advancement zones [96] and green infrastructure installation projects to help reduce the exposure of disadvantaged populations. Subsequent stormwater gardens were installed [97] that have served as pilots exportable to other neighborhoods. To identify suitable locations for additional eco-engineering applications a neighborhood screening tool was developed – Eco-Urban Assessment [98]. This tool utilizes locally available data sources and a model building software package (i.e. python model builder) to identify spatial intersections of critically important risks and conditions across pre-defined neighborhood divisions. The tool identified those neighborhoods with the highest asthma rates, dependents (< 18 years old), elderly (> 65), low/moderate income, elevated flood exposure, and lowest urban tree canopy (i.e. heat islands). The intersection or aggregation of these variables helped prioritize neighborhoods with highest risk and greatest need of eco-engineering interventions. The coupling of this tool with community engagement has galvanized neighborhood-scale leaders in support of eco-engineering activities including urban tree canopy enhancement and bioswales in proximity to high-use amenities (community centers, housing renewal projects, public transit hubs, school playgrounds, main streets, churches).

Urban centers require these focused neighborhood-scale applications within a regional planning framework to ensure comprehensive uptake and resilience [see 87]. Simultaneously with these neighborhood-scale projects in Bridgeport, the Regional Framework for Coastal Resilience project that encompassed this municipality and nine others in Southern Connecticut (10 municipality planning area) was initiated to amplify local resilient actions and conceptual design of regionally significant eco-engineering projects [94,99,100]. Fig. 6 provides

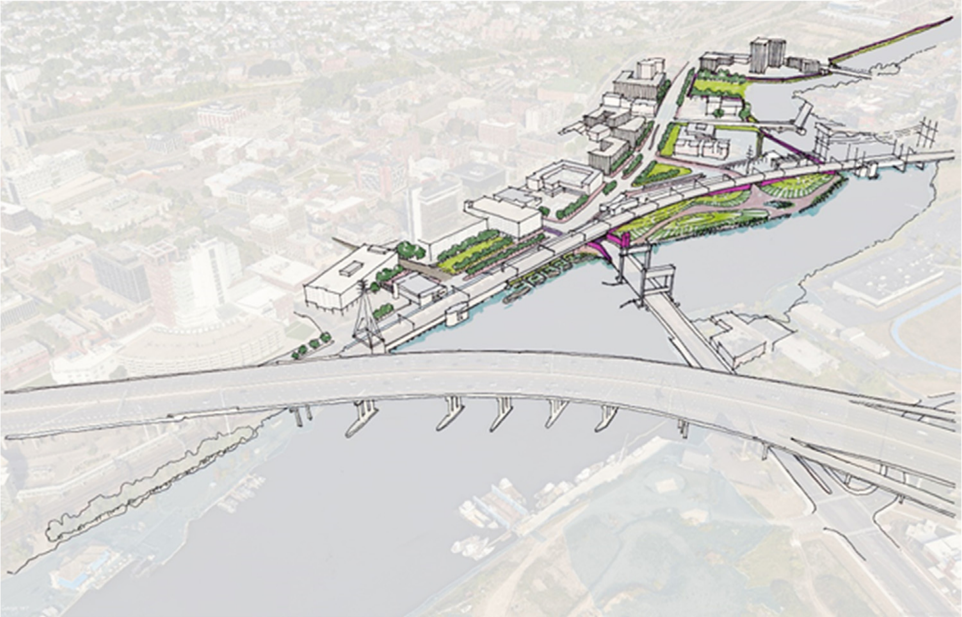

Fig. 6. Conceptual design with eco-engineering applications to produce a hybrid design to enhance resilience in an urban center (Bridgeport, Connecticut, USA) and ultimately protect critical infrastructure, public amenities, and utilize natural systems to both accommodate flooding and reduce risk in response to flooding from sea level rise and Category-3 hurricane (i.e. "resilient triple bottom line"). Design integrates typologies from Figs. 1 and 2 including flood water retention, bioswales, green streets, living shorelines, and obstacle removal. (Credit: The Nature Conservancy & Urban Ecology and Design Laboratory – Yale University; [100]).

rendering of eco-engineering alternatives to address current, routine flooding and longer-term sea level rise implications to a regionally significant, multi-modal transportation hub, municipal courthouse, regional commuter rail line, and a critical power sub-station. The design provides progressively sophisticated alternatives to safely accommodate accelerating levels of projected flooding out to 2100 and focus on utilizing existing undeveloped, publicly owned parcels. The design strategically integrates flood diversion structures (hard infrastructure) into the existing built environment coupled with flood retention through eco-engineering on the undeveloped parcels and adjoining streets and facilities. The intersection of critical local and regional infrastructure, enhancement of this public amenities and social good, and the restoration of ecosystems in the designs achieves a “resilient triple bottom line” essential for eco-engineering advancement. Coupling this type of design with a robust engagement and prioritization as illustrated here is critical to building momentum for implementation of eco-engineering projects in urban landscapes (as well as rural and suburban) at multiple, interdependent scales (local to regional).

6. Conclusions and recommendations

This article provides an overview of eco-engineering origins and principles, review of basis of risk and criteria for risk reduction, consideration of current challenges/limitations to advancing eco-engineering applications, assessment of opportunities to interject eco-engineering approaches, principles, and standards into several globally recognized resource management processes and supportive examples across diverse landscapes. Based on this review, clearly both opportunities and challenges exist that require additional research and application to advance eco-engineering during the 21st century.

Eco-engineering approaches and projects can arise from multiple perspectives and stakeholders across diverse coastal, freshwater, and urban landscapes (Figs. 1 and 2). Some projects are generated initially to enhance nature and biodiversity, whereas others focus on tourism, recreation, or flood risk reduction and climate change adaptation goals. Identifying these objectives beforehand is crucial to project success, but even more critically is the realization that eco-engineering can help achieve multiple objectives (see Fig. 5; supportive examples/Table 1). Therefore, a shift from traditional single objective engineering to multiple objective solutions is paramount along with an understanding that eco-engineering can and will be a key part of the new paradigm. Even if process steps are meticulously followed, eco-engineering projects remain challenging as they currently often require innovative techniques that lack proper design standards and performance metrics in response to locally specific constraints and opportunities.

Therefore, one should not expect broader acceptance of eco-engineering solutions until knowledge gaps are remedied. Overarching recommendations to enhance the acceptance and continued advancement of eco-engineering through science, design, policy, and multi-scalar processes are:

- Integrate ecosystem services and co-benefits options into established frames (IWRM, ICRM) at all stages (Fig. 5) for coastal, freshwater, and urban landscapes, and combinations thereof;
- Focus natural hazard mitigation and master growth plans on improving the resilience of existing habitats and ecosystems as a cost-effective approach to risk reduction at all scales (particularly once all co-benefits are accounted for);
- Seek improvements to ecosystem service models and tools (e.g. Indonesia, FbD, Belize ICZM Monterrey, Mexico (Table 1)) that allow for a more robust accounting of protective services and co-benefits in risk management planning including existing natural resources (refer to [44] for review of Eco-DRR/CCA decision tools and approaches);
- Compare projects outcomes with and without natural infrastructure. Include estimates at the project specific and national scale;
- Consider restoration, enhancement, and/or creation of habitats as key alternatives in risk management frameworks, plans, and actions. This should be done systematically, alongside other options such as tradition single objective engineered options;
- Advance exploration of hybrid design and applications in diverse situations (e.g. Indonesia, FbD, Bridgeport (Fig. 6)) with long term monitoring programs;
- Implement additional pilot projects across a variety of coastal conditions and broad geographic extent to fully demonstrate the effectiveness of natural infrastructure in reducing risk as compared to hard engineered approaches. Ensure that rigorous experimental design and long term monitoring is integral to new pilot projects;
- Work to develop eco-engineering standards and design guidelines for locally specific situations acceptable to the engineering and design communities as well as the regulatory/permitting agencies (Section 4.0 above, after [67]);
- Conduct robust community resilience building engagement around the benefits of natural infrastructure (see [47,94,95]); particularly include coastal and floodplain property owners (public and private);
- Convene and participate in interactive dialogue between engineering, design, policy, and natural resource management professionals that continue to explore the efficacy of natural infrastructure, hybrid approaches, and typical engineering practices (see [67]).

Only when these gaps are addressed will eco-engineering designs and application be able to compete with other options when disaster and climate risk objectives are being considered. In addition, general competency amongst practitioners is also needed. This requires an important capacity development effort at all levels of decision-making, both at the individual and institutional levels. Regardless of these needs, the use of natural solutions via eco-engineering is a viable option to explore given the global imperative to reduce risk and the unprecedented demand for solutions that improve resilience at global, national, and local scales.

References

[1] UNESCAP, Overview of natural disasters and their impacts in Asia and the Pacific, 1970–2014. ESCAP Technical Paper – Information and Communications Technology and Disaster Risk Reduction Division, 2015.

[2] S. Hallegatte, C. Green, R.J. Nicholls, J. Corfee-Morlot, Future flood losses in major coastal cities, Nat. Clim. Change 3 (2013) 802–806.

[3] UNISDR, Global assessment report on disaster risk reduction revealing risk redefining development. United Nations Office for Disaster Risk Reduction. 〈http://www.preventionweb.net/english/hyogo/gar/2011/en/home/executive.html〉 (Accessed 2 February 2017).

[4] W. Kron, Coasts: the high-risk areas of the world, Nat. Hazards 66 (3) (2013) 1363–1382.

[5] J.D. Woodruff, J.L. Irish, S.J. Camargo, Coastal flooding by tropical cyclones and sea-level rise, Nature 504 (2013) 44–52.

[6] B.G. Reguero, I.J. Losada, P. Diaz-Simal, F.J. Mendez, M.W. Beck, Effects of climate change on exposure to coastal flooding in Latin America and the Caribbean, PLoS One 10 (7) (2015), 〈http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0133409〉 (Accessed 15 March 2017).

[7] UNISDR, Making development sustainable: the future of disaster risk management, global assessment report on disaster risk reduction. United Nations Office for Disaster Risk Reduction, 2015.

[8] P. Peduzzi, B. Chatenoux, D. Dao, A. De Bono, C. Herold, J. Kossin, F. Mouton, O. Nordbeck, Global trends in tropical cyclone risk, Nat. Clim. Chang. 2 (2010) 289–294.

[9] IPCC, 2014: Annex II: Glossary [K.J. Mach, S. Planton, C. von Stechow (Eds.)]. In: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri, L.A. Meyer (Eds.)]. IPCC, Geneva, Switzerland, pp. 117–130.

[10] E. Cohen-Schacham, G. Walters, C. Janzen, S. Maginnis, In: IUCN (Ed.), Naure-based Solutions to Address Global Societal Challenges. IUCN, Switzerland. 2016.

[11] C. Nesshover, T. Assmuth, K.N. Irvine, G.M. Rusch, K.A. Waylen, B. Delbaere, D. Haase, L. Jones-Walters, H. Keune, E. Kovacs, K. Krauze, M. Kulvik, F. Rey, J. van Dijk, O.I. Vistad, M.E. Wilkinson, H. Wittmer, The science, policy and practice of nature-based solutions: an interdisciplinary perspective, Sci. Total Environ. 579 (2017) 1215–1227.

[12] UN, Paris Agreement. 〈http://unfccc.int/files/essential_background/convention/

application/pdf/english_paris_agreement⟩ (Accessed 15 March 2017).

[13] I. Kelman, Climate change and the Sendai framework for disaster risk reduction, Int. J. Disaster Risk Sci. 6 (2) (2015) 117–127.

[14] International Council for Science, International Social Science Council. Review of Targets for the Sustainable Development Goals: The Science Perspective. ⟨http://www.icsu.org/publications/reports-and-reviews/review-of-targets-for-the-sustainable-development-goals-the-science-perspective-2015/SDG-Report.pdf⟩ (Accessed 4 January 2017).

[15] F.G. Renaud, K. Sudmeier-Rieux, M. Estrella, The Role of Ecosystems in Disaster Risk Reduction, United Nations University Press, Tokyo, 2013.

[16] F.G. Renaud, K. Sudmeier-Rieux, M. Estrella, U. Nehren, Ecosystem-Based Disaster Risk Reduction and Adaption in Practice, Springer Publishing Company, New York, 2016.

[17] Organization for Economic Cooperation and Development, Infrastructure to 2030: Telecom, Land Transport, Water and Electricity. ⟨http://www.oecd.org/futures/infrastructureto2030/infrastructureto2030telecomlandtransportwaterandelectricity.htm⟩ (Accessed 4 February 2017).

[18] Association Society of Civil Engineers, Report Card for America’s Infrastructure. ⟨http://www.infrastructurereportcard.org/⟩ (Accessed 3 March 2017).

[19] H.P. Jones, D.G. Hole, E.S. Zavaleta, Harnessing nature to help people adapt to climate change, Nat. Clim. Change 2 (2012) 504–509.

[20] M. Spalding, M. Kainuma, L. Collins, World atlas of mangroves. Earthscan, London UNISDR, Global assessment report on disaster risk reduction revealing risk, redefining development, United Nations, New York, 2010.

[21] K.K. Arkema, G.M. Verutes, S.A. Wood, C. Clarke-Samuels, S. Rosado, M. Canto, A. Rosenthal, M. Ruckelshaus, G. Guannel, J. Toft, J. Faries, J.M. Silver, R. Griffin, A.D. Guerry, Embedding ecosystem services in coastal planning leads to better outcomes for people and nature, Proc. Natl. Acad. Sci. (2015) 201406483.

[22] World Bank, Managing Coasts with Natural Solutions: Guidelines for Measuring and Valuing Coastal Protection Services of Mangroves and Coral Reefs. MW Beck and G-M Lange, (Eds). Wealth Accounting and the Valuation of Ecosystem Services Partnership (WAVES). World Bank, Washington, DC., 2016.

[23] F. Ferrario, M.B. Beck, C. Storlazzi, F. Micheli, C. Sheppard, L. Airoldi, The effectiveness of coral reefs for coastal hazard risk reduction, Nat. Commun. 5 (3794) (2014) 1–9.

[24] C. Sheppard, C. Crain, M.W. Beck, The protective role of coastal marshes: a systematic review and meta-analysis, PLoS One 6 (11) (2011) 272–283.

[25] I. Moller, M. Kudella, F. Rupprecht, T. Spencer, M. Paul, B.K. van Wesenbeeck, G. Wolters, K. Jenson, T.J. Bouma, M. Miranda-Lange, S. Schimmels, Wave attenuation over coastal salt marshes under storm surge conditions, Nat. Geosci. Lett. 7 (2014) 727–731.

[26] M.W. Beck, R.D. Brumbaugh, L. Airoldi, A. Carranza, L.D. Coen, C. Crawford, O. Defeo, G.J. Edgar, B. Hancock, M.C. Kay, H.S. Lenihan, M.W. Luckenbach, C.L. Toropova, G. Zhang, X. Guo, Oyster reefs at risk and recommendations for conservation, restoration, and management, Bioscience 61 (2011) 107–116.

[27] B.W. Borsje, B.K. van Wesenbeeck, F. Dekker, P. Paalvast, T.J. Bouma, M.M. van Katwijk, M.B. de Vries, How ecological engineering can serve in coastal protection, Ecol. Eng. 37 (2011) 113–122.

[28] CCRIF, Annual Report 2010–2011. ⟨http://www.ccrif.org/sites/default/files/publications/CCRIFAnnualReport2010_2011.pdf⟩(Accessed 4 May 2017).

[29] S. Temmerman, P. Meire, P.J. Bouma, P.M. Herman, T. Ysebaert, H.T. de Vriend, Ecosystem-based coastal defense in the face of global change, Nature 5 (7478) (2013) 79–83 (504).

[30] S. Narayan, M.W. Beck, P. Wilson, C.J. Thomas, A. Guerrero, C.C. Shepard, B.G. Reguero, G. Franco, J.C. Ingram, D. Trespalacios, The value of coastal wetlands for flood damage reduction in the northeastern USA, Sci. Rep. (2017) 7, http://dx.doi.org/10.1038/s41598-017-09269-z.

[31] J.F. Warner, A. van Buuren, J. Edelenbos, Making Space for the River: Governance Experiences With Multifunctional River Flood Management in the US and Europe, IWA Publishing, London, 2013.

[32] Millennium Ecosystem Assessment, Ecosystems and Human Well-being: Synthesis, Island Press, Washington, DC, 2005⟨http://www.millenniumassessment.org/documents/document.356.aspx.pdf⟩ (Accessed 25 May 2017).

[33] Convention on Biological Diversity, Connecting Biodiversity and Climate Change Mitigation and Adaptation: Report of the 2nd Ad Hoc Technical Expert Group on Biodiversity and Climate Change, Technical Series No. 41. Secretariat of the Convention on Biological Diversity, Montreal, 2009.

[34] E.F. Granek, S. Polasky, C.V. Kappel, D.J. Reed, D.M. Stoms, E.W. Koch, C.J. Kennedy, L.A. Cramer, S.D. Hacker, E.B. Barbier, S. Aswani, M. Ruckelshaus, G.M.E. Perillo, B.R. Silliman, N. Muthiga, D. Bael, E. Wolanski, Ecosystem services as a common language for coastal ecosystem-based management, Conserv. Biol. 24 (2010) 207–216.

[35] F.G. Renaud, U. Nehren, K. Sudmeier-Rieux, M. Estrella, Development and opportunities for ecosystem-based disaster risk reduction and climate change adaptation, in: F. Renaud, K. Sudmeier-Rieux, M. Estrella, U. Nehren (Eds.), Ecosystem-based Disaster Risk Reduction and Adaptation: Liking Science, Policy and Practice, Springer International Publishing, New York, 2016.

[36] M. Estrella, N. Saalismaa, Ecosystem-based disaster risk reduction (Eco-DRR): an overview, in: F. Renaud, K. Sudmeier-Rieux, M. Estrella (Eds.), The Role of Ecosystems in Disaster Risk Reduction. United Nations University Press, New York, 2013.

[37] E.B. Barbier, Valuing ecosystem services as productive inputs, Econ. Policy 22 (2007) 177–229.

[38] R. Costanza, R. d’Arge, R. de Groot, S. Farber, M. Grasso, B. Hannon, K. Limburg, S. Naeem, R.V. O’Neill, J. Paruelo, R.G. Raskin, P. Sutton, M. van den Belt, The value of the world's ecosystem services and natural capital, Nature 387 (1997) 253–260.

[39] M.L. Martínez, A. Intralawan, G. Vázquez, O. Pérez-Maqueo, P. Sutton, R. Landgrave, The coasts of our world: ecological, economic and social importance, Ecol. Econ. 63 (2007) 254–272.

[40] S. Narayan, M.W. Beck, B.G. Reguero, I.J. Losada, B.K. van Wesenbeeck, The effectiveness, costs and coastal protection benefits of natural and nature-based defenses, PLoS One 11 (5) (2016), ⟨http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0154735⟩ (Accessed 2 February 2017).

[41] M.L. Pinsky, G. Guannel, K.K. Arkema, Quantifying wave attenuation to inform coastal habitat conservation, Ecosphere 4 (2013) 1–16.

[42] S. Temmerman, M.L. Kirwan, Building land with a rising sea, Science 80 (349) (2015) 588–589.

[43] A.S. Goudie, Encyclopedia of Geomorphology 1 Routledge, New York, 2004.

[44] A.A. Akanbi, Y. Lian, T.W. Soong, An Analysis on Managed Flood Storage Options for Selected Levees along the Lower Illinois River for Enhancing Flood Protection. Report No. 4: Flood Storage Reservoirs and Flooding on the Lower Illinois River. Champaign, Illinois, 1999.

[45] H.J. de Vriend, M. van Koningsveld, S.G.J. Aarninkhof, M.B. de Vries, M.J. Baptist, Sustainable hydraulic engineering through building with nature, J. Hydro-Environ. Res. 9 (2015) 159–171.

[46] R.E. van den Hoek, M. Brugnach, A.Y. Hoekstra, Shifting to ecological engineering in flood management: introducing new uncertainties in the development of a building with nature pilot project, Environ. Sci. Policy 22 (2012) 85–99.

[47] A.W. Whelchel, M.W. Beck, Decision tool and approaches to advance ecosystem-based disaster risk reduction and climate change adaptation in the twenty-first century, in: F. Renaud, K. Sudmeier-Rieux, M. Estrella, U. Nehren (Eds.), Ecosystem-based Disaster Risk Reduction and Adaptation: Liking Science, Policy and Practice, Springer International Publishing, New York, 2016.

[48] C. Zevenbergen, A. Cashman, N. Evelpidou, E. Pasche, S. Garvin, R. Ashley, Urban Flood Management, CRC Press, Taylor & Francis Group, 2011.

[49] T.H.F. Wong, Australian runoff quality: A guide to water sensitive urban design. Engineers Australia/National Committee on Water Engineering. ISBN 9780858258525, 2006.

[50] R. James, F. Otto, H. Parker, E. Boyd, R. Cornforth, D. Mitchell, M. Allen, Characterizing loss and damage from climate change, Nat. Clim. Chang. 4 (2014) 938–939.

[51] R. Mechler, T. Schinko, Identifying the policy space for climate loss and damage, Science 80 (354) (2016) 290–292.

[52] NOAA, What will Adaptation Cost? An Economic Framework For Coastal Community infrastructure, 2013.

[53] W.R. Travis, B. Bates, What is climate risk management? Clim. Risk Manag. 1 (2014) 1–4.

[54] UNFCCC, Decision 2/CP.19, United Nations Framework Convention on Climate Change, ⟨http://unfccc.int/documentation/documents/advanced_search/items/6911.php?Priref=600007788⟩ (Accessed 5 January 2017).

[55] B.G. Reguero, M.W. Beck, D.N. Bresch, J. Calil, I. Meliane, Comparing the cost effectiveness of Nature-Based and Coastal adaptation: a case study from the Gulf Coast of the United States. PLoS One, 2018.

[56] IPCC, Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation, A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK, and New York, NY, USA, 2012.

[57] M.W. Beck, G.M. Lange, Managing Coasts with Natural Solutions: Guidelines for Measuring and Valuing the Coastal Protection Services of Mangroves and Coral Reefs. Washington, D.C, 2016.

[58] B.G. Reguero, D.N. Bresch, M.W. Beck, J. Calil, I. Meliane, Coastal Risks, Nature-based defenses and the Economics of Adaptation: an application the Gulf of Mexico, USA. Coast. Eng.; No 34 Proceedings of the 34th Conference Coast. Eng. Seoul, Korea, 2014.

[59] B.G. Reguero, M.W. Beck, V.N. Agostini, P. Kramer, B. Hancock, Coral reefs for coastal protection: a new methodological approach and engineering case study in Grenada, J. Environ. Manag. (2018).

[60] K. Kroeker, B.G. Reguero, P. Rittelmeyer, M.W. Beck, Ecosystem service and coastal engineering tools for coastal protection and risk reduction, in: M.W. Beck, G.M. Lange (Eds.), Guidelines for Coastal and Marine Ecosystem Accounting: Incorporating the Protective Service Values of Coral Reefs and Mangroves in National Wealth Accounts, World Bank, Washington, DC, 2016.

[61] W.J. Mitsch, Ecological Engineering and Ecosystem Restoration, John Wiley & Sons, N.Y, 2004.

[62] G. Gaunnel, K. Arkema, K. Ruggiero, P. Verutes, The power of three: coral reefs, seagrasses and mangroves protect coastal regions and increase their resilience, PLoS One 11 (7) (2016).

[63] A. McIvor, T. Spencer, I. Moller, M. Spalding, Coastal defense services provided by mangroves, in: M.W. Beck, G.M. Lange (Eds.), Managing Coasts with Natural Solutions: Guidelines for Measuring and Valuing the Coastal Protection Services of Mangroves and Coral Reefs, World Bank, Washington, DC, 2016.

[64] D.E. Marois, W.J. Mitsch, Coastal protection from tsunamis and cyclones provided by mangrove wetlands - a review, Int. J. Biodivers. Sci., Ecosyst. Serv. Manag. 11 (2015) 171–183.

[65] S.L. Yang, B.W. Shi, T.J. Bouma, Estuaries Coasts 35 (2012) 169.

[66] J.M. van Loon-Steensma, Z. Hu, P.A. Slim, Modelled impact of vegetation heterogeneity and salt-marsh zonation on wave damping, J. Coast. Res. 32 (2) (2016) 241–252.

[67] A.W. Whelchel, A. Ryan, H. Drinkuth, S. Pellegrino, Workshop Summary of Findings Report on Non-Structural and Natural Infrastructure Alternatives:

Current Opportunitiesand Constraints for Connecticut's Coast. The Nature Conservancy, Coastal Resilience Program. Publication 15-1, New Haven, Connecticut. (Unpublished results).
[68] T.J. Bouma, J. van Belzen, T. Balke, Z. Zhu, L. Airoldi, A.J. Blight, A.J. Davies, C. Galvan, S.J. Hawkins, S.P.G. Hoggart, J.L. Lara, I.J. Losada, M. Maza, B. Ondiviela, M.W. Skov, E.M. Strain, R.C. Thompson, S. Yang, B. Zanuttigh, L. Zhang, P.M.J. Herman, Identifying knowledge gaps hampering application of intertidal habitats in coastal protection: opportunities and steps to take, Coast. Eng. 87 (2014) 147–157.
[69] E. McCreless, M.W. Beck, Rethinking our global coastal investment portfolio, J. Ocean Coast. Econ. 3 (2) (2016).
[70] Global Water Partnership, GWP in Action Annual Report. ISSN 1650–9137.
[71] B.K. van Wesenbeeck, M. van der Meulen, C. Pesch, H. de Vriend, M.B. de Vries, Nature-based approaches in coastal flood risk management: physical restrictions and engineering challenges, in: F. Renaud, K. Sudmeier-Rieux, M. Estrella, U. Nehren (Eds.), Ecosystem-Based Disaster Risk Reduction and Adaptation: Linking Science, Policy and Practice, Springer International Publishing, New York, 2016.
[72] P. Sayers, L. Yuanyuan, G. Galloway, E. Penning-Rowsell, S. Fuxin, W. Kang, C. Yiwei, T. Le Quesne, Flood Risk Management: A Strategic Approach, 2013.
[73] EEA, Flood risks and environmental vulnerability. Exploring the synergies between floodplain restoration, water policies and thematic policies. European Environment Agency EEA Report No 1. ISSN 1977–8449, 2016.
[74] C. Thia-Eng, Essential elements of integrated coastal zone management, Ocean Coast. Manag. 21 (1993) 81–108.
[75] World Bank. Implementing nature-based flood protection: Principles and implementation guidance. Washington, D.C, 2017.
[76] B.K. van Wesenbeeck, T. Balke, P. van Eijk, F. Tonneijck, H. Siry, M. Rudianto, J. Winterwerp, Aquaculture induced erosion of tropical coastlines throws coastal communities back into poverty, Ocean Coast. Manag. 116 (2015) 466–469.
[77] E. Chaussard, F. Amelung, H. Abidin, S.H. Hong, Sinking cities in Indonesia: alos PALSAR detects rapid subsidence due to groundwater and gas extraction, Remote Sens. Environ. 128 (2013) 150–161.
[78] J.C. Winterwerp, W.G. Borst, M.B. de Vries, Pilot study on the erosion and rehabilitation of a mangrove mud coast, J. Coast. Res. 21 (2005) 223–230.
[79] J.C. Winterwerp, P.L.A. Erftemeijer, N. Suryadiputra, P. van Eijk, L. Zhang, Defining eco-morphodynamic requirements for rehabilitating eroding mangrove-mud coasts, Wetlands 33 (2013) 515–526.
[80] F. Tonneijck, H. Winterwerp, B.K. van Wesenbeeck, R. Bosma, D. Debrot, Y.R. Noor, T. Wilms, Design and engineering plan. Towards a district level masterplan. 〈https://www.ecoshape.org/uploads/sites/2/2016/07/Ecoshape-2015-Result-1-5-Design-Engineering-Plan-v7-0-LAYOUT-Nature-style_2.pdf〉 (Accessed 6 March 2017), 2015.
[81] Floodplains by Design, New Levee on Puyallup River in Orting Successful After Major Flood. 〈http://www.floodplainsbydesign.org/news/new-levee-on-puyallup-river-in-orting-successful-after-major-flood/〉 (Accessed 3 March 2017).
[82] The Nature Conservancy, Great River News. Mother Nature takes a hand in floodplain restoration 〈https://www.nature.org/ourinitiatives/habitats/riverslakes/howwework/great-rivers-news-mother-nature-takes-a-hand-in-floodplain-restoration-on.xml〉 (Accessed 4 January 2017), 2009.
[83] S. van Vuren, A. Paarlberg, H. Havinga, The aftermath of "Room for the River" and restoration works: coping with excessive maintenance dredging, J. Hydro-Environ. Res. 9 (2015) 172–186.
[84] D. Benson, I. Lorenzoni, Climate change adaptation flood risks and policy coherence in integrated water resources management in England, Reg. Environ. Change (2016).
[85] A.K. Gain, J.J. Rouillard, D. Benson, Can Integrated Water Resources Management increase adaptive capacity to climate change adaptation? A critical review, J. Water Resour. Prot. 5 (2013) 11–20.
[86] E. Kalbus, T. Kalbacher, O. Kolditz, E. Kruger, J. Seegert, G. Rostel, G. Teutsch, Integrated Water Resource Management under different hydrological, climatic and socio-economic conditions, Environ. Earth Sci. 65 (5) (2012) 1363–1366.
[87] P.R. Crowe, K. Foley, M.J. Collier, Operationalizing urban resilience through a framework for adaptive co-management and design: five experiments in urban planning practice and policy, Environ. Sci. Policy (2016) 1766.
[88] H. Erixon, S. Borgstrom, E. Andersson, Challenges dichotomies - exploring resilience as an integrated and operative conceptual framework for large scale urban green structures, Plan Theory Pract. 14 (2013) 349–372.
[89] C. Wilkinson, Urban resilience: what does it mean in planning practice? Plan Theory Pract. 13 (2012) 319–324.
[90] S. Connop, P. Vandergert, B. Eisenberg, M.J. Collier, C. Nash, J. Clough, D. Newport, Renaturing cities using a regionally-focused biodiversity-led multifunctional benefit approach to urban green infrastructure, Environ. Sci. Policy (2016).
[91] S.T.A. Pickett, B. Mcgrath, M.L. Cadenasso, A.J. Felson, Ecological resilience and resilient cities, Build. Res. Inf. 42 (2014) 143–157.
[92] J. Ahern, From fail-safe to safe-to-fail: sustainability and resilience in the new urban world, Landsc. Urban Plan. 100 (2014) 341–343.
[93] A. Sharifi, Y. Yamagata, Urban resilience assessment: multiple dimensions, criteria, and indicators, in: Y. Yamagata, H. Maruyama (Eds.), Urban Resilience, Advanced Sciences and Technologies for Security Applications, Springer International Publishing, Switzerland, 2016.
[94] A.W. Whelchel, Plan for the future: advancing eco-engineering through science, conceptual design, and community resilience building, in: M. Johnson, A. Bayley (Eds.), Coastal Change: Ocean Conservation and Resilient Communities, Springer Publishing Company, New York, 2016.
[95] City of Bridgeport, Community Resilience Building Workshops Summary of Findings. The Nature Conservancy and Clean Air Cool Planet. Bridgeport, Connecticut. 〈https://docs.wixstatic.com/ugd/29a871_139c1683cb4a4f13996df61f5f1ae132.pdf〉, Unpublished results. (Accessed 5 February 2017).
[96] A. Ryan, A.W. Whelchel, A Salt Marsh Advancement Zone Assessment of Bridgeport, Connecticut. The Nature Conservancy, Coastal Resilience Program. Publication Series #1-G, New Haven, Connecticut (Unpublished results). 〈https://www.conservationgateway.org/ConservationPractices/Marine/crr/library/Documents/Bridgeport%20Salt%20Marsh%20Advancement%20Zone%20Assessment%20August%202014_Small.pdf〉 (Accessed 5 January 2017), 2014.
[97] A.J. Felson, M.A. Bradford, T.M. Terway, Promoting earth stewardship through urban design experiments, Front. Ecol. Environ. 11 (7) (2013) 362–367.
[98] D. Goldsman, M. Lefevre, A.W. Whelchel, Eco-Urban Assessment: Bridgeport, Connecticut. The Nature Conservancy, Connecticut Urban Program. Publication 01, New Haven, Connecticut. (Unpublished results).
[99] A.W. Whelchel, E. Livshits, M. Fulda, M. Sloan, C. Rappa, K. Deneault, The Southern Connecticut Regional Framework for Coastal Resilience Final Report. South Central Regional Council of Governments, The Nature Conservancy, Connecticut Metropolitan Council of Governments. North Haven, Connecticut, 2017.
[100] A.W. Whelchel, E. Livshits, M. Fulda, The Southern Connecticut Regional Framework for Coastal Resilience. Community Resilience Building Design Portfolio: Edges and Shorelines. South Central Regional Council of Governments, The Nature Conservancy, Connecticut Metropolitan Council of Governments. North Haven, Connecticut, 2017.
[101] D.A. Barone, K.K. McKenna, S.C. Farrell, Hurricane sandy: beach-dune performance at new Jersey beach profile network sites, Shore Beach 82 (4) (2014) 13–23.
[102] A. Rella, J. Miller, E. Hauser, An overview of the living shorelines initiative in New York and New Jersey, in: D.M. Bilkovic, M.M. Mitchell, M.K. La Peyre, J.D. Toft (Eds.), Living Shorelines: The Science and Management of Nature-Based Coastal Protection. CRC Press, New York, 2017.
[103] Louisiana Coastal Protection and Restoration Final Technical Report. U.S. Army Corps of Engineers, New Orleans District, Mississippi Valley Division. 〈http://biotech.law.lsu.edu/la/coast/lacpr/FinalReport/03%20LACPR%20Final%20Technical%20Report.pdf〉 (Accessed 1 May 2017).
[104] Louisiana's Comprehensive Master Plan for a Sustainable Coast, Coastal Protection and Restoration Authority of Louisiana. 〈http://coastal.la.gov/wp-content/uploads/2017/04/2017-Coastal-Master-Plan_Web-Single-Page_FinalCompressed-05162017.pdf〉 (Accessed 5 May 2017).
[105] K.F. Gotham, Coastal restoration as contested terrain: climate change and the political economy of risk reduction in Louisiana, Sociol. Forum 31 (51) (2016) 787–806.
[106] M. Vis, F. Klijn, K.M. De Bruijn, M. Van Buuren, Resilience strategies for flood risk management in the Netherlands, Int. J. River Basin Manag. 1 (2003) 33–40.
[107] H.T.C. van Stokkom, A.J.M. Smits, R.S.E.W. Leuven, Flood defense in the Netherlands, J. Water Int. 20 (1) (2005) 76–87.
[108] N.E.M. Asselman, F. Klijn, Making room for rivers: quantification of benefits from a flood risk perspective. E3S Web of Conferences 7, FLOODrisk2016, Proceedings of the 3rd European Conference on Flood Risk Management. 〈https://www.e3s-conferences.org/articles/e3sconf/pdf/2016/02/e3sconf_flood2016_12001.pdf〉. (Accessed 4 January 2017), 2016.
[109] Dockside Green, 〈http://www.docksidegreen.com/〉 (Accessed 5 January 2017).
[110] City of Tucson, Green Streets Active Practice Guidelines. 〈https://watershedmg.org/sites/default/files/documents/city-of-tucson-green-streets-active-practice-guidelines.pdf〉, Unpublished results, (Accessed 5 March 2017).