Anthropocene 44 (2023) 100417

Contents lists available at ScienceDirect

Anthropocene

journal homepage: www.elsevier.com/locate/ancene

Nature-based solutions for leveed river corridors

Matthew L. Chambers [a,j,*], Charles B. van Rees [b,j], Brian P. Bledsoe [a,j], David Crane [c], Susana Ferreira [d,j], Damon M. Hall [e], Rod W. Lammers [g], Craig E. Landry [d,j], Donald R. Nelson [h,j], Matt Shudtz [f,j], Burton C. Suedel [i]

[a] College of Engineering, University of Georgia, Athens, GA, USA
[b] Odum School of Ecology and River Basin Center, University of Georgia, Athens, GA, USA
[c] US Army Corps of Engineers Omaha District, Planning Section, Omaha, NE, USA
[d] Dept. of Agricultural and Applied Economics, University of Georgia, Athens, GA, USA
[e] Dept. of Biomedical, Biological & Chemical Engineering, University of Missouri, Columbia, MO, USA
[f] Carl Vinson Institute of Government, University of Georgia, Athens, GA, USA
[g] School of Engineering and Technology and Institute for Great Lakes Research, Central Michigan University, Mt. Pleasant, MI, USA
[h] Dept. of Anthropology, University of Georgia, Athens, GA, USA
[i] Environmental Laboratory, US Army Engineer Research and Development Center, US Army Corps of Engineers, Vicksburg, MS, USA
[j] Institute for Resilient Infrastructure Systems, University of Georgia, Athens, GA, USA

A R T I C L E I N F O

Keywords:
Nature-based solutions
Sustainable infrastructure systems
Flood risk management
Levee setbacks

A B S T R A C T

The conceptual framework for nature-based solutions (NbS) is well developed, however realizing the potential of NbS at scale and in widespread professional practice in infrastructure systems depends on overcoming operational challenges rooted in the historical policies and engineering practices of the action agencies capable of implementation. In this article, we explore levee setbacks as a NbS for improving the sustainability of leveed river corridors within the context of the United States (US) and its primary action agency of flood risk management, the Army Corps of Engineers (USACE). By identifying the social and environmental consequences of historical levee management and linking these consequences with historical policies and engineering practices, we highlight knowledge gaps, challenges and opportunities for progress with NbS. We also briefly discuss USACE's decision-making processes for infrastructure investments and the valuation of ecosystem services as it pertains to operationalizing setbacks in practice. We then develop a case study of a recent setback on the Missouri River to showcase how USACE overcame implementation challenges. Lessons from past levee corridor management in the US, and USACE's current corrective actions, may help foster understanding of how to overcome operational challenges in the implementation of setbacks in other social and political contexts.

1. Introduction

In 2019, following a historically wet winter in the Upper Midwestern United States (US) and an unseasonal early spring blizzard, communities on the Missouri River experienced their third massive flood in as many decades. Flood heights reached those associated with a 0.2% annual probability of occurrence in some reaches – colloquially, it was equivalent to a "500-year flood" – and lasted nine months with breaches or overtopping at nearly every levee in a three-hundred-and-fifty kilometer reach between Omaha, Nebraska and Kansas City, Missouri (Kay, 2003; US Army Corps of Engineers, 2023; US Geological Survey, 2023). The scale of economic impacts remain uncertain as the aftereffects are on-going, but recovery expenditures have exceeded billions of dollars, and are likely to rise (Skevas et al., 2023). Coming on the heels of previous major floods in 2011 and 1993, the successive disasters have left a lasting impression on those who live along the river and have created a general sense of exhaustion as decision-makers seek alternative approaches to managing flood risks (National Oceanic and Atmospheric Administration, National Centers for Environmental Information, 2023; National Oceanic and Atmospheric Administration, National Weather Service, 2023; New York Times, 2019a,b; The Nature Conservancy, 2023).

We call attention to the 2019 flood because one group of levee managers responded to the disaster in an uncommon way. Instead of

* Corresponding author at: College of Engineering, University of Georgia, Athens, GA, USA.
E-mail address: matt.chambers@uga.edu (M.L. Chambers).

https://doi.org/10.1016/j.ancene.2023.100417
Received 14 August 2023; Accepted 18 October 2023
Available online 3 November 2023

repairing their levee to its pre-flood condition, they worked with the US Army Corps of Engineers (USACE) to relocate the levee away from the river bank. The levee, known as L536, is now "set back". Its widened floodplain provides additional room for floodwater conveyance that will improve the community's flood protection and much of the reconnected floodplain is now federally protected conservation land, which has created opportunities for rehabilitating a levee-stressed ecosystem (Krause et al., 2015; Smith et al., 2017; Klijn et al., 2018; The Nature Conservancy, 2021). Setting back a levee is an example of a nature-based solution (NbS) and, as we will argue, is a simple and intuitive approach for improving the sustainability of leveed river corridors (Opperman et al., 2009; Cohen-Shacham et al., 2016; Serra-Llobet et al., 2022a; van Rees et al., 2023).

1.1. Background

America's major river corridors have been dramatically transformed by national civil works programs. Congress authorized civil works to promote economic development in the early twentieth century and empowered USACE as its chief architect (Tarlock, 2012; Ehrenwerth et al., 2022). Since then, USACE has engineered thousands of kilometers of river corridors to create stable navigation channels and manage flood risks for millions of Americans (Arnold, 1988; Zellmer and Klein, 2007; Alexander et al., 2012).

Levees are one of the primary tools USACE used to engineer rivers (Arnold, 1988; Zellmer and Klein, 2007; Alexander et al., 2012). Levees are typically earthen embankments designed to contain, control, or divert the flow of water so as to reduce the risk of flooding (National Research Council, 2013). Levees shape the way people live and work in river corridors by creating opportunities for development on floodplains that would otherwise inundate frequently (Tarlock, 2012; Olson and Speidel, 2021). They also shape riverine landscapes and ecosystems by disrupting natural flood dynamics (Poff et al., 1997; Knox et al., 2022a, 2022b,c).

America's historical focus on economic development has driven the unsustainable management of many leveed river corridors. What were once considered "improvements" – such as land reclamation or controls on channel migration – are now recognized for their social and ecological trade-offs (IFMRC, 1994; Poff et al., 1997; Pinter, 2005; Opperman et al., 2009; Baeten, 2022). The consequences of which are evident from rising trends in annualized flood damages (though multifactorial; Tobin, 1995; Pielke and Downton, 2000; Pielke et al., 2002; Cartwright, 2005) to the rapid loss of freshwater biodiversity (Tockner and Stanford, 2002; Maxwell et al., 2016; Albert et al., 2021). Furthermore, historical policy influenced engineering practice, leading to levees that track too close to river banks for sustainable management – a practice underscoring most of the adverse consequences experienced today (IFMRC, 1994; Zellmer and Klein, 2007; Opperman et al., 2009; Krause et al., 2015; Behm, 2021).

A growing body of literature on the science and practice of NbS has developed in response to global environmental degradation and the risks posed by anthropogenic climate change. NbS are actions to protect, sustainably manage, and restore ecosystems in ways that address societal challenges effectively and adaptively, and can include solutions to infrastructure challenges (Cohen-Shacham et al., 2016; O'Hogain and McCarton, 2018). Levee setbacks – like at L536 – are NbSs for insufficient flood protection and are adaptive measures that improve community resilience by providing additional buffering against the uncertainties of climate exacerbated flooding (Klijn et al., 2018; Serra-Llobet et al., 2022a). The restoration of surface water connectivity within the expanded floodplain creates opportunities to rehabilitate levee-stressed ecosystems and underscores the multiple-benefits potential of setbacks as a solution for flood risk management (FRM) and unsustainable environmental management (Opperman et al., 2010; Dahl et al., 2017; Smith et al., 2017; US Army Corps of Engineers, 2018a; Serra-Llobet et al., 2022a).

1.2. Purpose and scope

Despite a strong conceptual framework and justification for NbS, multidisciplinary reviews of specific NbS to priority infrastructure challenges are needed to facilitate the widespread implementation called for by researchers and decision-makers (Opperman et al., 2009; Maes and Jacobs, 2017; Cohen-Shacham et al., 2016; Kabisch et al., 2016; Nesshover et al., 2017; Keesstra et al., 2018; Cohen-Shacham et al., 2019; Nelson et al., 2020; Seddon et al., 2020a, 2020b; Seddon et al., 2021). In this article, we review levee setbacks as an exemplar NbS for improving the sustainability of leveed river corridors. Our analysis is limited to river corridors of the US to make use of data-rich case studies, though lessons learned from past management practices, and current corrective actions, may help clarify how setbacks can be operationalized in other contexts.

Innovation within the administrative structures and decision-making processes of the action agencies responsible for levee corridor management is critical for advancing the widespread application of setbacks (IFMRC, 1994; Tarlock, 2012; Ehrenwerth et al., 2022; Windhoffer et al., 2022). Accordingly, we briefly summarize USACE's historical levee policies and decision-making practices to identify operational challenges and opportunities to advance the use of setbacks. Our objectives are as follows:

1) Identify the most salient consequences of historical levee management.
2) Link consequences with historical policies and engineering practices.
3) Discuss setbacks as a NbS for improving the sustainability of leveed river corridors.
4) Showcase how USACE overcame implementation barriers with a case study of the L536 setback.
5) Highlight knowledge gaps, challenges, and opportunities for operationalizing setbacks.

2. Levees: A transformative feature of America's river corridors

America's intensive reliance on levees for flood protection and economic growth has been dubbed a "levee love affair" (Tobin, 1995). There are an estimated 229,000 km of levees on American rivers; enough to wrap the Earth nine times (Knox et al., 2022a,b,c). These levees protect at least eleven million people and have supported the cultivation and development of ~30% of the floodplain area in the contiguous US (Knox et al., 2022a,b,c; US Army Corps of Engineers, 2018b). USACE has cataloged ~23,000 km of these levees and recognizes an additional ~24,000 km with unknown condition and non-federal or private ownership, which suggests only 10–20% of the estimated levees are accounted for (US Army Corps of Engineers, 2018b; American Society of Civil Engineers, 2021; US Army Corps of Engineers, 2023).

The massive number of levees, and USACE's limited knowledge of their location and condition, are the result of historical policies that favored local planning authorities while promoting levees as the *de facto* FRM solution for much of America's existence (Arnold, 1988; Zellmer and Klein, 2007; Tarlock, 2012). The extensive use of levees is not without consequences; here, we highlight salient examples and link them with conventional corridor management practices.

2.1. Hydraulic effects

USACE historically used levees to channelize rivers for navigation. Levee systems were designed to confine floods within an engineered floodway, thereby deepening flows and flushing out navigational obstacles (snags, gravel bars, etc.). USACE's legal authorities were restricted to navigational improvements for much of their existence with no legal purview in FRM (from roughly the country's founding to 1917). However, during much of this time, USACE argued that flushing out navigational obstacles would also incise river beds, thereby increasing channel conveyance capacity, and negating the need for other types of flood control infrastructure (e.g. upper basin dams). By the early twentieth century, there were ~2,900 km of continuous levees along the Lower Mississippi River, for example (Zellmer and Klein, 2007; National Research Council, 2011).

Today, levees are more recognized for FRM. They provide localized food protection by blocking floodwaters from inundating a floodplain (Fig. 1). The blocked off floodplain creates a bottleneck in overbanking flows resulting in backwater while deepening and accelerating floodwaters through the leveed reach. Backwater is displaced floodwater that would otherwise inundate the levee protected floodplain and is a potential hazard for nearby communities, both upstream and on the opposite bank. (Yen, 1995; Heine and Pinter, 2012; Jacobson et al., 2015).

Bottlenecks are a predictable consequence of leveeing. USACE often recommends floodway discharges and minimum conveyance widths to reduce their risk (Camillo, 2012; Krause et al., 2015). USACE also builds spillways and or secondary floodways that are in-part, "pressure relief valves" made necessary by lost floodplain conveyance due to leveeing (e.g. Morganza Floodway) (Camillo, 2012; Olson and Speidel, 2021). Historical policies have not been adequate in forcing USACE to correct known levee-caused bottlenecks and unfortunately, in some cases, have incentivized levee construction that conflicts with minimum conveyance widths (Arnold, 1988; Krause et al., 2015). The levee system of the Lower Missouri River is a well-known example, where continuous leveeing along several hundred kilometers of river has resulted in multiple bottlenecks and multiple reaches with bridges or levees that are more confining than the suggested conveyance width (Jacobson et al., 2015; Krause et al., 2015; Behm, 2021).

2.2. Social consequences

The Nation Flood Insurance Act (NFIA, 1968) is one of America's signature FRM laws. NFIA defines a levee-protected floodplain as outside the "official floodplain" if generally speaking, the levee protects against the 100-year flood (1% chance of occurrence in any given year). For such levees, there are few development restrictions, nor is flood insurance legally required, nor are property sellers or governmental agencies required to inform buyers that the property is within a levee-protected floodplain. As a consequence, people do not know that they live and work in levee-protected areas and are ill-informed of the risks (Montz and Tobin, 2008; Ludy and Kondolf, 2012; Michel-Kerjan et al., 2011; Knowles and Kunreuther, 2014). Furthermore, the technical

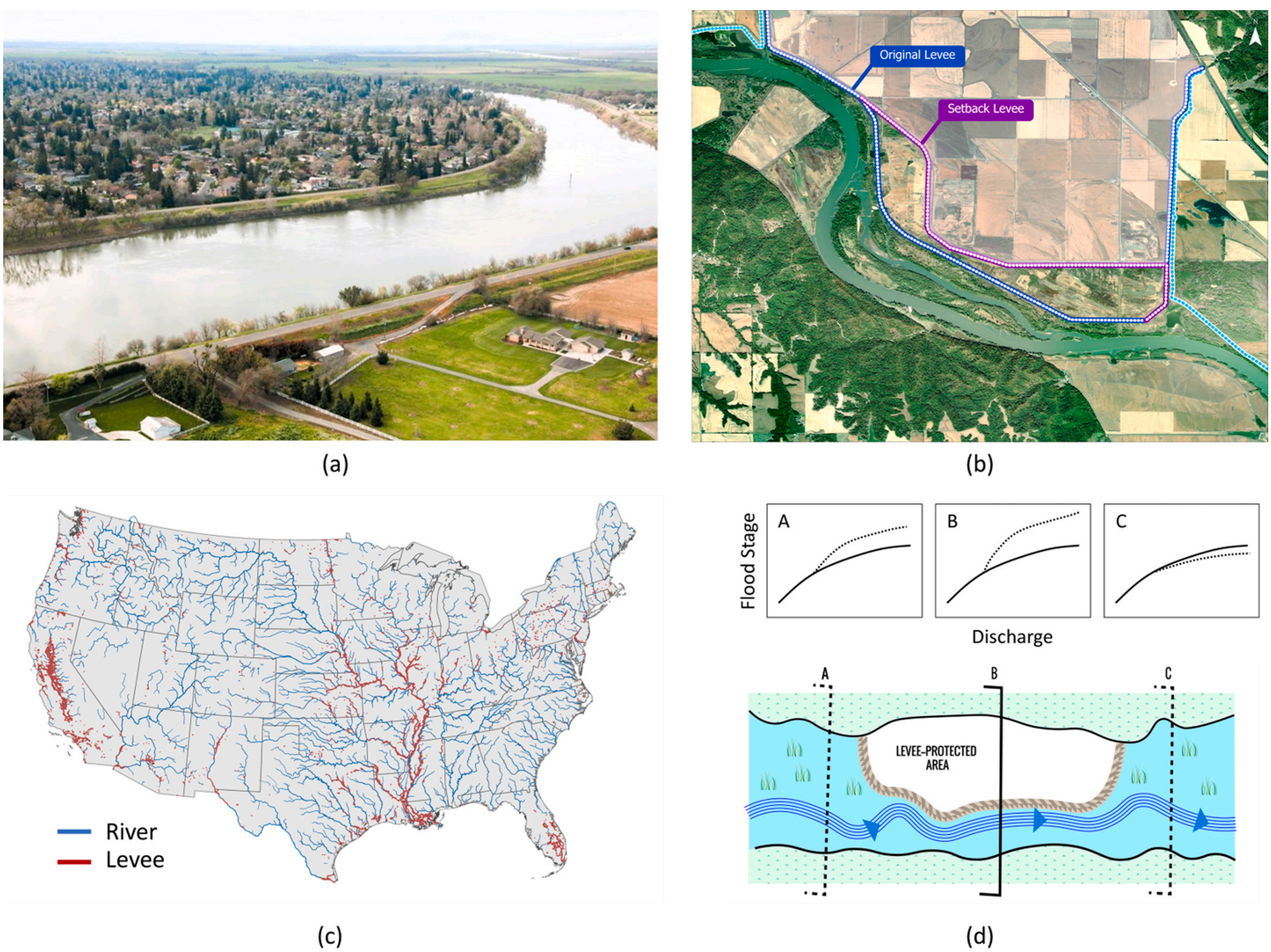

Fig. 1. (a) A levee protected community on the Sacramento River in California, USA. Note how the levees are built extremely close to the river on both banks. Photo sourced from US Army Corps of Engineers (2018b). (b) An example levee setback on the Missouri River, USA. (c) The number and continuity of levees in the National Levee Database; 80–90% of America's ~229,000 km of levees are not shown (Knox et al., 2022a,b,c; US Army Corps of Engineers, 2023). (d) The hydraulic effects of leveeing. Flood stage is increased upstream and adjacent to the levee (Heine and Pinter, 2012).

jargon used by federal agencies hampers risk communication. For example, the NFIA refers to risk from floods larger than the 100-year flood as residual risk. The word “residual” makes the risk sound insignificant, though the probability of a 101-year flood occurring within a 30-year home mortgage or a 50-year levee planning horizon is 26% and 40%, respectively (Michel-Kerjan and Kunreuther, 2011; Ludy and Kondolf, 2012; National Research Council, 2013; Serra-Llobet et al., 2022b).

The sense of security provided by levees supports development in levee-protected areas and drives escalating flood risk (Tarlock, 2012; Georgic and Klaiber, 2022). This social phenomenon is called the “levee effect”, and is partially responsible for rising annual flood damages (Tobin, 1995; Pielke and Downton, 2000; Pielke et al., 2002; Cartwright, 2005).

Some communities face a combination of escalating risk from the levee effect and escalating flood hazards from climate change, watershed land use, and floodwater displacement by nearby levees. Such communities must make a difficult management decision: Should they build levees taller or set them back in a managed retreat (Zhu et al., 2007; Zhu and Lund, 2009; Wang, 2021)? Setbacks with managed retreats involve “buying out” property owners such that their land can be used as floodwater storage to protect the broader community (The Nature Conservancy, 2021; Wang, 2021). Local authorities tend to raise levees rather than deal with the social difficulties of managed retreat, while not being accountable for the externalities created by displaced floodwaters (Pinter, 2005; Tarlock, 2012; Wang, 2021).

Furthermore, some communities in the Mississippi River watershed have become embroiled in what is effectively a levee construction arms race – called “The Levee Wars” (Wang, 2021; Vox and ProPublica, 2023). USACE has some oversight of levee construction and attempts to minimize stage rises associated with displaced floodwaters, but it is natural that levees will contribute some floodwater displacement and the cumulative effects can amount to substantial rises in stage over time (Pinter, 2005). For example, Heine and Pinter (2012) found significant rises, on the order of meters, along rivers in Iowa and Illinois following levee construction in the mid-twentieth and early twenty-first centuries.

2.3. Ecological consequences

Alluvial riverine ecosystems can be incredibly biodiverse and productive (Tockner and Stanford, 2002). Both attributes are supported by a river’s flow regime and connectivity across ecotones, which maintains habitat diversity through regular flood disturbance. A flow regime describes the nature of flooding in an ecosystem, such as its seasonality or the range of magnitudes (Bayley, 1995; Poff et al., 1997).

Independent of the ecological consequences of land use on the levee-protected floodplain, levees stress ecosystems by disrupting flow regimes and limiting connectivity across floodplain ecotones (Poff et al., 1997; Ward et al., 1999; Tockner et al., 2010). Levees separate the floodplain in two, creating a riverward and landward floodplain. The riverward floodplain is hydrologically connected, although bottlenecking is expected to alter flows locally and homogenize habitats by flushing out habitat features (shoals, large wood, etc.). The landward floodplain is partially disconnected from surface waters. Partial disconnection disrupts the dynamics of low magnitude floods and only allows inundation by large, infrequent, levee-failing floods. As such, we briefly summarize some of the more salient ecological consequences of lost connectivity (readers may refer to Wohl (2021) and Knox et al. (2022c) for more detailed reviews).

Hydrologic disconnection is accompanied by disconnection in the fluxes of matter (nutrients, sediment, wood; Junk et al., 1989; Tockner et al., 2000; Wohl et al., 2015; Wohl et al., 2019), thermal energy (Tockner et al., 2000; Tockner et al., 2010), and organisms across floodplain ecotones (Bayley, 1995; Ward et al., 1999). For example, levee construction may disrupt the flux of large wood from floodplain vegetation communities to the channel, as its supply is facilitated by floodwater scour (Wohl et al., 2019). Likewise, hydrologic disconnection prevents flood disturbances from continually reshaping the floodplain landform and renewing successional processes (Bayley, 1995; Poff et al., 1997; Opperman et al., 2010); which is critical for maintaining a "shifting habitat mosaic" and its dependent biodiversity (Ward, 1998; Stanford et al., 2005). Finally, partial disconnection reduces the productivity of riverine habitats (Junk et al., 1989; Thorp and Delong, 1994; Tockner et al., 2000; Tockner and Stanford, 2002). For example, floodplains provide shallow-water habitats that are critical for breeding and rearing numerous fish species (Ickes et al., 2005; Sommer et al., 2011; Stoffels et al., 2022). Increased abundance, growth rates, and biomass have been observed in rivers with connectivity by comparison to those with leveed or otherwise disconnected floodplains (Bayley, 1995; Sommer et al., 2001; Jeffres et al., 2008; Lyon et al., 2010).

2.4. Lost ecosystem services

Floodplain ecosystems provide a wide variety of supporting, regulating, provisioning, and cultural ecosystem services. As discussed, flood protection is among the most-recognized. Other examples include improvements to downstream water quality through sedimentation and nutrient storage (regulating); recreational opportunities (cultural); or habitat for recruitment in fisheries (provisioning) (Tockner and Stanford, 2002; Brauman et al., 2007; Opperman et al., 2017).

Levee construction, and the land use it supports, precludes the provision of many ecosystem services, resulting in an implicit tradeoff between the benefits of land use on the levee-protected floodplain and the foregone ecosystem services of an ecologically functional floodplain (Costanza et al., 1997; Strange et al., 1999). The loss of ecosystem services is a negative externality (de Groot et al., 2012; Farley, 2012). For example, the loss of water quality regulation is an externality for downstream communities with market (e.g., treatment cost of industrial influent), and non-market implications (e.g., lost aesthetic qualities).

2.5. Anthropogenic climate change

Many of the discussed consequences are likely to intensify with anthropogenic climate change. For example, the relative flood risk of communities upstream of a levee-caused bottleneck or the stress of aquatic organisms whose lifecyle depends on floodplain habitats. Interestingly, social effects are not entirely dependent on non-stationarity, but also uncertainty, as communities may react to the perceived threat of intensifying flood hazards regardless of whether they manifest. For example, predicted climate trends suggest flood hazards may increase or decrease depending on location in the Mississippi River watershed (Lewis et al., 2023), yet the levee wars could continue apace based on the perception of vulnerability.

Climate uncertainty will complicate estimates of levee reliability and management decisions concerning when to raise or setback levees (Zhu et al., 2007; Zhu and Lund, 2009). Uncertainties are compounded by the risk of levee failures at flood stages below levee overtopping (e.g. piping), which are often predicted with probabilistic functions that increase non-linearly with flood stage (US Army Corps of Engineers, 2020; National Research Council, 2013; Hui et al., 2016).

Furthermore, the complicated politics of FRM have historically erred toward local authorities (Arnold, 1988; Tarlock, 2012). There is to date, no national standard or requirement for levee design, construction, or operation and maintenance (US Army Corps of Engineers, 2018b; American Society of Civil Engineers, 2021). Without which, local authorities may choose to build or modify levees to address local concerns and ignore the interests of other stakeholders in the corridor. Differences in the values and risks faced by local authorities may make it difficult to enact widespread changes in corridor management policy in response to climate change.

3. How we got here: The socio-political context

In this section, we examine the historical context of how unsustainable levee practices became commonplace in the US. We focus in particular on the role of USACE as the primary action agency, national legislation that defines their legal authorities, and the decision-support tools USACE uses to plan infrastructure investments. Given USACE's authority over river corridor management, it is critical to understand their role if we are to operationalize setbacks in professional practice.

3.1. A brief history of levee policy

Much of America's historical river corridor management policy centers around challenges to navigation and flood control in the Mississippi, Ohio, and Sacramento River watersheds – three of the largest agricultural centers. It is also tangled-up in ideological debates concerning the role of the federal government in local FRM projects with major power shifts toward the federal government following catastrophic floods (Arnold, 1988; Zellmer and Klein, 2007).

In the early nineteenth century, Congress encouraged settlement of the Mississippi River watershed following acquisition of the southern and western sub-basins from the French Empire. Settlers often built levees atop poorly sited levees built by former French colonists or built levees close to river banks to expand the arable floodplain (Zellmer and Klein, 2007; Olson and Speidel, 2021). At this time, USACE had no authority in FRM and was primarily focused on enhancing navigation for national defense and commercial growth (Arnold, 1988).

The Swamp Land Acts of 1849 and 1850 marked the beginning of federal levee policy. These acts resulted in private ownership of river-adjacent wetlands and state support for levee construction on newly "reclaimed" land in the Lower Mississippi watershed. Private landowners were responsible for the design and construction of levees with no national design standards or regulations. Many organized into levee districts to pool the costs of construction and upkeep. Some levee districts still exist today and are part of the complicated patchwork of authorities in corridor management (Arnold, 1988; Pearcy, 2000; Zellmer and Klein, 2007).

In the 1850's, Congress funded studies to evaluate FRM strategies and ultimately developed a "levees-only" policy. Under this policy, USACE supported local authorities in creating continuously leveed river corridors. USACE also supported local authorities in repeatedly raising levees after major floods with precious few setbacks (Arnold, 1988; Zellmer and Klein, 2007).

It was not until the Flood Control Act (FCA) of 1917 that Congress granted explicit FRM authorities to USACE (Pearcy, 2000). USACE then embarked on a flurry of levee construction until a catastrophic flood on the Lower Mississippi River in 1927 demonstrated the limitations of a levees-only strategy (Zellmer and Klein, 2007). After passage of the 1928 and 1936 FCAs, USACE began designing secondary floodways to divert floodwaters where leveeing had dramatically reduced floodplain conveyance. Congress also authorized the construction of upper basin dams that have alleviated flood stresses on levees, such as those on the Missouri River (Arnold, 1988; Zellmer and Klein, 2007; Camillo, 2012). These actions demonstrate USACE's understanding that levee construction had so severely restricted floodplain conveyance that additional infrastructure was required to ensure flood protection. One alternative would have been broad scale setbacks, but setbacks were only applied sparingly at some poorly sited levees.

The FCA of 1936 defined USACE's civil works mission in terms of national economic development and further entrenched problematic levee management practices (Arnold, 1988; Tarlock, 2012). For example, USACE used channel training structures to stabilize the Missouri River navigation channel and accrete sediment at its margins to expand the arable floodplain. Levees were then built on top of the reclaimed land (Fig. 2) (National Research Council, 2011; Alexander et al., 2012). As such, the commercial prospects of enlarged floodplains often over-shadowed the risks associated with building levees in the high-energy areas of floodplains (Krause et al., 2015).

As many of the levees built following the FCA of 1936 predate modern water resources policies (e.g. National Flood Insurance Act), much of the science and professional judgment embodied in modern policy is not reflected in their designs or alignments (Zellmer and Klein, 2007; Tarlock, 2012; National Research Council, 2013; American Society of Civil Engineers, 2021). Furthermore, cost minimization objectives during construction led USACE to incorporate existing haphazardly aligned levees (often built by local municipalities or farmers) into planned levee system improvements. Cost minimization also led USACE to tie alignments into bridge embankments, which are typically located in naturally narrow reaches, instead of setting the embankments back to be in line with the levee at a more sensible conveyance width (IFMRC, 1994; Krause et al., 2015). Evidence of the risks posed by poorly aligned levees is clear from post-hoc analyses of catastrophes like the 1993

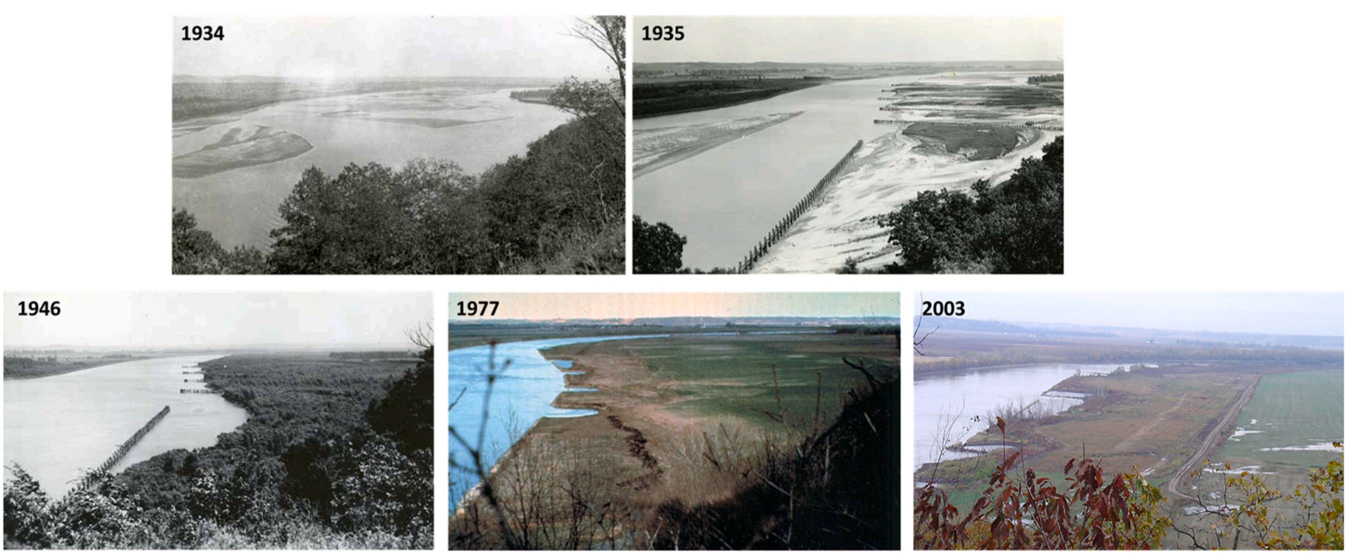

Fig. 2. A twentieth century example of USACE using bank stabilization structures to accrete arable land along the Missouri River near Indian Cave State Park downriver from Omaha, Nebraska (across the river from levee L536). By 2003, a levee was built on top of the reclaimed land in the high energy area of the floodplain (Photos courtesy of Dave Crane at the USACE Omaha District).

Mississippi River flood (IFMRC, 1994) and from levees with a history of repeated failures (Krause et al., 2015).

Also, during the mid-twentieth century, Congress passed a law creating the Levee Rehabilitation and Inspection Program, which is a critical source of funding for setbacks today. Commonly referred to as PL 84-99, it sets standards for levee design, operation, and maintenance that must be met for levee districts to access disaster relief funds. Continuing the theme of cost-effectiveness above other values, PL 84–99 reserves funds for repairs that bring damaged levees back to pre-flood conditions. That said, USACE must select the "least-cost, technically feasible" option when using PL 84–99 funds and setbacks are sometimes the least-costly option (Krause et al., 2015; US Army Corps of Engineers, 2012).

Repeated floods in the past few decades have reinforced the understanding that past levee corridor management practices have reduced the conveyance capacity of many river systems and have created new flood risks (IFMRC, 1994; Zellmer and Klein, 2007; Camillo, 2012; Tarlock, 2012). Secondary floodways and impoundments have not resolved the underlying issue of lost floodplain conveyance, and as a consequence, USACE and local authorities continuously raise levees. For example, a mainline levee on the Lower Mississippi River would have been ~2.4 m tall in 1882, ~6.7 m tall in 1927, and ~9.1 m today (Zellmer and Klein, 2007; Mississippi River Commission, 2017). USACE practitioners are well aware of setbacks as an option in scenarios where they continue to raise levees, but are often constrained by the administrative structures of their agency, as well as the local interests of levee districts, despite understanding the benefits of setbacks to the broader corridor. Furthermore, there is also a growing recognition that historical levee management practices are causing severe ecological damage (Krutilla, 1967; Poff et al., 1997; Knox et al., 2022a,b,c). The Endangered Species Act and Clean Water Act, in particular, are forcing USACE to incorporate environmental value propositions into levee design.

3.2. A brief history of USACE decision support tools

For much of USACE's tenure, cost-effectiveness was used as the basis for decision-making in infrastructure investments. Cost-effectiveness represents the idea that, with a clear, monolithic objective, the best option is the least costly alternative capable of accomplishing an objective. Cost-effectiveness has led to fairly simplistic decision-making (e.g., building levees on top of existing farmer levees despite poor alignments). Cost-effectiveness has been replaced by a limited form of Benefit-Cost Analysis (BCA), which prevailed through much of the twentieth century and into the modern era. BCA came into favor because it enables decision-making based on multiple dimensions that are subject to tradeoffs (e.g., construction costs, expected flood damages prevented, etc.). The FCA of 1936 offers some of the first text to understand how BCA was employed, notably, USACE "should improve… navigable waters… for flood control purposes if the benefits to whomsoever they accrue are in excess of the estimated costs." (Arnold, 1988; Tarlock, 2012; Ehrenwerth et al., 2022).

While scientific exploration and practical application of BCA has advanced rapidly in the past fifty years (OECD, 2018), USACE's administrative controls – defined in the Principles and Guidelines (P&G, 1983) – have largely limited USACE analytical efforts and hampered flexibility and innovation. P&G guidelines for economic analysis focuses primarily on National Economic Development (NED) benefits; which includes "net value of those goods and services that are marketed, and also of those that may not be marketed". USACE's approved methods for non-market valuation are limited and the lack of modern techniques for assessing ecosystem service benefits has arguably handicapped the selection of NbS in civil works planning (Tarlock, 2012; Ehrenwerth et al., 2022; Windhoffer et al., 2022). Other "principle accounts" recognized by the P&G include the non-monetary Environmental Quality (EQ) effects, Regional Economic Development (RED), and Other Social Effects (OSE). Rather frustratingly, planners must select one account and follow its stipulations, which limit multipurpose projects and the accounting of multiple benefits possible with NbS (e.g. ecological benefits in a FRM investment and vice-versa) (Ehrenwerth et al., 2022; Windhoffer et al., 2022).

3.3. Current levee policies

In 2007, Congress directed USACE to develop a new policy regarding alternative valuation in civil works planning. Congress mandated that NED benefits should no longer be the primary point of comparison between FRM infrastructure alternatives; rather "sustainable economic development" as defined in terms of avoiding unwise use of flood-prone areas and restoring the functions of natural systems (WRDA 2007 Section 2031).

The Obama administration (2008–2016) shaped Congress's instructions into the "Principles, Requirements, and Guidelines for Federal Investments in Water Resources," commonly known as the PR&G (2014). The PR&G defines ten key "requirements," five of which could lead to changes in valuation policy that support NbS: (1) Use a common framework for evaluation, based on an ecosystem services approach; (2) Identify, describe, and consider risks and uncertainty in the analyses, future conditions, and potential effects of each alternative, as well as use adaptive management to reduce uncertainty and maximize project goals; (3) Consider nonstructural approaches (e.g. natural floodplain storage or disincentivize development in flood prone areas); (4) Develop and fully consider an array of alternatives, including (a) those that require changes to statute or regulation, (b) nonstructural measures, (c) the plan preferred by the local sponsor, (d) the environmentally preferred alternative, and (e) mitigation measures associated with each alternative; and (5) Recommend a final action that is justified by the public benefits when compared to the costs.

Since creation of the PR&G (2014), Congress has used revisions of the Water Resources Development Act (WRDA) to drive changes in USACE's engineering practices. For example, the 2020 WRDA calls explicitly for a close cousin of NbS in civil works planning that could lead to levee setbacks, "projects that produce multiple benefits… including through the use of natural or nature-based features" (WRDA 2020 Section 124). Likewise, in 2022, USACE launched a major initiative to revise internal policies and procedures for agreement with the PR&G (87 Fed. Reg. 33756). Notably, these policy revisions attempt to address procedural and distributional equity concerns by developing new public engagement practices with the intention of better incorporating the values of marginalized communities in civil works projects (Graham, 2022). From a distributional standpoint, USACE is working to achieve the vision of the Justice40 Initiative, which sets a goal of ensuring that 40% of the benefits of certain climate-related federal investments are enjoyed by economically disadvantaged communities (Executive Order 8, 1400, 2021).

4. What's next? Looking forward with NbS

As national policy begins to shift toward investments in sustainable development, there is a growing opportunity to retrofit levees with NbS like setbacks. Below, we discuss the multiple benefits potential of setbacks, as well as the underlying physical, chemical, and or biological processes that support their provision. In doing so, we highlight the potential of setbacks as a practical and effective NbS for improving the sustainability of leveed river corridors.

4.1. Flood risk management

Setbacks offer a simple solution to many of the discussed social consequences of leveeing. Namely, buying out property and setting back levees removes people from harm's way. For those still protected by a setback levee, floodwater conveyance on the reconnected floodplain improves flood protection by reducing the likelihood of levee failure.

Most levees fail by overtopping, by under or through flow, or by some form of erosion (Schultz et al., 2010; US Army Corps of Engineers, 2020; US Army Corps of Engineers, 2018b). Setbacks can reduce the likelihood of each by changing flood hydraulics in two key ways. First, floodplain reconnection increases floodwater conveyance on the floodplain. This lowers flood stages and reduces the likelihood of overtopping, as well as failure modes driven by hydraulic loading, like flow under or through a levee. Second, expansion on the reconnected floodplain slows floodwaters and reduces the likelihood of erosive failures (National Research Council, 2013; Dahl et al., 2017; Smith et al., 2017).

Setbacks can greatly improve the climate resilience of a community by reducing its vulnerability. Climate vulnerability is reduced in much the same way that levee reliability is improved; additional floodwater conveyance buffers the levee against intensifying flood hazards. Buffering reduces a community's exposure, as well as its sensitivity to flooding, as fewer people will live in harm's way. In the US, this may mean fewer uninsured people will live in the high energy areas of floodplains – a catastrophe that has played out before, repeatedly (e.g., the 1993 flood in the Mississippi basin) (IFMRC, 1994; Zellmer and Klein, 2007). Furthermore, setbacks are possible solutions for climate vulnerable communities who need changes in corridor management now and cannot wait for state or national agencies to create comprehensive adaptation strategies.

A small but growing body of literature has begun to assess the potential FRM benefits of setbacks. Much of the literature are case studies (e.g., Smith et al., 2017, Serra-Llobet et al., 2022a) or economic assessments based on numerical flood hazard models (Dierauer et al., 2012; Remo et al., 2012; Guida et al., 2016). For example, economic assessments suggest setbacks with buyouts on the Mississippi River can reduce flood losses and are financially justifiable in the long-term (Dierauer et al., 2012; Remo et al., 2012). Other numerical modeling studies have evaluated multiple benefits in addition to flood losses, particularly habitat benefits (Guida et al., 2016) and sediment management (Theiling et al., 2018).

4.2. Environmental sustainability and ecosystem services

The sustainable delivery of ecosystem services depends on the restoration of ecosystem structure and function (Cardinale et al., 2012; Tilman et al., 2014; Opperman et al., 2017). Each will improve the quality and diversity of services and each depends on the scale of floodplain reconnection (Opperman et al., 2017). If ecosystem services are to fit into USACE's current BCA process, practitioners may need to treat the floodplain as natural capital that is substitutable with the potential commercial value of built capital on the levee-protected floodplain (a form of weak sustainability). Substitution is possible when ecosystem services are monetized (Costanza et al., 1997; de Groot et al., 2012).

Capital substitution implies there is a tradeoff between the benefits of commercial development on the levee-protected floodplain and the benefits of services provided by an ecologically functional floodplain. There may exist some balance between the relative proportions of each that produces a sustainable and economically efficient levee alignment (Farley, 2012; Reyers et al., 2013). To date, there exist few studies that explore how to "size" the flood-protected area with consideration for the commercial benefits of development, the externalities it produces, and ecosystem services. There is at least one study, Zhu and Lund (2009), that provides a foundational sizing analysis with simple economic considerations.

The environmental consequences of leveeing may not be reversible. Likewise, land use and other infrastructure in the reach (e.g. flow regulation by dams) may limit the extent to which floodplain reconnection can rehabilitate ecological structure and function (Poff et al., 1997; Peipoch et al., 2015; Opperman et al., 2017). Understanding this limitation, the researchers of environmental flows have sought to rehabilitate structure and function by focusing on restoring key components of natural flow regimes, such as those critical for habitat diversity, biodiversity, and connectivity across ecotones (Richter and Thomas, 2007; Poff and Matthews, 2013; Yarnell et al., 2015).

Bear in mind these considerations as we provide two simple examples of ecosystem services that may be restored with setbacks: water quality regulation and recreation. For example, floodplain ecosystems can provide a regulating service for downstream water quality by trapping suspended sediment and storing nutrients (Forshay and Stanley, 2005; Filoso and Palmer, 2011; Johnson et al., 2016; Gordon et al., 2020). Sedimentation occurs as flood velocities slow on the reconnected floodplain and can lower the downstream loading of sediment-bound nutrients (e.g., phosphorus). Biological transformation, such as plant uptake and denitrification, can remove dissolved nutrients from the water column (Orr et al., 2007; Lammers and Bledsoe, 2017).

A small, but growing, body of literature explores the potential water quality benefits of setbacks. For example, USACE modeling studies have considered setback alternatives on the Sangamon River in Illinois and found great potential for sediment (Theiling et al., 2018) and nutrient retention (Bartell et al., 2020) on reconnected floodplains. Furthermore, Hoagland et al. (2019), conducted nitrogen removal experiments on soil cores from a reconnected floodplain on the Cosumnes River in California. They estimate that 12–26% of the total annual nitrogen load could be removed, depending on flow conditions. Although, nutrient removal benefits may be more limited on rivers with high nutrient loads. Modeling suggests that complete levee removal on the Missouri River could double nitrogen removal, but the absolute increase would only be from ~1.7–3.6% of the total load (Jacobson et al., 2022).

A second example ecosystem service is recreation on the reconnected floodplain. Setback land ownership may be transferred to public or private conservation organizations and opened for public use, which could provide significant economic benefit (Kovacs et al., 2013). For example, there is opportunity from waterfowl hunting in the Central and Mississippi Flyways on restored floodplain habitats. Waterfowl hunting can provide tens of millions of dollars in direct economic benefit in a single state (Grado et al., 2001). Recreational opportunities are also one of the more tangible benefits and may be a driver of local support, which is critical for the selection of alternatives in USACE's civil works planning process.

4.3. Limitations on benefits

A number of factors can limit the services provided by setbacks. One example is that benefits may not be achievable at the same scales of floodplain reconnection. In other words, the floodplain area required to achieve a material improvement in one ecosystem service (e.g., climate regulation through carbon storage) may be quite different from the area required to improve levee reliability. Achieving a wide range of services may require identifying the "limiting service" that requires the largest scale reconnection. A second example is that setbacks may cause sedimentation in the leveed reach and reduce floodwater conveyance over time. Lost conveyance can elevate flood stages and increase the frequency of levee loading by increasing the frequency of overbanking (Jacobson et al., 2015; Theiling et al., 2018). A a third example, is that navigation channels are often supported by bank armoring structures (revetments) and channel training features (spur dikes, groins, etc.). In the presence of these structures, the rehabilitation of ecological structure and function may be limited, for example, by limiting natural meandering processes (important for ecosystem successional dynamics; Ward, 1998) or sediment dynamics in the channel (scour by dikes at low flow; US Government Accountability Office, 2011). Likewise, a setback will not resolve the ecological consequences of flow regime modification or sediment starvation by upstream dam operation (Poff et al., 1997; Yarnell et al., 2015). And finally, one of the most important limitations results from historical land use on the levee-protected floodplain, such as the application of agrochemicals.

4.4. An example setback on the Missouri River, USA

Levee L536 is typical of many levees in the US (Fig. 3). It was built by USACE in 1951 with funds appropriated under a revision of the FCA (1944). Management of the levee was then transferred to a local levee district, which in its current iteration, is a non-profit organized by local landowners.

The levee was designed to maximize the area of protected floodplain. It was built close to one the continent's largest rivers on land accreted by dikes, with less than 300 m of floodplain in some locations. Its 9 km of frontage passes through the active high energy floodplain and crosses the scars of historic channel braids.

The levee is located in a particularly vulnerable reach, which has numerous bottlenecks (levees and bridges) and runs ~320 km between southeastern Nebraska and northwestern Missouri. Unfortunately, L536 has failed repeatedly with overtopping during the 1952, 1993, 2011, and 2019 floods and breaches in 1952 and 2019.

The 2019 flood was devastating and clarified the need for greater flood protection. Fortunately, the levee district had maintained compliance with the PL84–99 inspection program (previously discussed) and was eligible for USACE's support. A setback was estimated to be the least costly option due to substantial repair costs at seven breaches. However, PL84–99's "most technically feasible" condition created several difficulties. First, the levee district was responsible for buying out 3.24 sq. km of private land as part of a cost-share stipulation; which at 3.5 million dollars, was unaffordable. To fund buy-outs, the district and USACE collaborated with multiple non-profit, federal, and state agencies to leverage a Natural Resources Conservation Service (NRCS) conservation program called the Emergency Watershed Protection Program - Floodplain Easement Option (EWPP-FPE); in which case, property owners sell land rights to NRCS and the land is placed in conservation.

Second, under PL84–99, the levee district is responsible for supplying the raw sand and clay materials used by USACE in levee construction. Fortunately, the levee district had access to quality borrow materials, but the borrow was available on lands that would become part of the NRCS conservation easements; meaning the conservation lands would have shallow open pit mines after construction. This was unacceptable to NRCS, and would have precluded the granting of easements, had the partner agencies not brainstormed a solution to transform the mines into wetland habitats by giving them gentle side slopes, irregular bank lines, topographic diversity, and seeding them with native vegetation.

In total, the setback took four years to plan and build. It cost 103.5 million dollars, with 100 million in construction, and 3.5 million in real estate acquisition. The setback length is approximately 8 km, suggesting a construction cost of ~12.5 million dollars a kilometer. It reconnected 4.2 km^2 of floodplain, making it the largest setback on the Missouri River to date.

The setback offers greater flood protection and climate resilience. USACE's hydraulic modeling suggests that conveyance on the reconnected floodplain will reduce flood stages by 0.25 m during the 1% ACE flood (100-year flood). In addition, the levee is setback at critical locations with high flood stresses (e.g., the outside of a meander bend), the new levee is built to modern design standards (with a 5:1 landward slope to reduce breaching during overtopping); and it is sited on a more geotechnically competent foundation.

The setback also integrates new and existing conservation land into a 32.3 km^2 habitat complex. The complex includes high-value habitat like a side channel chute created by USACE to support pallid sturgeon

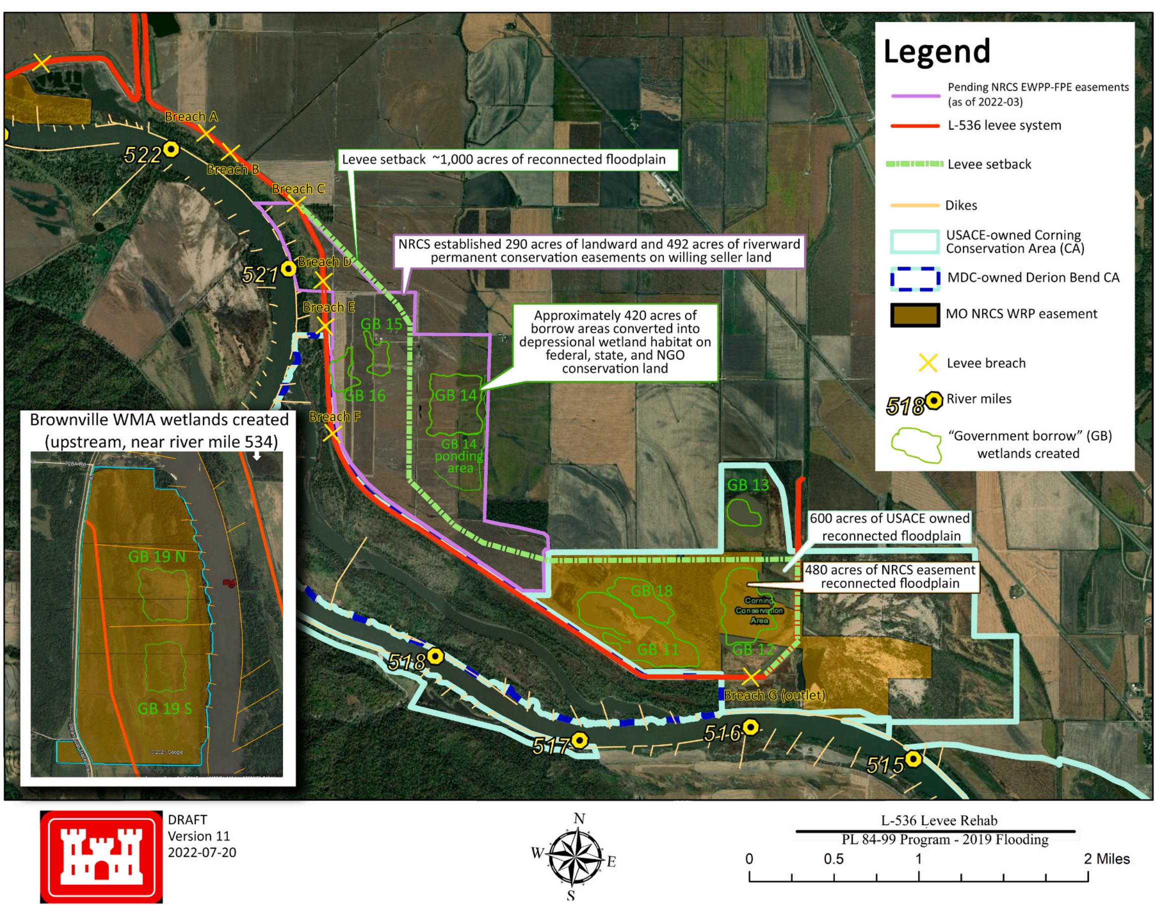

Fig. 3. L-536 levee setback on the Missouri River. Courtesy of Dave Crane at the USACE Omaha District.

conservation (protected under the Endangered Species Act). The chute is designed to retain juvenile sturgeon within this reach of the Missouri River, but may have additional benefits, for example, as a conduit for aquatic species to more easily access the reconnected floodplain. In addition, over 1.7 km^2 of borrow pits were converted into wetland habitat, as previously discussed.

Since the end of construction in 2023, there has been little time to monitor and field verify ecological benefits. However, monitoring at two previously completed setbacks just upstream may provide insight. Murphy et al., (2014, 2015) observed many rare and declining bird, odonata, reptile, and fish taxa at both sites. Haas et al. (2020) encountered a large age-0 native fish hot spot when sampling during the 2019 flood. And finally, waterfowl surveys have recorded tens of thousands of ducks, geese, and raptors using wetland habitats in the setbacks (IDNR, 2020).

It is interesting to note that the L536 setback was built with PL84–99 funding and not USACE's mainstay civil works program. A setback was unlikely to occur had the levee not been destroyed by multiple floods, which is unfortunate, because it suggests disaster must strike before changes in corridor management are enacted. USACE does not have sole authority, and their actions are dependent on private landowner interests and the interests of various federal and state agencies. This setback is an example of how critical local champions are (the levee district), as well as outside support from non-profit and governmental agencies that can facilitate buyouts (NRCS, The Nature Conservancy, etc.).

5. Getting from here to there: Changing USACE policy and practice

Achieving sustainable river corridor management with NbS in the US will require significant changes to USACE policies and practices – changes that USACE is already undertaking. One of the most important changes is that USACE evolve into a more multidisciplinary institution. Where once West Point-trained engineers were the predominant force within the agency, today engineers work closely with ecologists, economists, biologists, planning experts, and more. Their multiple viewpoints and ontologies ensure that USACE's water resources projects deliver a host of benefits. Furthermore, Congress and Executive Branch leadership have called for a significant overhaul of USACE's civil works valuation policies, opening the door for modernizing the BCA process and improving equity in corridor management practices.

5.1. Practitioner guidance

In some respects, USACE's regional district offices serve as petri dishes for the policies and practices of the agency as a whole. Our colleagues at one district say we are in the "Wild West of NbS'' while they wait for the agency's management to issue the new PR&G, but are nevertheless under pressure to explore NbS in the absence of clearly defined guidance.

Recent internal polling from USACE's Engineering With Nature® program provides some insights into the most substantial hurdles practitioners face in the implementation of NbS (Fig. 4). One take-away is that "Knowledge gaps'' are the greatest obstacle, by far, meaning, practitioners are uncertain of how to plan and valuate specific NbS alternatives. Another common response is "High-cost, unfavorable BCA", which reflects practitioner uncertainty about how to valuate ecosystem services. Without clear guidance, ecosystem services are not typically included in BCAs, and drive down benefit-cost ratios. Another common response was "Performance uncertainty and risk." Meaning, practitioners are uncertain of how NbS will perform in practice and therefore, feel there is too much risk in recommending a NbS alternative at the completion of civil works planning.

Most survey responses suggest USACE's NbS tool kit is underdeveloped. This is a problem academics can help solve, as practitioner

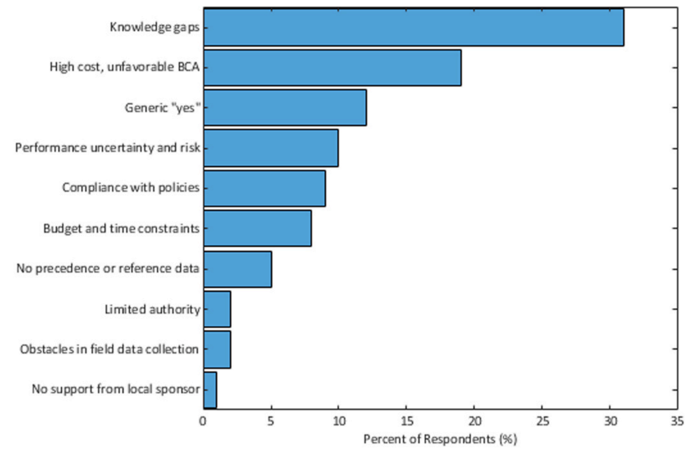

Fig. 4. Issues in the implementation of NbS through USACE's civil works program. Sourced from internal polling conducted by USACE's Engineering With Nature® program. Results reflect responses from 153 individuals in all business lines (engineering, planning, operations, ERDC, IWR, regulatory, and headquarters) and representing 43 offices distributed around the US.

uncertainty may be dispelled through the development of fundamental knowledge of the performance and valuation of NbS services in real world examples. Setbacks are arguably a straightforward example, because their primary FRM service is monetized as flood losses mitigated within a planning horizon. Whereas other benefits, like ecosystem services are supported by decades of research; practitioners just need tractable and repeatable methods at the typical scales of civil works projects.

5.2. Innovating decision support tools

Economists use the concept of willingness to pay (WTP) as a measure of economic value. The intuition is that the value a person ascribes to something is what that person is willing to sacrifice for it. WTP, when the person has *de facto* property rights to a good or service, reflects individual preferences, social values (like altruism), available information, attitudes, and beliefs. When goods and services are traded in markets, their market price can be used as an approximation of WTP. However, for public services, like most of the ecosystem services discussed, individuals do not choose their personal level of consumption directly in markets; they do so indirectly, e.g., by relocating or voting. Thus, economists have developed non-market valuation methods to estimate the implicit WTP for public goods from observed behavior (revealed preference approaches) or from survey responses (stated preference approaches).

From an economic perspective, there are well-developed theories, survey design practices, and statistical models for environmental valuation and innovative approaches being offered to address the shortcomings of BCA that have attained professional acceptance (Freeman et al., 2014; OECD, 2018; Johansson and Kriström, 2019). In the US, for example, non-market valuation studies are routinely used in damage assessments that, particularly for oil spills, can amount to billions of dollars. Despite these developments, there is a disconnect with practical implementation. For example, as currently practiced by USACE in NED projects, net benefits are expressed monetarily with emphasis on flood losses mitigated and little accounting for ecological benefits, or how benefits are distributed across the population.

BCA is described as a tool for assessing economic efficiency, as it can inform decisions about how society's scarce resources can be put to the greatest social good with distributional consequences being a separate consideration (Arrow et al., 1996). With growing societal concerns about equity, it is worth noting that best practices in BCA call for a full accounting of the net effects of how benefits are distributed (OECD, 2018), and revisiting how the economics profession has proposed to modify BCA to incorporate distributional considerations. It is well known that, (1) failure to account for all project benefits and costs, and (2) the use of a monetary metric in the aggregation of net benefits can have distributional consequences. For example, if benefits from expected flood risk reductions are measured using market prices only, projects that protect property and businesses in wealthy areas will be of higher value in a BCA than those that protect poorer areas. Ongoing efforts at USACE to revise their guidelines to fully account for the distribution of environmental and social benefits of projects can go a long way toward addressing questions of fairness. On this, USACE would be joining BCA best practices that call for the quantification of all the benefits and costs of a project, including those (e.g., many ecosystem goods and services) that are not captured in markets and for which there are no market prices. That is, BCA itself does not impose a hierarchy between "economic", "ecological" or "social" costs and benefits. In practice, however, because economic effects are more easily monetizable than ecological or social effects, they typically play a more prominent role in decision making.

The use of money as the numeraire in BCA has distributional implications that go beyond the relative ease of incorporating economic effects into an analysis (compared to ecological and social). If we take the bottom line net present value in a typical implementation of BCA as a change in social well-being, then the distributional implication is that a gain of a dollar produces the same increase in social well-being regardless of who receives it. This implication ignores two tenets about individual preferences and a good society: first, that the marginal utility of wealth decreases with wealth, and second, that excessive wealth inequality leads to a less desirable society (Hammitt, 2021).

Distributional implications of BCA were formally acknowledged a half century ago (Weisbrod, 1968) but the practical implementation of alternative BCAs has lagged. Among them, the use of weighted BCA, where the weights are designed to overweight impacts to certain groups and underweight impacts to others is gaining momentum (Adler, 2016; Hammitt, 2021). Weighted BCA is recommended by the UK's official BCA guidance (HM Treasury, 2022); described as a method that "can be possibly used" by the EU's guidance (European Commission, 2014); and is prominent in the ongoing proposed revisions to US Federal BCA guidelines (Office of Management and Budget, 2023a,b). The choice of weights is clearly normative and should be transparent. In principle, the weights could be chosen to mimic a specific social welfare function which is used to rank distributions of well-being in a society and can incorporate preferences for both efficiency and equity (Hammitt, 2021). In practice, the weights proposed in the guidance documents above reflect the declining marginal utility of consumption to give more weight to benefits accruing to poorer groups. It may also be advisable to publish the distribution of net benefits across sub-population so that anyone interested could apply their own distributional weights (Nyborg, 2012; OECD, 2018).

5.3. Equitable planning processes

NbS are not inherently more equitable than conventional infrastructure (Turner et al., 2022; Woroniecki et al., 2022) and given the billions of dollars of projected infrastructure investment over the coming decades it is critical to get equity right. The alternative is to, at best, maintain current levels of inequity, or, at worst, increase and lock in inequities for future generations (Eriksen et al., 2021). Through Executive Orders and regulatory changes, the current US administration is focused on elevating environmental justice throughout all federal agencies. The Justice40 initiative and the revision of the USACE PR&G are two examples. An initial step to implementing these types of reform is enhanced equitable planning processes, which starts with increased, meaningful community engagement early on in civil works planning. Doing so increases community capacities and long-term resilience (EnCoRe, 2023).

Levee setbacks invoke significant changes in a community, which involve losses and gains that are both tangible and intangible (Clarke et al., 2018). For example, one tangible change is that setbacks require that some community members relocate such that the community, as a whole, can have greater flood protection. Related intangible outcomes may include affective loss of place. However, equity is not focused solely on outcomes. Rather, equitable NbS reference dynamic processes that include the three intertwined aspects of recognitional, procedural, and distributional equity (Seigerman et al., 2023). Contemporary inequities are rooted in social, political, and economic systems and recognitional equity starts with a deep understanding of the historical context and the processes that contributed to the current state (Nelson et al., 2020). This contextual understanding is critical to developing NbS that do not exacerbate inequities (Eriksen et al., 2021; Turner et al., 2022). Fundamentally, this requires identification and engagement of the range and diversity of affected people and communities (Meerow et al., 2019; Matin et al., 2018). This includes proximate and downstream communities, property holders, and in the case of the US, consultation with Tribal Nations with historical treaty rights and cultural affiliations.

The growing literature on managed retreat provides important lessons for setback planning and implementation. For example, social inequities in managed retreat can frequently be traced to top-down planning and exclusion from decision-making (Tubridy et al., 2022). To counteract these tendencies, strong procedural equity requires effective engagement strategies that bring people to the table and give them voice and power within the deliberative and decision-making process. This co-production of knowledge is a conscious choice that facilitates the active participation of disempowered groups in shaping knowledge and decisions (Lemos et al., 2018). Procedural inequities can also stem from a problematic over reliance on traditional BCAs that focus solely on monetizable measures (Tubridy et al., 2022; Maldonado, 2014; Siders, 2019). These discount the value of low-income areas and do not address the historical interrelations of race, income, wealth, and property, for example. They also fail to account for the full range of possible outcomes, emphasizing the importance of innovating BCA.

The ways that risk and benefits are distributed across space, populations, and time are direct reflections of representational and procedural equity. Inherent to top-down approaches that privilege monetary metrics are ideologies of the market, individualism and property that can disadvantage particular communities (Marino, 2018) and which may not align with notions of intergenerational equity. In addition to financial considerations, setbacks may require relocation and invoke loss of place and attachments to specific locations (O'Donnell, 2022). The growing acknowledgement of the social and psychological impacts of ecological grief and nostalgia (Biesel, 2023; Cunsolo et al., 2018; Comtesse et al., 2021) point to the importance of exploring a broader range of distributional outcomes to fully understand the gains, losses and trade-offs that emerge. This refers to grief experienced in relation to ecological losses and landscapes and which, like financial burdens, can be inequitably distributed.

6. Conclusions

The conceptual framework and justification for NbS is well developed; however, operationalizing and mainstreaming NbS in professional practice will require interdisciplinary knowledge of specific NbS (e.g. levee setbacks) to priority challenges of the Anthropocene, including insufficient infrastructure services (flood protection), unsustainable management of engineered systems (leveed river corridors), and climate regulation (depleted natural capital in floodplain ecosystems). Much like this review of levee setbacks, analogous reviews could synthesize multidisciplinary knowledge to identify pathways to operationalizing other types of NbS, whether they be at the intersection of environmental flows, dam operations, and floodplain reconnection, or solutions to climate risk inequities in urban areas, for example.

A similar story of unsustainable levee management practices, as we have discussed for the US, is probable for many societies around the world, but with their own unique historical linkages connecting policy with engineering practice. Shifting to new management paradigms with NbS will require interdisciplinary understanding of the legal authorities and administrative structures of action agencies tasked with river corridor management within the broader social-ecological-technical systems. Innovation will also depend on identifying policy levers and windows of opportunity based on understanding of how and when legal authorities can change, for example during periodic updates to legislation, decision support tools, and engineering guidance (e.g., WRDA in the US).

If management of engineered river corridors is to be sustainable and adaptive in a changing environment, it will necessarily be informed by the oversights and mistakes of past generations. Developments in environmental science and economics provide pathways for redesigning infrastructure with more holistic and exacting estimates of how investments will affect social welfare and the distribution of services. Levee setbacks reflect this sentiment implicitly; a setback is an adjustment for erroneous design logic that placed levees too close to rivers for the safety of communities, or alternatively, as a correction for past value judgments that underestimated the necessity of functional floodplain ecosystems. Setbacks can be designed to balance flood protection services and commercial growth opportunities with the provision of diverse ecosystem services. However, to reach a point where practitioners can identify economically efficient or satisficing setback realignments in a straightforward and repeatable manner, they will need comprehensive tools for evaluating ecosystem services across varying spatial scales. Future academic research can help by translating knowledge into tractable and repeatable methods, or by developing fundamental knowledge of the performance of specific NbS and their application.

Declaration of competing interest

The authors have no competing financial interests or personal relationships that could have influenced this work.

Data Availability

The authors do not have permission to share data.

Acknowledgements

We thank our USACE collaborators in the Omaha and Kansas City districts and Engineer Research and Development Center, the US Geological Survey, and Viv Bennett of The Nature Conservancy for their expertise and support. They provided historical knowledge, insights into past levee setback projects, understanding of levee engineering practices, and expertise in riverine systems. This work was supported by the US Army Corps of Engineers Engineering With Nature® Initiative through Cooperative Ecosystem Studies Unit Agreement W912HZ-20-2-0031.

References

Adler, M., 2016. Benefit-cost analysis and distributional weights: an overview. Rev. Environ. Econ. Policy 10 (2), 264–285.

Albert, J.S., Destouni, G., Duke-Sylvester, S.M., Magurran, A.E., Oberdorff, T., Reis, R.E., Winemiller, K.O., Ripple, W.J., 2021. Scientists' warning to humanity on the freshwater biodiversity crisis. Ambio 50 (1), 85–94. https://doi.org/10.1007/s13280-020-01318-8.

Alexander, J.S., Wilson, R.C., and Green, W.R., 2012. A brief history and summary of the effects of river engineering and dams on the Mississippi River system and delta: U.S. Geological Survey Circular 1375.

American Society of Civil Engineers, 2021. Report Card for America's Infrastructure, Levees. (accessed, 01 June, 2023).

Arnold, J.L., 1988. The evolution of the 1936 Flood Control Act. United States Army Corps of Engineers. Off. Hist. Rep.

Arrow, K.J., Cropper, M.L., Eads, G.C., Hahn, R.W., Lave, L.B., Noll, R.G., Portney, P.R., Russell, M., Schmalensee, R., Smith, V.K., Stavins, R.N., 1996. Is there a role for benefit-cost analysis in environmental, health, and safety regulation? Science 272 (5259), 221–222. https://doi.org/10.1126/science.272.5259.221.

Baeten, J., 2022. Improving an unworthy river: The Army Corps and the Wabash River, 1820-1935. Indiana Mag. Hist. 118 (2), 83–112.

Bartell, S.M., Woodard, C.T., Theiling, C.H., Dahl, T.A., 2020. Development and application of the CASM-SL to support nutrient management in potential Sangamon River levee setbacks. (ERDC TR-20-9). U.S. Army Engineer Research and Development Center.

Bayley, P.B., 1995. Understanding large river floodplain ecosystems. Bioscience 45 (3), 153–158. https://doi.org/10.2307/1312554.

Behm, R.L., 2021. Levee Setback White Paper. Behm Hazard Mitigation, LLC, Omaha, Nebraska.

Biesel, S., 2023. Confronting Legacies of Loss: Negotiating Intergenerational Inequalities in Afro-Brazilian "Traditional" Communities. University of Georgia.

Brauman, K.A., Daily, G.C., Duarte, T.K., Mooney, H.A., 2007. The nature and value of ecosystem services: an overview highlighting hydrologic services. Annu. Rev. Environ. Resour. 32, 67–98. https://doi.org/10.1146/annurev.energy.32.031306.102758.

Camillo, C.A., 2012. Divine Providence: The 2011 Flood in the Mississippi River and Tributaries Project. US Army Corps Eng. 142. ⟨https://digitalcommons.unl.edu/usarmyceomaha/142⟩.

Cardinale, B.J., Duffy, J.E., Gonzalez, A., Hooper, D.U., Perrings, C., Venail, P., Narwani, A., Mace, G.M., Tilman, D., Wardle, D.A., Kinzig, A.P., Daily, G.C., Loreau, M., Grace, J.B., Larigauderie, A., Srivastava, D.S., Naeem, S., 2012. Biodiversity loss and its impact on humanity. Nature 486 (7401), 59–67. https://doi.org/10.1038/nature11148.

Cartwright, L., 2005. An Examination of Flood Damage Data Trends in the United States. J. Contemp. Water Res. Educ. 130 (1), 20–25. https://doi.org/10.1111/j.1936-704X.2005.mp130001004.x.

Clarke, D., Murphy, C., Lorenzoni, I., 2018. Place attachment, disruption and transformative adaptation. J. Environ. Psychol. 55, 81–89. https://doi.org/10.1016/j.jenvp.2017.12.006.

Cohen-Shacham, E., Walters, G., Janzen, C., Maginnis, S., 2016. Nature-based Solutions to address global societal challenges. IUCN, Gland, Switzerland, p. Xiii + 97. https://doi.org/10.2305/IUCN.CH.2016.13.en.

Cohen-Shacham, E., Andrade, A., Dalton, J., Dudley, N., Jones, M., Kumar, C., Maginnis, S., Maynard, S., Nelson, C.R., Renaud, F.G., Welling, R., Walters, G., 2019. Core principles for successfully implementing and upscaling Nature-based Solutions. Environ. Sci. Policy 98, 20–29. https://doi.org/10.1016/j.envsci.2019.04.014.

Committee on Criteria for Community Participation in the Gulf Research Program's Enhancing Community Resilience (EnCoRe) Initiative, Policy and Global Affairs, National Academies of Sciences, Engineering, and Medicine, 2023. Strengthening Equitable Community Resilience: Criteria and Guiding Principles for the Gulf Research Program's Enhancing Community Resilience (EnCoRe) Initiative. National Academies Press, p. 26880. https://doi.org/10.17226/26880.

Comtesse, Hannah, Verena Ertl, Sophie, M.C. Hengst, Rita Rosner, Smid, Geert E., 2021. Ecological grief as a response to environmental change: a mental health risk or functional response? Int. J. Environ. Res. Public Health 18, 2.

Costanza, R., dArge, R., deGroot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., ONeill, R.V., Paruelo, J., Raskin, R.G., Sutton, P., vandenBelt, M., 1997. The value of the world's ecosystem services and natural capital. Nature 387 (6630), 253–260.. https://doi.org/10.1038/387253a0.

Cunsolo, Ashlee, Ellis, N.R., 2018. Ecological grief as a mental health response to climate change-related loss. Nat. Clim. Change 8 (4), 275–281. https://doi.org/10.1038/s41558-018-0092-2.

Dahl, T.A., Theiling, C.H., Echevarria, W., 2017. Overview of levee setback projects and benefits. ERDC/CHL CHETN-VII-17. U.S. Army Engineer Research and Development Center. https://doi.org/10.21079/11681/22767.

de Groot, R., Brander, L., van der Ploeg, S., Costanza, R., Bernard, F., Braat, L., Christie, M., Crossman, N., Ghermandi, A., Hein, L., Hussain, S., Kumar, P., McVittie, A., Portela, R., Rodriguez, L.C., ten Brink, P., van Beukeringh, P., 2012. Global estimates of the value of ecosystems and their services in monetary units. Ecosyst. Serv. 1 (1), 50–61. https://doi.org/10.1016/j.ecoser.2012.07.005.

Dierauer, J., Pinter, N., Remo, J.W.F., 2012. Evaluation of levee setbacks for flood-loss reduction, Middle Mississippi River, USA. J. Hydrol. 450, 1–8. https://doi.org/10.1016/j.jhydrol.2012.05.044.

Ehrenwerth, J.R., Jones, S.B., Windhoffer, E., Fischbach, J.R., Hughes, S., Hughes, T., Pippin, S., Shudtz, M., and Jones, S., 2022. Enhancing Benefits Evaluation for Water Resources Projects: Towards a More Comprehensive Approach for Nature-Based Solutions. Evolution of Benefits Evaluation and Prioritization of Water Resources Projects. ⟨https://ewn.erdc.dren.mil/wp-content/uploads/2022/10/EvolutionofUSACEWaterReourcesProjectSelection.pdf⟩.

Eriksen, S., Schipper, E.L.F., Scoville-Simonds, M., Vincent, K., Adam, H.N., Brooks, N., Harding, B., Khatri, D., Lenaerts, L., Liverman, D., Mills-Novoa, M., Mosberg, M., Movik, S., Muok, B., Nightingale, A., Ojha, H., Sygna, L., Taylor, M., Vogel, C., West, J.J., 2021. Adaptation interventions and their effect on vulnerability in developing countries: Help, hindrance or irrelevance. World Dev. 141, 105383 https://doi.org/10.1016/j.worlddev.2020.105383.

European Commission. Guide to Cost-Benefit Analysis for Investment Projects: Economic appraisal tool for Cohesion Policy 2014–2020 (December 2014).

Executive Order 14008, 2021. Issued January 27th. Tackling the Climate Crisis at Home and Abroad, 86. Federal Register, pp. 7619–7633. Issued January 27th.

Farley, J., 2012. Ecosystem services: The economics debate. Ecosyst. Serv. 1 (1), 40–49. https://doi.org/10.1016/j.ecoser.2012.07.002.

Filoso, S., Palmer, M.A., 2011. Assessing stream restoration effectiveness at reducing nitrogen export to downstream waters. Ecol. Appl. 21 (6), 1989–2006.. https://doi.org/10.1890/100854.1.
Forshay, K.J., Stanley, E.H., 2005. Rapid nitrate loss and denitrification in a temperate river floodplain. Biogeochemistry 75 (1), 43–64. https://doi.org/10.1007/s10533-004-6016-4.
Freeman III, A.M., Herriges, J.A., Kling, C.L., 2014. The measurement of environmental and resource values. Theory and Methods. RFS Press, New York, New York.
Georgic, W., Klaiber, H.A., 2022. A flood of construction: the role of levees in urban floodplain development. Land Econ. 98 (1), 78–97. https://doi.org/10.3368/le.98.1.071520-0106R1.
Gordon, B.A., Dorothy, O., Lenhart, C.F., 2020. Nutrient retention in ecologically functional floodplains: a review. Water 12 (10) https://doi.org/ARTN276210.3390/w12102762.
Grado, S.C., Kaminski, B.M., Munn, I.A., Tullos, T.A., 2001. Economic impacts of waterfowl hunting on public lands and at private lodges in the Mississippi Delta. Wildl. Soc. Bull. 29 (3), 846–855.
Graham W., H., 2022. Deputy Commanding General for Civil and Emergency Operations, dated 16th December, subject "Implementation of the Interim Environmental Justice Strategic Plan"
Guida, R.J., Remo, J.W.F., Secchi, S., 2016. Tradeoffs of strategically reconnecting rivers to their floodplains: the case of the Lower Illinois River (USA. Sci. Total Environ. 572, 43–55. https://doi.org/10.1016/j.scitotenv.2016.07.190.
Haas, J., Ruskamp, R., Hall, J., Steffensen, K., 2020. Annual Report Pallid Sturgeon Population Assessment and Monitoring Program v2.0 and Habitat Assessment and Monitoring Program. Prepared for the U.S. Army Corps of Engineers – Missouri River Recovery Program and the Nebraska Game and Parks Commission.
Hammitt, J.K., 2021. Accounting for the distribution of benefits and costs in benefit–cost analysis. J. Benefit-Cost. Anal. 12 (1), 64–84.
Heine, R.A., Pinter, N., 2012. Levee effects upon flood levels: an empirical assessment. Hydrol. Process. 26 (21), 3225–3240. https://doi.org/10.1002/hyp.8261.
HM Treasury The Green Book, 2022. Appraisal and evaluation in central government.
Hoagland, B., Schmidt, C., Russo, T.A., Adams, R., Kaye, J., 2019. Controls on nitrogen transformation rates on restored floodplains along the Cosumnes River, California. Sci. Total Environ. 649, 979–994. https://doi.org/10.1016/j.scitotenv.2018.08.379.
Hui, R., Jachens, E., Lund, J., 2016. Risk-based planning analysis for a single levee. Water Resour. Res. 52 (4), 2513–2528. https://doi.org/10.1002/2014wr016478.
Ickes, B.S., J. Vallazza, J. Kalas, and B. Knights, 2005. River floodplain connectivity and lateral fish passage: A literature review. U.S. Geological Survey, Upper Midwest Environmental Sciences Center, La Crosse, Wisconsin, June 2005. 25 pp. https://www.umesc.usgs.gov/documents/reports/2005/05cp002.pdf.
Iowa Department of Natural Resources (IDNR), 2020. Corps Area Waterfowl Survey Data. Unpublished data.
IFMRC, Interagency Floodplain Management Review Committee, 1994. Sharing the challenge: floodplain management into the 21st century. Report to the Administration Floodplain Management Task Force. U.S. Government Printing Office, Washington D.C.
Jacobson, R.B., Lindner, G., Bitner, C., 2015. In: Hudson, P.F., Middelkoop, H. (Eds.), The Role of Floodplain Restoration in Mitigating Flood Risk, Lower Missouri River, USA. Geomorphic Approaches to Integrated.
Jacobson, R.B., Bouska, K.L., Bulliner, E.A., Lindner, G.A., Paukert, C.P., 2022. Geomorphic controls on floodplain connectivity, ecosystem services, and sensitivity to climate change: an example from the lower Missouri River. In: Water Resources Research, 58 https://doi.org/ARTNe2021WR03120410.1029/2021WR031204.
Jeffres, C.A., Opperman, J.J., Moyle, P.B., 2008. Ephemeral floodplain habitats provide best growth conditions for juvenile Chinook salmon in a California river. Environ. Biol. Fishes 83 (4), 449–458. https://doi.org/10.1007/s10641-008-9367-1.
Johansson, P.O., and Kriström, B., 2019. On the Formulation of the Alternative Scenario in Cost-Benefit Analysis. https://doi.org/10.2139/ssrn.3401694.
Johnson, T.A.N., Kaushal, S.S., Mayer, P.M., Smith, R.M., Sivirichi, G.M., 2016. Nutrient retention in restored streams and rivers: a global review and synthesis. Water 8 (4) https://doi.org/ARTN11610.3390/w8040116.
Junk, W., P.B. Bayley, and R.E. Sparks, 1989. The flood pulse concept in river-floodplain systems. In the Proceedings of the International Large River Symposium (LARS). Can. Spec. Publ. Fish. Aquat. Sci. 106.
Kabisch, N., Frantzeskaki, N., Pauleit, S., Naumann, S., Davis, M., Artmann, M., Haase, D., Knapp, S., Korn, H., Stadler, J., Zaunberger, K., Bonn, A., 2016. Nature-based solutions to climate change mitigation and adaptation in urban areas: perspectives on indicators, knowledge gaps, barriers, and opportunities for action. Ecol. Soc. 21 (2) https://doi.org/Artn 3910.5751/Es-08373-210239.
Kay, R. (2003, May). Flow Regime of the Missouri River Below Gavins Point Dam. In the Proceedings of US Army Corps of Engineers Watershed System Conference. Portland, Oregon. ⟨https://www.researchgate.net/publication/314207964_Flow_Regime_of_the_Missouri_River_Below_Gavins_Point_Dam⟩.
Keesstra, S., Nunes, J., Novara, A., Finger, D., Avelar, D., Kalantari, Z., Cerda, A., 2018. The superior effect of nature-based solutions in land management for enhancing ecosystem services. Sci. Total Environ. 610, 997–1009. https://doi.org/10.1016/j.scitotenv.2017.08.077.
Klijn, F., Asselman, N., Wagenaar, D., 2018. Room for rivers: risk reduction by enhancing the flood conveyance capacity of the netherlands' large rivers. Geosciences 8 (6), 1–20. https://doi.org/10.3390/geosciences8060224.
Knowles, S.G., Kunreuther, H.C., 2014. Troubled waters: the national flood insurance program in historical perspective. J. Policy Hist. 26 (3), 327–353. https://doi.org/10.1017/S0898030614000153.
Knox, R.L., Morrison, R.R., Wohl, E.E., 2022a. Identification of artificial levees in the contiguous United States. Water Resour. Res. 58 (4) https://doi.org/ARTNe2021WR03130810.1029/2021WR031308.
Knox, R.L., Morrison, R.R., Wohl, E.E., 2022b. A river ran through it: floodplains as America's newest relict landform. Sci. Adv. 8 (25) https://doi.org/ARTNeabo108210.1126/sciadv.abo1082.
Knox, R.L., Wohl, E.E., Morrison, R.R., 2022c. Levees don't protect, they disconnect: a critical review of how artificial levees impact floodplain functions. Sci. Total Environ. 837 https://doi.org/ARTN15577310.1016/j.scitotenv.2022.155773.
Kovacs, K., Polasky, S., Nelson, E., Keeler, B.L., Pennington, D., Plantinga, A.J., Taff, S.J., 2013. Evaluating the return in ecosystem services from investment in public land acquisitions. Plos One 8 (6) https://doi.org/ARTNe6220210.1371/journal.pone.0062202.
Krause, T.D., Baxter, K., Crane, D.J., Behm, R.L. (2015, April 19 – 23). Evaluation of levee setbacks as a sustainable solution along the Missouri River. In Proceedings of the 3rd Joint Federal Interagency Conference (10th Federal Interagency Sedimentation Conference and 5th Federal Interagency Hydrologic Modeling Conference). Reno, Nevada.
Krutilla, J.V., 1967. Conservation Reconsidered. Am. Econ. Rev. 57, 777–786.
Lammers, R.W., Bledsoe, B.P., 2017. What role does stream restoration play in nutrient management. Crit. Rev. Environ. Sci. Technol. 47 (6), 335–371. https://doi.org/10.1080/10643389.2017.1318618.
Lemos, M.C., Arnott, J.C., Ardoin, N.M., et al., 2018. To co-produce or not to co-produce. Nat. Sustain 1 (12), 722–724.
Lewis, J.W., Lytle, S.E., Tavakoly, A.A., 2023. Climate change projections of continental-scale streamflow across the Mississippi River Basin. Theor. Appl. Clim. 151, 1013–1034 https://doi.org/10.1007/s00704-022-04243-w.
Ludy, J., Kondolf, G.M., 2012. Flood risk perception in lands "protected" by 100-year levees. Nat. Hazards 61 (2), 829–842.. https://doi.org/10.1007/s11069-011-0072-6.
Lyon, J., Stuart, I., Ramsey, D., O'Mahony, J., 2010. The effect of water level on lateral movements of fish between river and off-channel habitats and implications for management. Mar. Freshw. Res. 61 (3), 271–278. https://doi.org/10.1071/Mf08246.
Maes, J., Jacobs, S., 2017. Nature-based solutions for europe's sustainable development. Conserv. Lett. 10 (1), 121–124.. https://doi.org/10.1111/conl.12216.
Maldonado, J., 2014. A multiple knowledge approach for adaptation to environmental change: lessons learned from coastal Louisiana's tribal communities. J. Political Ecol. 21 (1) https://doi.org/10.2458/v21i1.21125.
Marino, E., 2018. Adaptation privilege and Voluntary Buyouts: perspectives on ethnocentrism in sea level rise relocation and retreat policies in the US. Glob. Environ. Change 49, 10–13. https://doi.org/10.1016/j.gloenvcha.2018.01.002.
Matin, N., Forrester, J., Ensor, J., 2018. What is equitable resilience? World Dev. 109, 197–205.
Maxwell, S., Fuller, R., Brooks, T., Watson, J.E.M., 2016. Biodiversity: the ravages of guns, nets and bulldozers. Nature 536, 143–145. https://doi.org/10.1038/536143a.
Meerow, S., Pajouhesh, P., Miller, T.R., 2019. Social equity in urban resilience planning. Local Environ. 24 (9), 793–808. https://doi.org/10.1080/13549839.2019.1645103.
Michel-Kerjan, E., Kunreuther, H., 2011. Redesigning flood insurance. Science 333 (6041), 408–409. https://doi.org/10.1126/science.1202616.
Mississippi River Commission, 2017. History of the Lower Mississippi levee system. ⟨https://www.mvd.usace.army.mil/Portals/52/docs/MRC/MRT_Levees.pdf?ver=2017–07-27–141912-910⟩.
Montz, B.E., Tobin, G., A., 2008. Livin' large with levees: lessons learned and lost. Nat. Hazards Rev. 9 (3), 150–157. https://doi.org/10.1061/(ASCE)1527-6988(2008)9:3(150).
Murphy, K.T., Kinkhead, K.E., Dinsmore, S.J., Frese, P., 2014. Missouri River Multiple Species Inventory & Monitoring Project Annual Report. Iowa State University and Iowa Department of Natural Resources.
Murphy, K.T., Kinkhead, K.E., Dinsmore, S.J., Frese, P., 2015. Missouri River Multiple Species Inventory & Monitoring Project Annual Report. Iowa State University and Iowa Department of Natural Resources.
National Oceanic and Atmospheric Administration, National Centers for Environmental Information. Extreme Wetness of 2019 Sets Records. ⟨https://www.ncei.noaa.gov/news/extreme-wetness-2019-sets-records⟩ (accessed 22 May 2023).
National Oceanic and Atmospheric Administration, National Weather Service. Spring Flooding Summary 2019. ⟨https://www.weather.gov/dvn/summary_SpringFlooding_2019⟩ (accessed 22 May 2023).
National Research Council, 2011. Missouri River Planning: Recognizing and Incorporating Sediment Management. The National Academies Press, Washington, DC. https://doi.org/10.17226/13019.
National Research Council, 2013. Levees and the National Flood Insurance Program: Improving Policies and Practices. The National Academies Press, Washington, DC. https://doi.org/10.17226/18309.
Nelson, D.R., Bledsoe, B.P., Ferreira, S., Nibbelink, N.P., 2020. Challenges to realizing the potential of nature-based solution. Curr. Opin. Environ. Sustain. 45, 49–55. https://doi.org/10.1016/j.cosust.2020.09.001.
Nesshover, C., Assmuth, T., Irvine, K.N., Rusch, G.M., Waylen, K.A., Delbaere, B., Haase, D., Jones-Walters, L., Keune, H., Kovacs, E., Krauze, K., Kulvik, M., Rey, F., Van Dijk, J., Vistad, O.I., Wilkinson, M.E., Wittmer, H., 2017. The science, policy and practice of nature-based solutions: An interdisciplinary perspective. Sci. Total Environ. 579, 1215–1227. https://doi.org/10.1016/j.scitotenv.2016.11.106.
New York Times, 2019a. As Floods Inundate the Midwest, Many Ask: Will Our Levees Be the Next to Fail? ⟨https://www.nytimes.com/2019/03/22/us/midwest-flooding-levees.html⟩ (accessed 22 May 2023).

New York Times, 2019b. 'Breaches Everywhere': Flooding Bursts Midwest Levees, and Tough Questions Follow. ⟨https://www.nytimes.com/2019/03/31/us/midwest-floods-levees.html?auth=login-google1tap&login=google1tap⟩ (accessed 22 May 2023).
Nyborg, K., 2012. The ethics and politics of environmental cost-benefit analysis. Routledge.
O'Donnell, T., 2022. Managed retreat and planned retreat: a systematic literature review. Philos. Trans. R. Soc. B: Biol. Sci. 377 (1854), 20210129. https://doi.org/10.1098/rstb.2021.0129.
O'Hogain, S., McCarton, L., 2018. A technology portfolio of nature-based solutions, innovations in water management. Springer international publishing AG, part of Springer Nature, Cham Switzerland. https://doi.org/10.1007/978-3-319-73281-7.
OECD, 2018. Cost-Benefit Analysis and the Environment: Further Developments and Policy Use. OECD Publishing, Paris. https://doi.org/10.1787/9789264085169-en.
Office of Management and Budget (2023a) Public Comment on Guidelines and Discount Rates for Benefit-Cost Analysis of Federal Programs. Revisions to OMB Circular No. A-94.
Office of Management and Budget (2023b) Request for Comments on Proposed OMB Circular No. A-4, "Regulatory Analysis"
Olson, K.R., Speidel, D.R., 2021. Managing the lower Mississippi river landscape for strategic navigational and flood control. Open J. Soil Sci. 11, 285–330. https://doi.org/10.4236/ojss.2021.116016.
Opperman, J.J., Luster, R., McKenney, B.A., Roberts, M., Meadows, A.W., 2010. Ecologically functional floodplains: connectivity, flow regime, and scale. J. Am. Water Resour. Assoc. 46 (2), 211–226. https://doi.org/10.1111/j.1752-1688.2010.00426.x.
Opperman, J.J., Moyle, P.B., Larsen, E.W., Florsheim, J.L., Manfree, A.D., 2017. Floodplains: processes and management for ecosystem services. University of California Press, Oakland, California.
Opperman, J.J., Galloway, G.E., Fargione, J., Mount, J.F., Richter, B.D., Secchi, S., 2009. Sustainable floodplains through large-scale reconnection to rivers. Science 326 (5959), 1487–1488. https://doi.org/10.1126/science.1178256.
Orr, C.H., Stanley, E.H., Wilson, K.A., Finlay, J.C., 2007. Effects of restoration and reflooding on soil denitrification in a leveed midwestern floodplain. Ecol. Appl. 17 (8), 2365–2376. https://doi.org/10.1890/06-2113.1.
Pearcy, M.T., 2000. A history of the ransdell-humphreys flood control act of 1917. La. Hist.: J. La. Hist. Assoc. 41 (2), 133–159. ⟨http://www.jstor.org/stable/4233654⟩.
Peipoch, M., Brauns, M., Hauer, F.R., Weitere, M., Valett, H.M., 2015. Ecological simplification: human influences on riverscape complexity. Bioscience 65 (11), 1057–1065. https://doi.org/10.1093/biosci/biv120.
Pielke Jr., R.A., Downton, M.W., 2000. Precipitation and damaging floods: trends in the United States, 1932-97. J. Clim. 13 (20), 3625–3637. https://doi.org/10.1175/1520-0442(2000)0132.0.Co;2.
Pielke Jr., R.A., Downton, M.W., Barnard Miller, J.Z., 2002. Flood Damage in the United States, 1926–2000: A Reanalysis of National Weather Service Estimates. UCAR, Boulder, CO.
Pinter, N., 2005. Environment - One step forward, two steps back on US floodplains. Science 308 (5719), 207–208. https://doi.org/10.1126/science.1108411.
Poff, N.L., Matthews, J.H., 2013. Environmental flows in the Anthropocence: past progress and future prospects. Curr. Opin. Environ. Sustain. 5 (6), 667–675. https://doi.org/10.1016/j.cosust.2013.11.006.
Poff, N.L., Allan, J.D., Bain, M.B., Karr, J.R., Prestegaard, K.L., Richter, B.D., Sparks, R.E., Stromberg, J.C., 1997. The natural flow regime. Bioscience 47 (11), 769–784. https://doi.org/10.2307/1313099.
Remo, J.W.F., Carlson, M., Pinter, N., 2012. Hydraulic and flood-loss modeling of levee, floodplain, and river management strategies, Middle Mississippi River, USA. Nat. Hazards 61 (2), 551–575. https://doi.org/10.1007/s11069-011-9938-x.
Reyers, B., Biggs, R., Cumming, G.S., Elmqvist, T., Hejnowicz, A.P., Polasky, S., 2013. Getting the measure of ecosystem services: a social-ecological approach. Front. Ecol. Environ. 11 (5), 268–273. https://doi.org/10.1890/120144.
Richter, B.D., Thomas, G.A., 2007. Restoring environmental flows by modifying dam operations. Ecol. Soc. 12, 1.
Schultz, M.T., Gouldby, B.P., Simm, J.D., Wibowo, J.L., 2010. Beyond the Factor of Safety: Developing Fragility Curves to Characterize System Reliability. ERDC/GSL SR-10-1. U.S. Army Engineer Research and Development Center. ⟨http://hdl.handle.net/11681/4766⟩.
Seddon, N., Chausson, A., Berry, P., Girardin, C.A.J., Smith, A., Turner, B., 2020a. Understanding the value and limits of nature-based solutions to climate change and other global challenges. Philos. Trans. R. Soc. B-Biol. Sci. 375 (1794) https://doi.org/ARTN 2019012010.1098/rstb.2019.0120.
Seddon, N., Smith, A., Smith, P., Key, I., Chausson, A., Girardin, C., House, J., Srivastava, S., Turner, B., 2021. Getting the message right on nature-based solutions to climate change. Glob. Change Biol. 27 (8), 1518–1546. https://doi.org/10.1111/gcb.15513.
Seddon, N., Daniels, E., Davis, R., Chausson, A., Harris, R., Hou-Jones, X., Huq, S., Kapos, V., Mace, G.M., Rizvi, A.R., Reid, H., Roe, D., Turner, B., Wicander, S., 2020b. Global recognition of the importance of nature-based solutions to the impacts of climate change. Glob. Sustain. 3 https://doi.org/ARTN e1510.1017/sus.2020.8.
Seigerman, C.K., McKay, S.K., Basilio, R., Biesel, S.A., Hallemeier, J., Mansur, A.V., Piercy, C., Rowan, S., Ubiali, B., Yeates, E., Nelson, D.R., 2023. Operationalizing equity for integrated water resources management. JAWRA J. Am. Water Resour. Assoc. 59 (2), 281–298. https://doi.org/10.1111/1752-1688.13086.
Serra-Llobet, A., Tourment, R., Montane, A., Buffin-Belanger, T., 2022b. Managing residual flood risk behind levees: Comparing USA, France, and Quebec (Canada). J. Flood Risk Manag. 15 (2) https://doi.org/10.1111/jfr3.12785.
Serra-Llobet, A., Jahnig, S.C., Geist, J., Kondolf, G.M., Damm, C., Scholz, M., Lund, J., Opperman, J.J., Yarnell, S.M., Pawley, A., Shader, E., Cain, J., Zingraff-Hamed, A., Grantham, T.E., Eisenstein, W., Schmitt, R., 2022a. Restoring rivers and floodplains for habitat and flood risk reduction: experiences in multi-benefit floodplain management from California and Germany. Front. Environ. Sci. 9 https://doi.org/ARTN 77856810.3389/fenvs.2021.778568.
Siders, A.R., 2019. Social justice implications of US managed retreat buyout programs. Clim. Change 152 (2), 239–257. https://doi.org/10.1007/s10584-018-2272-5.
Skevas, T., Massey, R., Hunt, S.L., 2023. Farm impacts of the 2019 Missouri River floods and economic valuation of flood risk reduction. J. Environ. Mgt. 344, 1–9. https://doi.org/10.1016/j.jenvman.2023.118483.
Smith, D.L., Miner, S.P., Theiling, C.H., Behm, R., Nestler, J.M., 2017. Levee setbacks: an innovative, cost-effective, and sustainable solution for improved flood risk management. ERDC/EL SR-17-3. U.S. Army Engineer Research and Development Center. https://doi.org/10.21079/11681/22736.
Sommer, T.R., Harrell, W.C., Nobriga, M.L., 2011. Habitat use and stranding risk of juvenile Chinook salmon on a seasonal floodplain. North Am. J. Fish. Manag. 25 (4), 1493–1504. https://doi.org/10.1577/M04-208.1.
Sommer, T.R., Nobriga, M.L., Harrell, W.C., Batham, W., Kimmerer, W.J., 2001. Floodplain rearing of juvenile chinook salmon: evidence of enhanced growth and survival. Can. J. Fish. Aquat. Sci. 58 (2), 325–333. https://doi.org/10.1139/f00-245.
Stanford, J.A., Lorang, M.S., & Hauer, F.R., 2005. The shifting habitat mosaic of river ecosystems. International Association of Theoretical and Applied Limnology, Vol 29, Pt 1, Proceedings, 29, 123–136. ⟨https://doi.org/10.1080/03680770.2005.11901979⟩.
Stoffels, R.J., Humphries, P., Bond, N.R., Price, A.E., 2022. Fragmentation of lateral connectivity and fish population dynamics in large rivers. Fish Fish. 23 (3), 680–696. https://doi.org/10.1111/faf.12641.
Strange, E.M., Fausch, K.D., Covich, A.P., 1999. Sustaining ecosystem services in human-dominated watersheds: biohydrology and ecosystem processes in the South Platte River Basin. Environ. Manag. 24 (1), 39–54.
Tarlock, D., 2012. United States Flood Control Policy: The Incomplete Transition from the Illusion of Total Protection to Risk Management. Duke Environ. Law Policy Forum 23.
The Nature Conservancy, 2021. Large-Scale Levee Setback Playbook. ⟨https://www.nature.org/en-us/about-us/where-we-work/united-states/missouri/stories-in-missouri/missouri-river-levees/⟩.
The Nature Conservancy. Reconnecting the Missouri River Floodplain. ⟨https://www.nature.org/en-us/about-us/where-we-work/united-states/missouri/stories-in-missouri/missouri-river-levees/⟩ (accessed 22 May 2023).
Theiling, C., Kirkeeng, T., Haring, C., Dahl, T., 2018. Levee Setback Utility for Mission Integration in the Sangamon River Floodplain. ERDC/EL TR-18-12. U.S. Army Engineer Research and Development Center. https://doi.org/10.21079/11681/28984.
Thorp, J.H., Delong, M.D., 1994. The riverine productivity model: an heuristic view of carbon-sources and organic-processing in large river ecosystems. Oikos 70 (2), 305–308.. https://doi.org/10.2307/3545642.
Tilman, D., Isbell, F., Cowles, J.M., 2014. Biodiversity and ecosystem functioning. Annu. Rev. Ecol., Evol., Syst. Vol 45 (45), 471–493. https://doi.org/10.1146/annurev-ecolsys-120213-091917.
Tobin, G.A., 1995. The levee love-affair: a stormy relationship. Water Resour. Bull. 31 (3), 359–367 https://doi.org/DOI 10.1111/j.1752-1688.1995.tb04025.x.
Tockner, K., Stanford, J.A., 2002. Review of riverine flood plains: present state and future trends. Environ. Conserv. 29 (3), 308–330. https://doi.org/10.1017/S037689290200022X.
Tockner, K., Malard, F., Ward, J.V., 2000. An extension of the flood pulse concept. Hydrol. Process. 14 (16–17), 2861–2883 https://doi.org/Doi10.1002/10991085(200011/12)14:16/17<2861::Aid-Hyp124>3.0.Co;2-F.
Tockner, K., Pusch, M., Borchardt, D., Lorang, M.S., 2010. Multiple stressors in coupled river-floodplain ecosystems. Freshw. Biol. 55, 135–151. https://doi.org/10.1111/j.1365-2427.2009.02371.x.
Tubridy, F., Lennon, M., Scott, M., 2022. Managed retreat and coastal climate change adaptation: the environmental justice implications and value of a co-production approach. Land Use Policy 114, 105960. https://doi.org/10.1016/j.landusepol.2021.105960.
Turner, B., Devisscher, T., Chabaneix, N., Woroniecki, S., Messier, C., Seddon, N., 2022. The role of nature-based solutions in supporting social-ecological resilience for climate change adaptation. Annu. Rev. Environ. Resour. 47 (1), 123–148. https://doi.org/10.1146/annurev-environ-012220-010017.
US Army Corps of Engineers, 2018a. Yakima River Gap to Gap Ecosystem Restoration Project, Yakima County, Washington. ⟨https://www.yakimacounty.us/DocumentCenter/View/32464/v2FONSI-and-DPR-EA_Sec_1135_Yakima_River_Gap-to-Gap⟩.
US Army Corps of Engineers, 2018b. Levee Portfolio Report: A Summary of Risks and Benefits Associated with the USACE Levee Portfolio.
US Army Corps of Engineers. National Levee Database. ⟨https://levees.sec.usace.army.mil/#/⟩ (accessed 18 May 2023).
US Army Corps of Engineers, 2012. Assessment of conceptual nonstructural alternative levee setbacks along the Missouri River (Lower L-575 / Upper L-550 and Lower L-550). ⟨https://protectthemissouri.files.wordpress.com/2010/10/conceptual_levee_setbacks_final_report-2.pdf⟩.
US Army Corps of Engineers, 2020. Geotechnical system response curves for risk assessment. (ETL 1110–2-588). ⟨https://www.hec.usace.army.mil/confluence/fdadocs/fdatutorials/files/54657657/86903513/1/1644454279559/ETL+1110-2-588.pdf⟩.
US Geological Survey. The National Map. ⟨https://www.usgs.gov/tools/national-map-viewer⟩ (accessed 18 May 2023).

US Government Accountability Office, 2011. Mississippi River, Actions are needed to help resolve environmental and flooding concerns about the use of river training structures (USGAO-12–41).

van Rees, C.B., Jumani, S., Abera, L., Rack, L., McKay, S.K., Wenger, S.J., 2023. The potential for nature-based solutions to combat the freshwater biodiversity crisis. PLoS Water 2 (6), e0000126. https://doi.org/10.1371/journal.pwat.0000126.

Vox and ProPublica. How "Levee Wars" are making floods worse. ⟨https://www.propublica.org/video/how-levee-wars-are-making-floods-worse⟩ (accessed 22 May 2023).

Wang, H., 2021. Flood your neighbors: Spillover effects of levee building. In the Proceedings of the 95th Annual Conference of the Agricultural Economics Society, March 29–30, Warwick, UK.

Ward, J.V., 1998. Riverine landscapes: biodiversity patterns, disturbance regimes, and aquatic conservation. Biol. Conserv. 83 (3), 269–278. https://doi.org/10.1016/S00063207(97)00083-9.

Ward, J.V., Tockner, K., Schiemer, F., 1999. Biodiversity of floodplain river ecosystems: ecotones and connectivity. Regul. Rivers-Res. Manag. 15 (1–3), 125–139. https://doi.org/10.1002/(Sici)1099-1646(199901/06)15:1/33.0.Co;2-E.

Weisbrod, B., 1968. Income redistribution effects and benefit-cost analysis.

Windhoffer, E., Hughes, S., Hughes, T., Grismore, A., Littman, A., Haertling, A., Fischbach, J.R., 2022. Consideration of Nature-Based Solutions in USACE Planning Studies. The Water Institute of the Gulf. Funded by the U.S. Army Corps of Engineers Engineer Research and Development Center,, Vicksburg, MS. ⟨https://thewaterinstitute.org/assets/docs/projects/Consideration-of-Nature-Based-Solutions-in-USACE-Planning-Studies.pdf⟩.

Wohl, E., 2021. An integrative conceptualization of floodplain storage. Rev. Geophys. 59 (2) https://doi.org/ARTN e2020RG00072410.1029/2020RG000724.

Wohl, E., Bledsoe, B.P., Jacobson, R.B., Poff, N.L., Rathburn, S.L., Walters, D.M., Wilcox, A.C., 2015. The natural sediment regime in rivers: broadening the foundation for ecosystem management. Bioscience 65 (4), 358–371. https://doi.org/10.1093/biosci/biv002.

Wohl, E., Kramer, N., Ruiz-Villanueva, V., Scott, D.N., Comiti, F., Gurnell, A.M., Piegay, H., Lininger, K.B., Jaeger, K.L., Walters, D.M., Fausch, K.D., 2019. The natural wood regime in rivers. Bioscience 69 (4), 259–273. https://doi.org/10.1093/biosci/biz013.

Woroniecki, S., Spiegelenberg, F.A., Chausson, A., Turner, B., Key, I., Md, Irfanullah, H., Seddon, N., 2022. Contributions of nature-based solutions to reducing people's vulnerabilities to climate change across the rural Global South. Clim. Dev. 1–18. https://doi.org/10.1080/17565529.2022.2129954.

Yarnell, S.M., Petts, G.E., Schmidt, J.C., Whipple, A.A., Beller, E.E., Dahm, C.N., Goodwin, P., Viers, J.H., 2015. Functional flows in modified riverscapes: hydrographs, habitats and opportunities. Bioscience 65 (10), 963–972. https://doi.org/10.1093/biosci/biv102.

Yen, B.C. (1995, November). Hydraulics and effectiveness of levees for flood control. In the Proceedings of US-Italy Research Workshop on the Hydrometeorology, Impacts, and Management of Extreme Floods, Perugia, Italy.

Zellmer, S., Klein, C., 2007. Mississippi river stories: lessons from a century of unnatural disasters. college of law. Fac. Publ. 12. ⟨https://digitalcommons.unl.edu/lawfacpub/12⟩.

Zhu, T.J., Lund, J.R., 2009. Up or out? Economic-engineering theory of flood levee height and setback. J. Water Resour. Plan. Manag. 135 (2), 90–95. https://doi.org/10.1061/(Asce)0733-9496(2009)135:2(90).

Zhu, T.J., Lund, J.R., Jenkins, M.W., Marques, G.F., Ritzema, R.S., 2007. Climate change, urbanization, and optimal long-term floodplain protection. Water Resour. Res. 43 (6) https://doi.org/ArtnW0642110.1029/2004wr003516.