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Review

Levees don't protect, they disconnect: A critical review of how artificial levees impact floodplain functions

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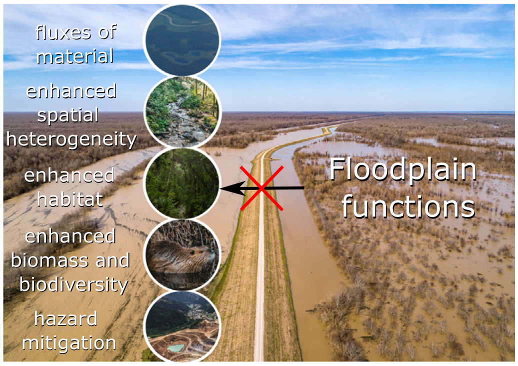
HIGHLIGHTS

- Artificial levees protect infrastructure but disconnect floodplains from channels.
- Levees compromise floodplain functions such as fluxes and biodiversity.
- Restoration case studies on floodplains highlight the impacts of artificial levees.
- Documented floodplain restoration is concentrated in North America and Europe.
- Upstream flow regulation severely limits restoration effectiveness.

GRAPHICAL ABSTRACT



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ABSTRACT

Despite the recognition of floodplain importance in the scientific community, floodplains are not afforded the same legal protection as river channels. In the United States alone, flood-related economic losses were much higher in the second half of the 20th century than the first half despite the expenditure of billions of dollars on flood defenses. Partially to blame are the low appraisal and understanding of human impacts to floodplain functions. Here, we explore the impacts of levees on floodplain functions and analyze case studies of floodplain restoration through levee removal. Floodplain functions include (1) fluxes of water, solutes, and particulate materials; (2) enhanced spatial heterogeneity of hydrology and biogeochemistry; (3) enhanced habitat abundance and diversity; (4) enhanced biomass and biodiversity; and (5) hazard mitigation. Case studies of floodplain restoration involving artificial levee adjustment are heavily concentrated in North America, Europe, and Japan, and those case studies assess floodplain functions within 30 years of restoration. In the United States, restoration through levee removal comprises less than 1% of artificial levee length and 1–2% of disconnected floodplains. In Europe, restoration effectiveness was severely limited by upstream flow regulation. Most case studies were impacted by stressors outside the study site and took place in lowland alluvial rivers. Reconfiguration was successful at achieving limited aims while reconnection set floodplains on a trajectory to more fully restore floodplain functions. Case studies illustrated the tension between restoration scale and study resolution in time and space as well as the role of site-specific characteristics in determining restoration outcomes. Numerous knowledge gaps surrounding the integrative relationships between floodplain functions must be addressed in future studies. The ubiquity of flow regulation demands that future floodplain restoration occur in a whole-of-basin manner. Monitoring of restoration must take place for longer periods of time and include multiple functions.

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Contents

1. Introduction

Floodplains are recognized by river scientists as a critical component of river ecosystems. Conceptual models emphasizing the role of floodplains include the flood pulse concept (Junk et al., 1989), riverine productivity model (Thorp and Delong, 1994), shifting habitat mosaic (Tockner et al., 2010), and the river wave concept (Humphries et al., 2014). Nevertheless, floodplains are not afforded the same legal protection as active channels (e.g., US Clean Water Act, EU Water Framework Directive) despite a long history of human alteration of floodplain forms and processes. Predictable flood pulses on large rivers in Egypt and Mesopotamia led to the development of some of the world's first complex societies (Butzer, 1976; Sparks, 1995), and subsequent cultures focused development on floodplains and learned to exploit floodplain functions (Tockner and Stanford, 2002). Collectively, human activities have resulted in simplified floodplains with substantially reduced functions along many rivers (Peipoch et al., 2015).

Despite a policy of minimizing flood losses during the 20th century (White, 2000), the United States (U.S.) experienced 2.5 times the economic losses ($3 billion annual flood losses) in the second half of the century after the expenditure of billions of dollars on flood protection projects (Tobin, 1995). An estimated 98% of the 5.3 million km of U.S. rivers are impacted by human activities (Graf, 2001). Some components of these activities, such as flow regulation, have been documented nationally and globally (e.g., Graf, 1999; Lehner et al., 2011; Grill et al., 2019), as have the impacts of roads and railroads (e.g., Blanton and Marcus, 2009). One key component of modern floodplain management is the construction of artificial levees (Hudson et al., 2008). However, the national or global impacts of artificial levees have not been evaluated until recently (Knox et al., 2022a, 2022b), mainly because of incomplete databases of artificial levees.

Natural fluvial levees are long, ribbon-like bodies of sediment deposited at river channel-floodplain margins when floodwaters lose competence (Brierley et al., 1997), whereas artificial levees are human-made linear features constructed between channels and floodplains to contain peak flows in the channel (Tobin, 1995). We define the floodplain as a frequently flooded, low-relief landform created by erosional and depositional processes under the contemporary hydrologic regime (Dunne and Aalto, 2013). In previous work, we identified over 182,000 km of undocumented artificial levees in the contiguous U.S. and determined that the overall effect of artificial levees on flooding was to shift the location of inundation (Knox et al., 2022a, 2022b). We also determined that over 30% of the contiguous U.S. 100-year floodplain was either cultivated or developed land cover. This prior work emphasized the problematic effects of artificial levees at a national scale rather than local scales, which has been the focus of most studies assessing the impacts of levees.

Local and regional studies have found that artificial levees shift the location of flooding by increasing stage upstream from levees and increasing downstream conveyance (Tobin, 1995; Criss and Shock, 2001; Heine and Pinter, 2012; Czech et al., 2016; Knox et al., 2022b). This can lead to increased channel velocities, bed coarsening, and incision (Frings et al., 2009). Levees also limit lateral connectivity and the exchange of nutrients, sediment, and organisms between the channel and floodplain, resulting in significant ecological harm (Blanton and Marcus, 2009; Sparks et al., 2017; Wohl, 2018). The presence of artificial levees encourages human development of floodplains and increases the vulnerability of populations and infrastructure to flood damage (White et al., 2001; Pinter, 2005).

The loss of floodplain functions resulting from artificial levee installation is seldom considered when calculating economic losses from flooding (Opperman et al., 2009; Jacobson et al., 2015). That accounting requires a better understanding of floodplain functions, which is a non-trivial pursuit given floodplain ecosystem complexity and floodplain connection to the atmosphere, channels, and uplands (Gren et al., 1995). Although there are a myriad of floodplain functions, we group them into the following major categories (Fig. 1):

(i) fluxes of water, solutes, and particulate materials;
(ii) enhanced spatial heterogeneity of hydrology and biogeochemistry processes;
(iii) enhanced habitat abundance and diversity;
(iv) enhanced biomass and biodiversity; and
(v) hazard mitigation.

The restoration of floodplains is an ongoing research activity at the leading edge of applied hydrologic science (Wohl et al., 2005). We broadly define the term restoration as any including diverse alterations designed to improve the hydrologic, geomorphic, and/or ecologic processes and replace missing elements of the river system (Wohl et al., 2015). Most river restoration in the U.S. is very small scale (individual projects impact river reaches less than 1 km long) and lacks documentation of effectiveness (Bernhardt et al., 2005). And, given the integrative nature of floodplain functions, it is problematic that most river and floodplain restoration projects are aimed at single benefits (Serra-Llobet et al., 2022). However, there is some evidence that reconnection of rivers and floodplains is more effective than artificial reconfiguration (Bernhardt and Palmer, 2011). Because floodplains exist at a key socio-economic-ecologic nexus, a transdisciplinary approach for management is needed that incorporates different types of knowledge with the goal of benefiting humans and floodplain ecology (Auerswald et al., 2019). Our aim is to demonstrate the irreplaceable value of floodplain functions to humans, while emphasizing the importance of a transdisciplinary approach to understanding and managing floodplains.

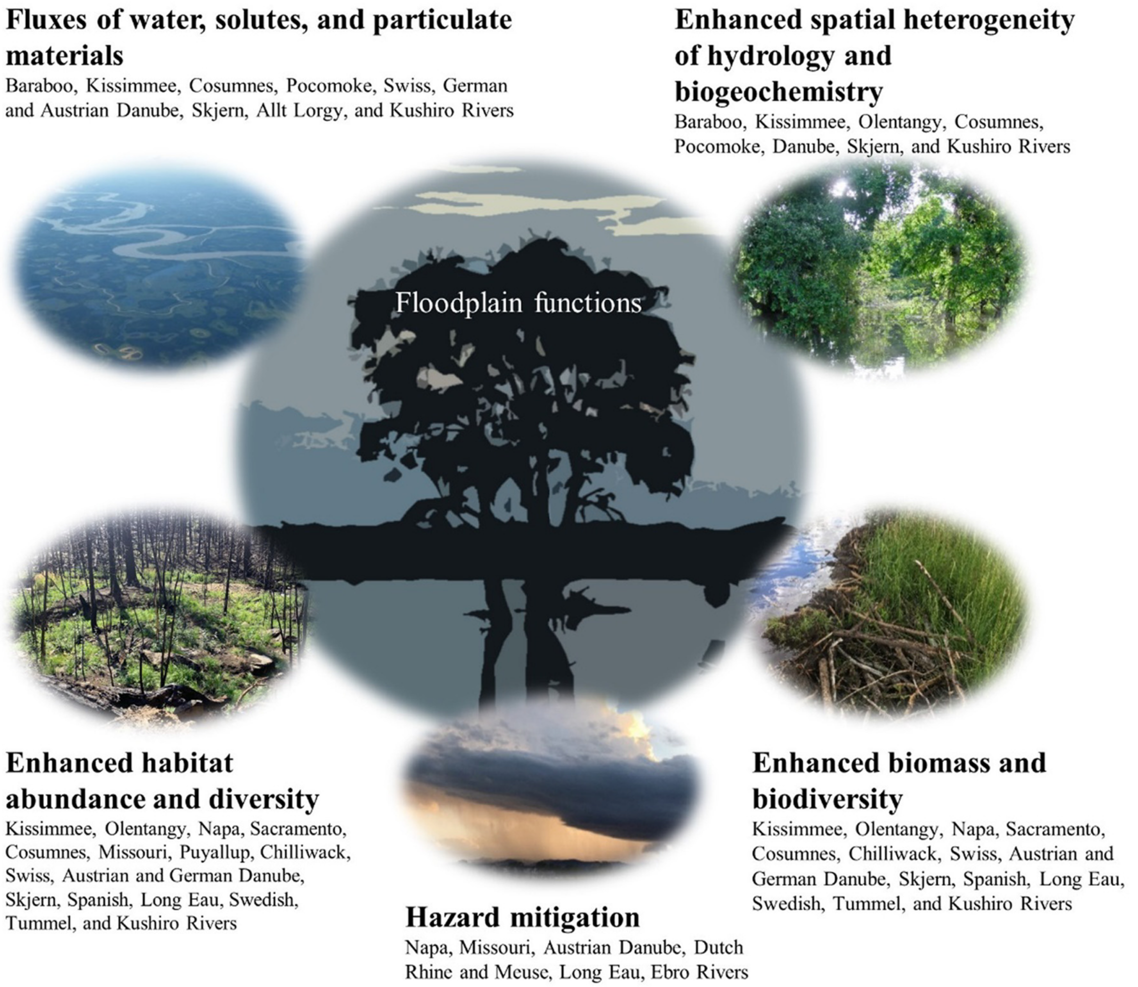

Fig. 1. Floodplain functions and selected rivers with case studies (Tables 1 and 2) analyzing the impacts of restoration impacting that function.

In contrast to the small scale of restoration (e.g., Bernhardt et al., 2005), restoration should be attempted at the watershed scale (Wohl et al., 2005) because alterations such as artificial levees are usually paired with engineering (e.g., dams and reservoirs) that regulates water and sediment discharge (Auerswald et al., 2019). Because of this and the demand for hydropower (Kuriqi et al., 2019), the restoration of environmental flows related to the natural flow regime and the ecological functioning of the riverine system is increasingly considered during restoration (Geist and Hawkins, 2016). Despite the assertion that the principal barriers to floodplain restoration are not technical, each portion of river and each watershed to be restored include unique characteristics and each restoration project has specific designs and limitations (Serra-Llobet et al., 2022), so that universally applicable approaches to achieve desired outcomes in restoration remain unknown (Geist and Hawkins, 2016).

The objectives of this study are to:

(i) define floodplain functions in a thorough, integrative manner and identify knowledge gaps;
(ii) identify how artificial levees impact floodplain functions; and
(iii) review case studies of floodplain restoration involving the alteration of artificial levees and identify lessons learned.

Our previous work illustrated the effects of more than 228,000 km of artificial levees (almost enough levees to wrap around Earth six times) on floodplain extent in the U.S. (Knox et al., 2022a, 2022b). If the cumulative effects of artificial levees are anything close to those documented for dams (which store a year's worth of runoff in the U.S. (Graf, 1999)), then the consequences are of massive ecological significance. To grasp this significance, we present floodplain functions in an integrative, in-depth manner, rather than the common approach that both separates closely linked physical, chemical, and biological processes (Wohl, 2021) and presents floodplain functions in a simplified, cursory fashion. The high degree of floodplain functions' interdependence (discussed in the next section) magnifies the damaging impacts of artificial levees. The urgency to understand floodplain functions from an integrative perspective is that much more acute given the role of artificial levees as just one of many stressors that impact over 98% of river kilometers in the U.S. (Graf, 2001). Given that, we wanted to assess the role of floodplain restoration involving artificial levee removal or alteration to understand how this damage can be ameliorated.

The novelty of this study stems from the combination of our approach and objectives. Floodplain functions and services are more likely to be considered within disciplinary boundaries rather than in an integrative fashion. We suspect that the preponderance of unsuccessful restoration outcomes (Bernhardt and Palmer, 2011) and the need to "learn restoration by doing" (e.g., Serra-Llobet et al., 2022) reflect gaps in the basic scientific knowledge that informs attempts to quantify and predict floodplain functions. Far from having close to perfect knowledge of the science of floodplains, restoration and management can be prone to ignore or minimize existing knowledge gaps. We begin to ameliorate these issues by synthesizing research that addresses floodplain functions. We also bring together a thorough review of case studies of floodplain restoration involving levee adjustment so that we can start to answer the question of how to repair the damage to floodplain functions caused by artificial levees.

Here, we identify floodplain functions and, for each function, review relevant literature, discuss the impacts of artificial levees, and identify knowledge gaps (Section 2). We identify case studies of restoration involving the adjustment of artificial levees from North America, Europe, and Japan to identify what is working and to situate this type of restoration in the wider literature (Section 3). In the conclusion, we emphasize our findings and suggest ideas for future work (Section 4). We draw on this review to support the contention that artificial levees do not just protect human infrastructure, they also disconnect a vitally important component of the landscape that is of great value to humans and the environment.

2. Importance of floodplain functions and impacts of levees

The importance of floodplain functions to ecological and human wellbeing is multifaceted and has been documented in the scientific literature for the past half century. We briefly highlight the current knowledge and knowledge gaps of floodplain functions, how artificial levees impact floodplain functions, and their importance below (Fig. 2).

2.1. Material fluxes

Non-living material stored on floodplains includes water, solutes, sediment, particulate organic matter (>0.45 μm in diameter), and large wood (≥10 cm diameter and 1 m length) (Wohl, 2021). Inundation hydrology describes the many sources of surface and subsurface water present in floodplains including groundwater, tributaries, overbank flow, overland flow from adjacent uplands, and precipitation (Mertes, 2000). Solutes stored on floodplains include dissolved forms of nitrogen (Noe et al., 2013), phosphorus (Records et al., 2016), and organic matter (Cuffney, 1988) present in surface and subsurface waters. Sediment is stored in floodplain features through vertical accretion from overbank flows, lateral accretion and channel-fill deposits from channel migration and avulsion, and colluvial and eolian deposits (Allen, 1965; Meade and Moody, 2010). Particulate organic matter such as leaf litter is heavily influenced by the type of riparian vegetation and the season (Tank et al., 2010) and can enter floodplains from channels, adjacent uplands (transport by wind, overland flow, and tributaries), and direct litterfall from floodplain vegetation. Reduced by orders of magnitude by human influence in many river systems, dead biomass in the form of large wood creates physical and ecological functions on floodplains (Wohl et al., 2019). Large wood can also enter floodplains from adjacent uplands, overbank flow from channels, or direct recruitment from floodplain forests (Wohl, 2020).

The most widespread human alteration to floodplains is disconnection from stream flow, which alters the volume and duration of storage of all materials by severing transport onto the floodplain from the channel; altering surface and subsurface water storage in the floodplains and associated biogeochemical processes and decay; or reducing floodplain erosion and deposition (Wohl, 2021). Although artificial levee installation is one of several ways to disconnect streams and floodplains, artificial levees can also drastically change floodplain storage through several mechanisms leading to terrestrialisation (Tena et al., 2020). In terms of water storage, the degree to which disconnected floodplains become like the adjacent uplands is dependent on other water inputs from tributaries and precipitation (e.g. Park and Latrubesse, 2017), groundwater inflow (e.g. Burt, 1996), and subsurface

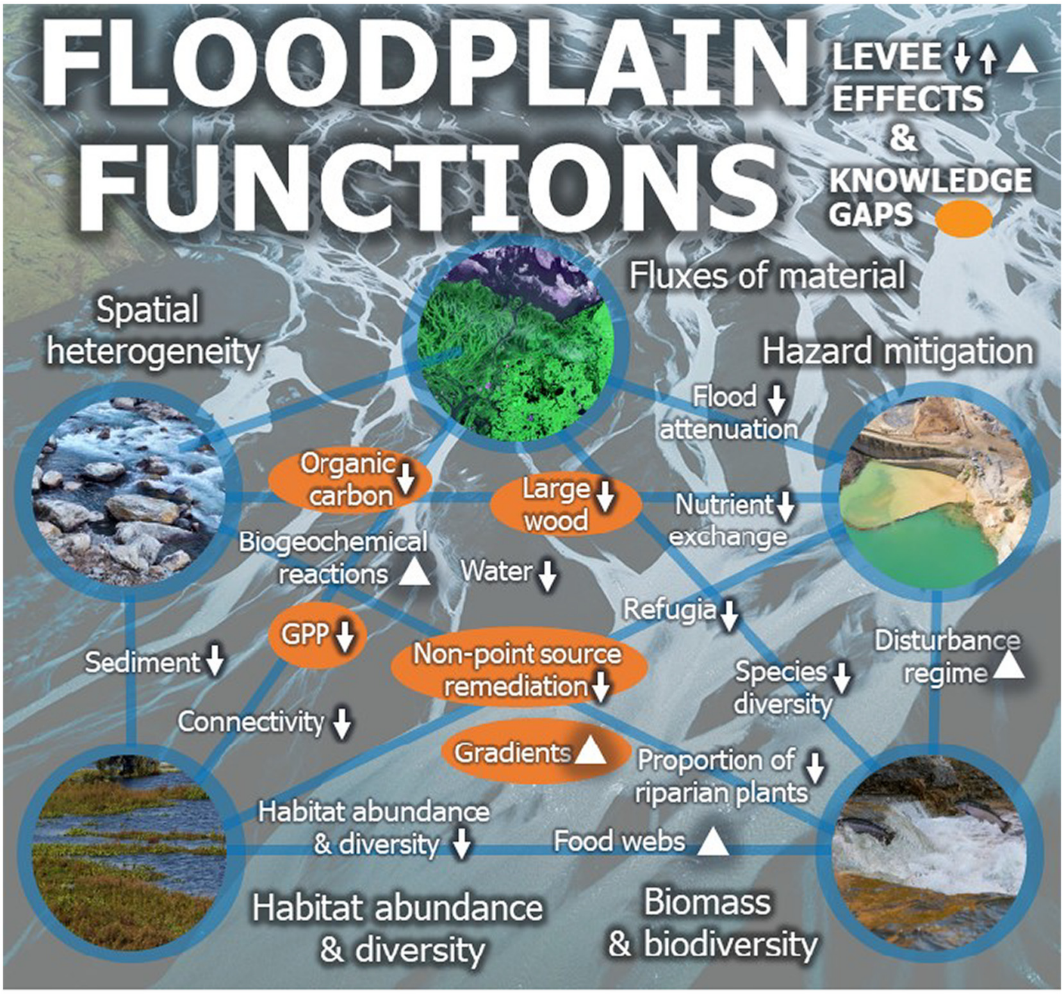

Fig. 2. Artificial levee effects and knowledge gaps for floodplain functions. Effects are indicated by up or down arrows or a triangle to indicate change. Large knowledge gaps are emphasized by the orange bubbles.

connection to the channel (e.g. Kupfer et al., 2015). Although the elimination of overbank flooding and lateral migration can decrease water and sediment storage, within-channel fluctuations in discharge can still influence low-lying floodplain areas such as secondary channels and floodplain wetlands (Tockner et al., 2000; Hudson et al., 2012; Lininger and Latrubesse, 2016). Additionally, reduced lateral channel movement and reworking of floodplain sediments associated with artificial levee installation and bank stabilization may increase storage of particulate organic matter in some cases (e.g. Sutfin et al., 2021). Levees may be much less influential for organic carbon storage in riparian forests compared to the degree of forestation and groundwater fluctuations (Rieger et al., 2014).

Floodplain storage contributions to base flow in un-altered tropical streams (e.g. Lininger and Latrubesse, 2016) indicate the potential impacts to river systems from disruptive interventions, such as levees. Artificial levees reduce dissolved and particulate carbon, nitrogen, and phosphorus input from channels to floodplains (Noe and Hupp, 2005). Artificial levees can decrease floodplain sedimentation to 0 mm/yr, with accidental breaches providing the only sediment supply in the form of sand-splays (Florsheim and Mount, 2002; Florsheim and Mount, 2003). Sediment storage loss can occur during levee breaches when simultaneous sand splays and scour reposition sediment covering more than hundreds of thousands of hectares on large rivers, resulting in anthro-geomorphic pond features called “wielen” in Dutch (Galat et al., 1998; Hudson et al., 2008).

Even though artificial levee installation impedes the influence of overbank flow on floodplain storage, the results can be far reaching due to secondary effects such as terrestrialisation and organism extinction; the interconnectedness of floodplains with the atmosphere, channel, and uplands; and other human activities common on floodplains with levees, such as land cover changes. In the contiguous U.S., artificial levees are most associated with land cover changes to cultivated land covers (Rajib et al., 2021; Knox et al., 2022b). The installation of agricultural drain tiles can result in sediment compaction, reduced recharge to floodplain aquifers, and loss of storage through increased drainage (Blann et al., 2009). The link between hydrologic connectivity and spatial diversity of geomorphic units (Hudson and Colditz, 2003; Hudson et al., 2012; Park and Latrubesse, 2017) indicates that floodplain simplification brought about from levee construction can lead to storage alteration. Conversion to agricultural activities can increase nitrate storage because of application of artificial fertilizers (Wang et al., 2013). Phosphorus will follow a similar trend given the agricultural sources of phosphorus and the role of floodplains as a phosphorus sink (Sharpley et al., 2013). Complex organic carbon dynamics rely on many different factors (Sutfin et al., 2016), with different case studies illustrating the varying impacts of levees, degree of forestation, and groundwater fluctuations on carbon storage (Hanberry et al., 2015; Wohl et al., 2017a).

Knowledge gaps related to floodplain storage are summarized in Wohl et al. (2021) and include floodplain delineation, characterization of relevant aspects of floodplains that affect storage (e.g., stratigraphy), the difficulty of three-dimensional modeling, and understanding the integrative response of floodplain functions to drivers of change. Knowledge gaps for storage of organic carbon and large wood on floodplains stem from limited geographic diversity in the location of existing studies, as well as limited understanding of the impacts of climate change on storage, and of typical residence times (Sutfin et al., 2016; Wohl, 2017). The lack of understanding of human influences and increased conveyance on phosphorus storage in rivers and floodplains stems from the absence of those aspects in conceptual models of phosphorus dynamics (Records et al., 2016).

2.2. Enhanced spatial heterogeneity of hydrology and biogeochemistry

Floodplains are landforms in which the mixing of waters with different sources leads to increased biogeochemical reactions (Harvey and Gooseff, 2015). Considered ecosystem control points, floodplains host important biogeochemical processes that greatly impact ecosystem dynamics (Appling et al., 2014; Bernhardt et al., 2017). Water is the medium that transports energy, solutes, and particulates between hillslopes, floodplains, channels, and other areas (Covino, 2017) and is considered the master driver of floodplain structure and functions (Wohl, 2021). Variations in the spatial mixing of surface waters in the perirheic zone can strongly influence floodplain geomorphology, biogeochemical reactions, and habitat (Mertes, 1997). Productivity is related to the juxtaposition of heterogeneous flow paths and microbial activity (Dwivedi et al., 2018). Floodplains are commonly depositional, low-energy locations with high primary productivity where large amounts of organic matter mix with reactive nitrogen and phosphorus (Noe, 2013). When not inhibited by artificial levees, this productivity often coincides with flood pulses (Tomasek et al., 2019).

Repeated flooding and associated recycling of organic matter and nutrients is the principal driver of productivity in a river-floodplain system (Junk et al., 1989). Flood pulses enable the creation of a stream-soil interface on floodplains where numerous biogeochemical reactions occur due to the abundance of electron donors and acceptors (Hedin et al., 1998). The specific type of floodplain inundation highly affects biogeochemical processing by altering the relationships between vegetation, microbial activity, and chemical reactions (Baldwin and Mitchell, 2000). Inundation dynamics impact nutrient decomposition and mineralization rates (Brinson et al., 1981) as well as translocation of nitrogen and phosphorus within floodplain vegetation (Clawson et al., 2001). Phosphorus dynamics are complex and involve the interplay between soil, hydrologic conditions, and climate (Records et al., 2016). Phosphorus processes include biological assimilation, sorption to sediment, and precipitation reactions of inorganic salts (House, 2003). Soil nutrient mineralization rates of nitrogen and phosphorus are enhanced by greater inputs of sediment and water to floodplains (Noe et al., 2013).

Artificial levees lead to decreased nutrient exchange between floodplains and rivers (Jenkins and Boulton, 2003). Disconnection of floodplains leading to terrestrialisation completely changes the floodplain inundation hydrology, significantly impacting biogeochemical reactions (Sanchez-Pérez and Trémolières, 2003). Decreased sediment storage on disconnected floodplains impacts biogeochemical reactions involving the sorption of phosphorus to sediment (Darke et al., 1996). Disconnection can also lead to a large decrease in organic matter delivery and production on floodplains, thus impacting multiple biogeochemical reactions and food webs (Heiler et al., 1995).

Knowledge gaps for hyporheic exchange flows and associated biogeochemical dynamics include the inability to apply knowledge acquired at specific spatial scales to other scales and the inability to avoid bias inherent in individual techniques (Harvey and Gooseff, 2015). There are few studies or numerical models that allow either the scaling or aggregation of biogeochemical processes in floodplains (Bernhardt et al., 2017; Dwivedi et al., 2018). Similarly, the influence of lateral and longitudinal gradient interactions on biogeochemical processes in floodplains is poorly understood (Noe et al., 2013). Additionally, there is a lack of information on how biogeochemical properties vary by depth and how to predict depth variations based on surface measurements (Appling et al., 2014).

2.3. Enhanced habitat abundance and diversity

Floodplain habitat diversity derives from different patterns of hydrologic, solute, and sediment connectivity interacting over spatially heterogeneous landscapes (Bayley, 1995). Junk et al. (1989) emphasized the seasonal flood pulse as a primary driver of these dynamic interactions. Applying the process domain concept (Montgomery, 1999) in this context, floodplains are the dynamic canvas on which flooding provides a natural and biologically advantageous spatial and temporal habitat disturbance (Junk et al., 1989; Tockner and Ward, 1999; Arscott et al., 2002) and sufficient space to accommodate diverse habitats (Bellmore and Baxter, 2014).

Disturbance can be considered a physical force or process that stresses an ecological system relative to its reference state (Rykiel, 1985) and can be of natural (e.g. flood, wildfire, drought) or anthropogenic origin (Magoulick and Kobza, 2003). Anthropogenic disturbances alter the floodplain physical landscape so that fundamental geomorphic thresholds are broken, making floodplains less resilient to future disturbance

(Brierley et al., 2005; Karpack et al., 2020). We define resilience as the degree to which a system can persist by absorbing disturbance and maintaining similar relationships between populations and driving variables (Holling, 1973). In floodplains, resilience derives from the pathways by which hydrobiogeomorphic complexity and nested feedback loops can absorb disturbance and maintain equilibrium (Wohl et al., 2021). Fully functioning floodplains possess multiple process domains and diverse biota that facilitate small adjustments to hydrologic, geologic, biologic, or anthropogenic disturbances (Castro and Thorne, 2019). Biogeochemical cycling of nutrients provides several dynamic feedback loops that mediate ecological and hydrogeomorphic disturbance across multiple temporal and spatial scales (Atkinson et al., 2018).

The spatiotemporal heterogeneity and connectivity of floodplains enhance not only floodplain resilience but the resilience of the entire basin (McCluney et al., 2014; Wohl et al., 2022). In the same sense, fully functioning floodplains can be considered as river beads, which are spatially heterogeneous locations within the river network whose ability to store water and organic material, facilitate biogeochemical reactions, and enhance biodiversity lead to greater resilience in the entire network (Hauer et al., 2016; Wohl et al., 2018). River beads were originally described for mountain stream networks in which river segments with floodplains alternate downstream with laterally constrained segments with little to no floodplain development (Stanford et al., 1996). Along lowland rivers with laterally extensive and longitudinally continuous floodplains, the entire length of the river corridor acts as a bead. Resilience is enhanced by hierarchically organized physical, chemical, and biological processes operating across overlapping habitat scales (Beechie et al., 2010). Contextualizing floodplains within the watershed and emphasizing connection as far as the ocean (Mitsch et al., 2001; Wohl and Iskin, 2021) indicates the potential role floodplains can play in resilience.

Artificial levees ultimately decrease floodplain habitat diversity and complexity through the elimination of hydrobiogeomorphic pathways and feedback loops by which floodplains can respond to disturbance. This begins with the reduction of water and sediment resulting from disconnection from stream flow. Levees disrupt the flood pulse that is the driving force of floodplain productivity. This disruption leads to the elimination of numerous biogeochemical pathways by which the floodplain can respond to disturbance. Cascading effects within food webs ensure the subsequent elimination of numerous biota that can no longer contribute to floodplain functions. The end state of artificial levee impacts to floodplains is a spatially and temporally homogenized floodplain with reduced biogeochemical activity that has minimal ability to absorb disturbance (Poff et al., 2007; McCluney et al., 2014; Wohl et al., 2017b; Bouska et al., 2019).

Existing research clearly indicates that hydrologically connected floodplains enhance habitat abundance and diversity. However, the ability to predict how the changes associated with hydrologic disconnection (e.g., altered dynamics of organic matter, solutes, and sediment) influence biogeochemical and physical habitat configuration remains limited by lack of integrative field measurements and numerical models. More research is also needed to determine the role of habitat patches at different scales in floodplain ecosystems, as most research has instead emphasized gradients (Bellmore and Baxter, 2014).

2.4. Enhanced biomass and biodiversity

The documented high biomass and high biodiversity of floodplains (Naiman et al., 1993) result at least in part from habitat diversity. High biodiversity in floodplains is based on organic matter productivity and food webs for numerous fish and other organisms (Opperman et al., 2017). Floodplains provide the habitat availability and connectivity needed for fish at different times in their life cycles (Schiemer, 2000). Floodplains can contain a great diversity of aquatic invertebrates and greater community respiration because of microbial activity (Bellmore and Baxter, 2014). The role of microbial communities in biogeochemical reactions in floodplain soils are directly impacted by hydrologic connectivity and organic matter availability (Argiroff et al., 2017). Organic carbon stocks strongly predict bacterial production (Cole et al., 1988), whereas hydrologic connectivity exerts an equally important control on bacterial community composition and the degree of enzymatic activity (Mayr et al., 2020). The key control on denitrification rates are microbial processes dictated by nitrate and oxygen concentrations (Bernhardt et al., 2017). Microbial activity and different conditions imposed by hydrologic connectivity are two factors that influence mineralization of nitrogen and phosphorus, a key bottleneck geochemical process (Noe et al., 2013).

Connectivity between channels and floodplains enlarges habitats and biological productivity (Jenkins and Boulton, 2003). Amoros and Bornette (2002) emphasize the importance of connectivity operating at different spatial and temporal scales. They recognize four major habitat components (water temperature, suspended solids/turbidity, nutrient content, and substrata composition) that heavily influence biodiversity operating across the scales of a hydrologically connected floodplain and individual waterbodies. Amoros and Bornette (2002) describe a different set of processes occurring across the two spatial scales at two different time scales. The flood pulse drives different amounts of connectivity on monthly to yearly time scales, influencing productivity, nutrient exchange, biogeochemical processing, and the exchange of organisms whose life cycles are dependent on varying environmental conditions. This mosaic of patterns can result in antagonistic processes whereby complex responses drive gradients in different directions at varying times and locations (Amoros and Bornette, 1999). Examples of these processes, such as ecological succession, lateral channel migration, and river bed incision, enhance biodiversity at decadal and longer time scales by balancing the trend towards terrestrialisation with the formation and rejuvenation of water bodies (Ward and Stanford, 1995; Amoros and Bornette, 2002).

Biogeomorphic agents lend functional floodplains a self-healing capacity (Johnson et al., 2020). Riparian vegetation acts as a buffer between floodplains and streams and helps to trap and store particulate matter and facilitate biogeochemical uptake of solutes (Schlesinger et al., 1996). Riparian vegetation and large wood mediate disturbance events by providing localized resistance (Brooks and Brierley, 2002). Wetlands in functional floodplain lakes exhibit greater resilience to drought (Shi et al., 2017). Beaver (*Castor* spp.) increase resilience to drought and wildfire (Hood and Bayley, 2008; Fairfax and Whittle, 2020) through the creation of spatially and environmentally complex beaver meadows (Westbrook et al., 2011).

Artificial levee installation disrupts the flood pulse that is the driving force for productivity in formerly connected channels and floodplains. This disruption alters the disturbance regime around which most floodplain processes are based. Levees disrupt every aspect of biologically complex floodplains as conceived by Amoros and Bornette (2002). Levees decrease hydrologic connectivity important at the floodplain scale and can alter the individual waterbody through terrestrialisation. Temporally, levees and other engineering disturbances homogenize the natural rhythm of flood pulses (Moyle and Mount, 2007; Poff et al., 2007). At larger temporal scales, artificial levees and associated engineering works, such as bank stabilization and dams, either freeze floodplain processes (e.g., channel migration) or completely alter processes (e.g., ecological succession and incision). Artificial levees decrease edge habitat and ecosystem diversity (Florsheim and Mount, 2003). Reviews of floodplain habitat restoration efforts indicate the deleterious effect of artificial levees on species diversity (Roni et al., 2019). The terrestrial and disconnecting effects of artificial levees are especially deleterious to floodplains because floodplain foodwebs are based on allochthonous and autochthonous carbon sources (Opperman et al., 2017). The role that connectivity plays in the bottleneck processes of N and P mineralization indicates another fundamental way that levees alter floodplain ecosystems.

As noted in the previous section, the lack of integrative field data and numerical models limits the ability to quantify and predict how hydrologic disconnection affects processes that sustain biomass and biodiversity, including the availability of nutrients and habitat. Little is understood, for example, about the impacts of floodplain connectivity on soil micro-organisms and their associated biogeochemical reactions (Argiroff et al., 2017). This is particularly important to understand anthropogenic influences on floodplains

(Mayr et al., 2020). The relative importance of transport versus emergence for macroinvertebrate colonization is also poorly understood for floodplain wetlands connected to dryland rivers (Jenkins and Boulton, 2003).

2.5. Hazard mitigation

Fully functional floodplains offer mitigation against a wide range of natural and anthropogenic hazards (Sheaffer et al., 2002). They store flood water and attenuate peak flows (Woltemade and Potter, 1994; Škute et al., 2008; Lininger and Latrubesse, 2016), as demonstrated by numerous case studies. For example, extensive interventions along the Netherlands' portion of the Rhine River reduced the 1 in 1250 year flood levels by 0.3 m (Klijn et al., 2018). Large floodplain areas (> 200 km^2) along the Latvian Daugava River reduce annual water stage amplitudes by 3–4 m and store up to 20% of the daily runoff during flood initiation (Škute et al., 2008). The reconnection of floodplains and channels along the Austrian Danube resulted in a flood peak reduction of 110 m^3s^{-1} per river kilometer (Hudson, 2021). Artificial levees are effective up to their design standard (Tobin, 1995). Consequently, adjacent floodplains that have been disconnected by the levees offer little mitigation against flood waters and peak flow attenuation, except during extreme floods that cause levees to fail (e.g., the 1993 Mississippi River flood, Galloway (1995)).

As primarily depositional environments, floodplains attenuate downstream fluxes of excess sediment following upland disturbance such as changes in land cover, urbanization, or wildfire (Poeppl et al., 2017; Wohl et al., 2022). The degree to which a floodplain can attenuate these fluxes depends partly on the degree of hydrologic and sediment connectivity with the active channel.

Floodplains also mitigate hazards associated with contaminants from non-point sources by sequestering the contaminants. Case studies in the UK indicate that floodplains and river corridors can store lead and zinc from mine waste for up to 5000 years (Dennis et al., 2009). Floodplains can also provide an environment in which some types of contaminants can be biogeochemically remediated (Marron, 1992; Dennis et al., 2009; Gordon et al., 2020). Mean removal of nitrate-N and particulate P from floodplains in North America and Europe was 200 kg-N ha^{-1} yr^{-1} and 21.0 kg-P ha^{-1} yr^{-1} (Gordon et al., 2020). Impacted floodplains can only process and remove pollution from non-point sources to the degree that connection exists between the non-point sources and the floodplain (e.g., are the sources upstream or on the floodplain itself?) and the degree to which the necessary biogeochemical processes remain functional despite disconnection. Disconnected floodplains cannot attenuate fluxes of sediment or waste products from point sources, such as metal mining, unless those fluxes are delivered by hillslopes fringing the floodplain.

Finally, as portions of the river corridor that commonly have lower flow velocity and high surface-subsurface hydrologic exchange, floodplains can provide refugia for diverse organisms during natural and anthropogenic disturbances (Sedell et al., 1990; Stella et al., 2011). Analogous to sediment storage, the degree to which floodplains provide refugia depends on hydrologic connectivity with the active channel (as this influences the mobility of organisms) and the three-dimensional spatial heterogeneity of the floodplain that creates habitat diversity.

Among the knowledge gaps related to hazard mitigation by floodplains are poorly constrained estimates of nutrient dynamics. Some estimates of excess nutrient removal from floodplains, for example, are based on less than 50 studies and could be subject to outliers (Gordon et al., 2020). The same difficulties associated with floodplain delineation in three-dimensions (e.g., Wohl, 2021), along with site-specific patterns of erosion and deposition, have made it difficult to interpret the floodplain's role in contaminant storage and remediation (Dennis et al., 2009). Sediment residence time on floodplains varies substantially in relation to factors such as floodplain area, channel planform and lateral migration rate, and position of the sediment within the floodplain (Konrad, 2012; Wohl, 2015), and these variations make it difficult to accurately predict remobilization of stored sediment and associated contaminants.

3. Synthesis discussion - what do case studies tell us?

A thorough literature review of floodplain restoration studies published in English-language journals indicates that the great majority of floodplain restoration projects have been undertaken in North America, Europe, and Japan. We used Google Scholar and began with key word searches to include “levee setbacks”, “setback levee”, “restoration levee”, “levee removal”, and “reconnected floodplain”. We also used similar terms with geographic place names or programs from known or suspected restorations (e.g., “RFR levee removal”). Google Scholar returns thousands to tens of thousands of articles for most of these searches so we quickly transitioned to using Google Scholar to data-mine references and citing papers, searching out an increasingly larger web of related research. Works that were especially helpful in this regard include Gumiero et al. (2013), González et al. (2015), and Opperman et al. (2017). Selected case studies of floodplain restoration that involve artificial levee alteration (removal, notching, lowering, or setting back) in North America (Table 1) and Europe and Japan (Table 2) illustrate the wide-ranging impacts of artificial levees on floodplain functions. Here, we discuss the major implications of the case studies. We separate North American and European/Japanese case studies based on the much longer period of human involvement in Old World (Europe) river and floodplain management (e.g., Hudson et al., 2008) and the more gradual geomorphic readjustments of Old World river systems compared to New World (colonial) river systems (e.g., Brierley et al., 2005). We hypothesize that, given these differences, the response of floodplain functions to restoration efforts will be noticeably different. The degree of artificial levee adjustment (low, medium, high) is categorized in the “magnitude” column of each case study, with the range set by the case studies. “Low” indicates alterations made to single levees in one or several places with impacts that can be described along a river reach less than 10 km long. “High” indicates alterations made to artificial levees along river lengths measured in the hundreds of kilometers. “Medium” alterations fall between low and high and the alterations to artificial levees are measured in tens of kilometers.

We organized our case study synthesis around five main themes but were able to discuss other ideas as well. The first four themes are drawn from the case studies themselves. The fifth theme attempts to place these case studies into the wider floodplain restoration literature. The main themes are:

(i) limits of selected case studies;
(ii) reconnection and reconfiguration;
(iii) restoration-scale dilemma;
(iv) unique place-based challenges; and
(v) context within restoration literature.

3.1. Limits of selected case studies

The limits of the case studies are apparent in geographic extent (Fig. 3), the degree of restoration compared to the degree of alteration by artificial levees and other stressors (Tables 1 and 2; Knox et al., 2022a, 2022b), and the limited elapsed time between restoration and data collection (Tables 1 and 2). Case studies represent the northern hemisphere mid-latitudes ranging between 27°N (Kissimmee River, U.S.) and 66°N (Pite and Ume River, Sweden). Conspicuously absent are documented examples of floodplain restoration via levee alteration from South America, Africa, and Australia.

The case studies summarized here indicate that the floodplain area impacted by restoration is very small compared to the total area impacted by artificial levees and other stressors. Using the United States as an example, the length of artificial levee alteration from case studies in Table 1 (the largest two examples are 161 km on the Sacramento River (Golet et al., 2008) and 70 km on the Kissimmee River (Koebel and Bousquin, 2014)) and impacts are far less than 1% of total artificial levee length estimates in the continental U.S. (~228,000 km, Knox et al., 2022a). In terms of floodplain reconnection to channels, restoration efforts only reconnect 1–2% of

Table 1

Selected case studies of efforts to restore floodplains by levee alteration in North America.

Location	Floodplain functions analyzed	Summary	Elapsed time[a] (years)	Magnitude[b]	Other stressors[c]	Reference
Baraboo River, Wisconsin, US	Fluxes, enhanced spatial heterogeneity of hydrology and biogeochemistry	Controlled reconnected floodplain (a gate was installed in the levee) experienced water storage flux based on weather and high temporal and spatial denitrification rates	1–2	Low	None known	Orr et al., 2007
Kissimmee River, Florida, US	Fluxes, enhanced spatial heterogeneity of hydrology and biogeochemistry, enhanced habitat diversity and biodiversity	Reconnection of river and floodplain through canal and levee modification	1–20	High	Headwater lakes are managed for flood control and biodiversity	Toth et al., 1998; Toth, 2010; Toth and van der Valk, 2012; Koebel and Bousquin, 2014; Jones, 2017; Koebel et al., 2021
Olentangy River, Ohio, US	Enhanced spatial heterogeneity of hydrology and biogeochemistry, enhanced habitat diversity and biodiversity	Invasive species removal and levee breaches partially reconnect floodplain and decrease vegetation biodiversity while improving exchanges of total N and C	3–4	Low	Discharge is controlled by Delaware Lake releases; research site is in an urban watershed	Zhang and Mitsch, 2007; Swab et al., 2008
Bear River, CA, US	Hazard mitigation	vegetation plan for hazard mitigation limits levee setback effectiveness	17	Low	Discharge regulated by dams	Serra-Llobet et al., 2022
Napa River, CA, US	Enhanced habitat diversity and biodiversity, hazard mitigation	Varying responses of vegetation to levee removal in straightened reaches	8–30	Medium	Urban watershed	Bechtol and Laurian, 2005; Diggory and Parker, 2011.
Sacramento River, California, US	Enhanced habitat diversity and biodiversity	Levee setbacks resulted in greater abundance and diversity with larger elapsed time	3–12	High	Discharge regulated by dams and diversions	Golet et al., 2008
Cosumnes River, California, US	Fluxes, enhanced spatial heterogeneity of hydrology and biogeochemistry, enhanced habitat diversity and biodiversity	Levee breaches reconnected the river and floodplain; sand splay complexes added topographic variability; induced high levels of anaerobic ammonium oxidation, denitrification, and primary productivity; plant communities responded more stochastically	3–20	Medium	Discharge is unregulated by dams	Florsheim and Mount, 2002; Swenson et al., 2003; Ahearn et al., 2006; Sheibley et al., 2006; Trowbridge, 2007; Hoagland et al., 2019
Pocomoke River, Maryland, US	Fluxes, enhanced spatial heterogeneity of hydrology and biogeochemistry	Levee breaches improve trapping of P, N and sediment on floodplains, thereby improving water quality	1	Low	Watershed is heavily altered by human use	Noe et al., 2019
Missouri River, Iowa, US	Enhanced habitat diversity and biodiversity, hazard mitigation	Levee setback resulted in reduced flood stages and improved biodiversity	5	Low	Discharge is heavily regulated for navigation, flood control, and power generation	Smith et al., 2017
Puyallup and Carbon Rivers, Washington, US	Enhanced habitat diversity	Levee setbacks on glacially fed river results in greater riparian habitat diversity	6	Medium	Discharge is regulated for power generation	Konrad et al., 2008
Chilliwack River, Canada	Enhanced habitat diversity and biodiversity	Floodplain reconnection resulted in new habitat for coho salmon	1–4	Medium	None known	Ogston et al., 2015

[a] Elapsed time indicates the years between levee alteration and data collection.

[b] Magnitude indicates the degree of levee alteration.

[c] Other stressors indicate other anthropogenic stressors that continue to operate in that river's basin.

disconnected floodplain area (the two largest examples are ~54 km^2 on the Sacramento River (Golet et al., 2008) and ~80 km^2 on the Kissimmee River (Koebel and Bousquin, 2014)) in the U.S. (8100 km^2, Knox et al., 2022b). We cannot make comparable quantitative assessments for Europe or Japan because the total extent of artificial levees there is unknown.

Artificial levees are just one (very influential) anthropogenic factor stressing floodplain functions, with almost every floodplain restoration project contending with outside stressors that impact restoration effectiveness (Tables 1 and 2). Effective restoration for target species must occur at the relevant habitat scale (Lepori et al., 2005). Nearby artificial levee (either upstream/downstream or setback) constraints on effectiveness of restoration on the Cosumnes and Pocomoke Rivers and rivers in Switzerland (Rohde et al., 2005) indicate the ability of anthropogenic features to adversely impact low and medium magnitude restoration. Negative impacts of flow regulation include the combination of minimal environmental flows with regulated flows (e.g., the Dutch portions of the Rhine and Meuse Rivers), a complete lack of environmental flows (e.g., the Spanish Órbigo River), and physical barriers to the movement of rare species (e.g., the German portion of the Danube). Many case studies recognized that effectiveness was limited by the degree of elapsed time between restoration and data collection, an issue that may become more important as the scale of restoration increases (Wohl et al., 2015). Case studies with limited time between implementation and evaluation included those on the Olentangy, Napa, Sacramento, and Cosumnes Rivers in the US, as well as rivers in Germany, Denmark, Sweden, and Spain.

We do not necessarily see a consistent difference in the effectiveness of Old versus New World floodplain restoration projects. Site-specific details, such as magnitude of the restoration effort and constraints external to the restoration (e.g., flow regulation), appear to exert a greater influence than length of history of human alteration. The length of time that a site has been altered could certainly influence floodplain response to restoration. Plausible scenarios include such a long period of alteration that aquatic or riparian species have gone extinct or terrestrialisation of the floodplain has been so thorough that simply inundating the floodplain cannot restore lost functions. However, the existing literature on floodplain restoration projects is not yet sufficient to determine whether there is a consistent difference in floodplain response in Old versus New World settings as a result of the differences in history of alteration.

3.2. Reconnection and reconfiguration

Bernhardt and Palmer (2011) make the distinction between restoration that involves reconfiguration (designing artificial channels or connections to floodplains) and reconnection (removing barriers to connection between natural channels and floodplains). They note the scant record of reconfiguration successes. Restoration is an experimental process situated within a wider social context (Gross, 2002) that involves value assignment and

Table 2
Selected case studies of efforts to restore floodplains by levee alteration in Europe and Japan.

Location	Floodplain functions analyzed	Summary	Elapsed time[a] (years)	Magnitude[b]	Other stressors[c]	Reference
Rhine, Rhone, Moesa, Hinterrhein, Emme, and Thur Rivers, Switzerland	Fluxes, enhanced habitat diversity and biodiversity	Comparison of carbon storage and soil organic matter stabilization from levee setbacks and natural floodplains; potential catchment scale effects on habitat and biodiversity relationships	4–11	Medium	Relocated banks stabilized; discharge is regulated on some rivers by dams or locks	Rohde et al., 2005; Pasquale et al., 2011; Bullinger-Weber et al., 2014
Danube River, Austria	Fluxes, enhanced spatial heterogeneity of hydrology and biogeochemistry, enhanced habitat diversity and biodiversity, hazard mitigation	Reconnecting floodplains on free-flowing part of channel below vienna impacts microbiota and fish guilds with mixed results	1–20	Medium	Flow is highly regulated by upstream chain of impoundments	Tockner and Schiemer, 1997; Tockner et al., 1998, 1999; Schiemer et al., 1999; Luef et al., 2007; Reckendorfer et al., 2013; Chaparro et al., 2019; Ramler and Keckeis, 2019; Mayr et al., 2020
Elbe River, Germany	Enhanced habitat diversity and biodiversity, hazard mitigation	Levee setback resulted in 50 cm flood peak reduction and improved habitat and biodiversity	14	Low	None listed	Serra-Llobet et al., 2022
Danube River, Germany	Fluxes, enhanced spatial heterogeneity of hydrology and biogeochemistry, enhanced habitat diversity and biodiversity	Floodplain reconnection and improved habitat diversity results in improved biodiversity; target riparian vegetation establishment inhibited by floods and limited study time	1–3	Medium	Flow is regulated for hydropower	Stammel et al., 2012; Pander et al., 2018; Stammel et al., 2021.
Isar River, Germany	Enhanced habitat diversity and biodiversity, hazard mitigation	Levee setbacks along urban river improve hazard mitigation and habitat	11	Low	Flow is regulated for hydropower	Serra-Llobet et al., 2022
Rhine and Meuse Rivers, The Netherlands	Enhanced habitat diversity and biodiversity, hazard mitigation	Room for the river, which involves levee setbacks, reduces flood levels and flood consequences; other stressors reduced restored habitat and fish biodiversity over time	13–30	High	Rivers and basins continue to be highly influenced by humans through canalization, flow regulation for hydropower, and land cover changes	Klijn et al., 2018; Schmitt et al., 2018; Stoffers et al., 2021
Skjern River, Denmark	Fluxes, enhanced habitat diversity and biodiversity	Restoration design allows limited reconnection of floodplain; habitat improvement rate is low	8–10	High	Basin is mostly agricultural and channel lacks large wood due to stream management	Pedersen et al., 2007; Kristensen et al., 2014
Órbigo River, Spain	Enhanced habitat diversity and biodiversity	Levee removal altered riparian vegetation towards natural state	2–4	High	Flow regime is regulated by upstream reservoir to allow diversions for agriculture	Martínez-Fernández et al., 2017
Middle Ebro River, Spain	Enhanced habitat diversity and biodiversity, hazard mitigation	Levee removal and flood flow improved habitat diversity and biodiversity	3–20	Medium	Limited flow regulation by dams and diversions	Gumiero et al., 2013; González et al., 2017
Long Eau River, England	Enhanced habitat diversity and biodiversity, hazard mitigation	Levee removal and setback improved flood mitigation and improved floodplain biodiversity	17	Low	Highly regulated, dredged, banks are mown	Gumiero et al., 2013
Pite and Ume Rivers, Sweden	Enhanced habitat diversity and biodiversity	Levee removal on streams used for timber harvest increased floodplain connectivity and biodiversity with different results on habitat and biodiversity relationships between vegetation and aquatic organisms	1–20	Medium	Ongoing restoration efforts of the same type continue; the Ume is regulated	Lepori et al., 2005; Helfield et al., 2007; Helfield et al., 2012
Tummel River, Scotland	Enhanced habitat diversity and biodiversity	Floodplain landforms and vegetation biodiversity return to natural state after 50 years of levee abandonment	100	Medium	Flow regulated for hydropower	Parsons and Gilvear, 2002.
Allt Lorgy, Scotland	Fluxes	Levee alteration increased channel-floodplain interaction and bank erosion	5	Low	Restored section represents ~70% length of impacted length	Williams et al., 2020
Kushiro River, Japan	Fluxes, enhanced spatial heterogeneity of hydrology and biogeochemistry, enhanced habitat diversity and biodiversity	Levee removal induced floodplain reconnection and riparian vegetation biodiversity	1	Medium	Channelized reaches upstream	Nakamura et al., 2014

[a] Elapsed time indicates the years between levee alteration and data collection.
[b] Magnitude indicates the degree of levee alteration.
[c] Other stressors indicate other anthropogenic stressors that continue to operate in that river's basin.

careful consideration of potential costs, benefits, and tradeoffs of possible outcomes. Several case studies indicate that reconfiguration strategies are one way in which practitioners select certain components and outcomes over others. By employing hardened intake structures to secondary channels, for example, the designers of the Chilliwack restoration assigned greater value to habitat stability in the near term at the cost of potential habitat decline in the long term due to decreased scouring flows (Ogston et al., 2015). In similar fashion, designers of the Skjern River restoration engineered channel floodplain connections to limit smolt predation at the cost of limited floodplain inundation and habitat development (Kristensen et al., 2014). In contrast, the reconnection of channels replaced by straightened canals seems to be very effective over a range of elapsed times (e.g., Kissimmee, Napa, and Kushiro Rivers). Compared to different restoration methods, floodplain-channel reconnection can be an effective method to improve fish biodiversity (Ramler and Keckeis, 2019). A secondary point is that some of these successful restorations represent studies with comparatively longer elapsed time, indicating that restoration outcomes should be evaluated over a longer time horizon.

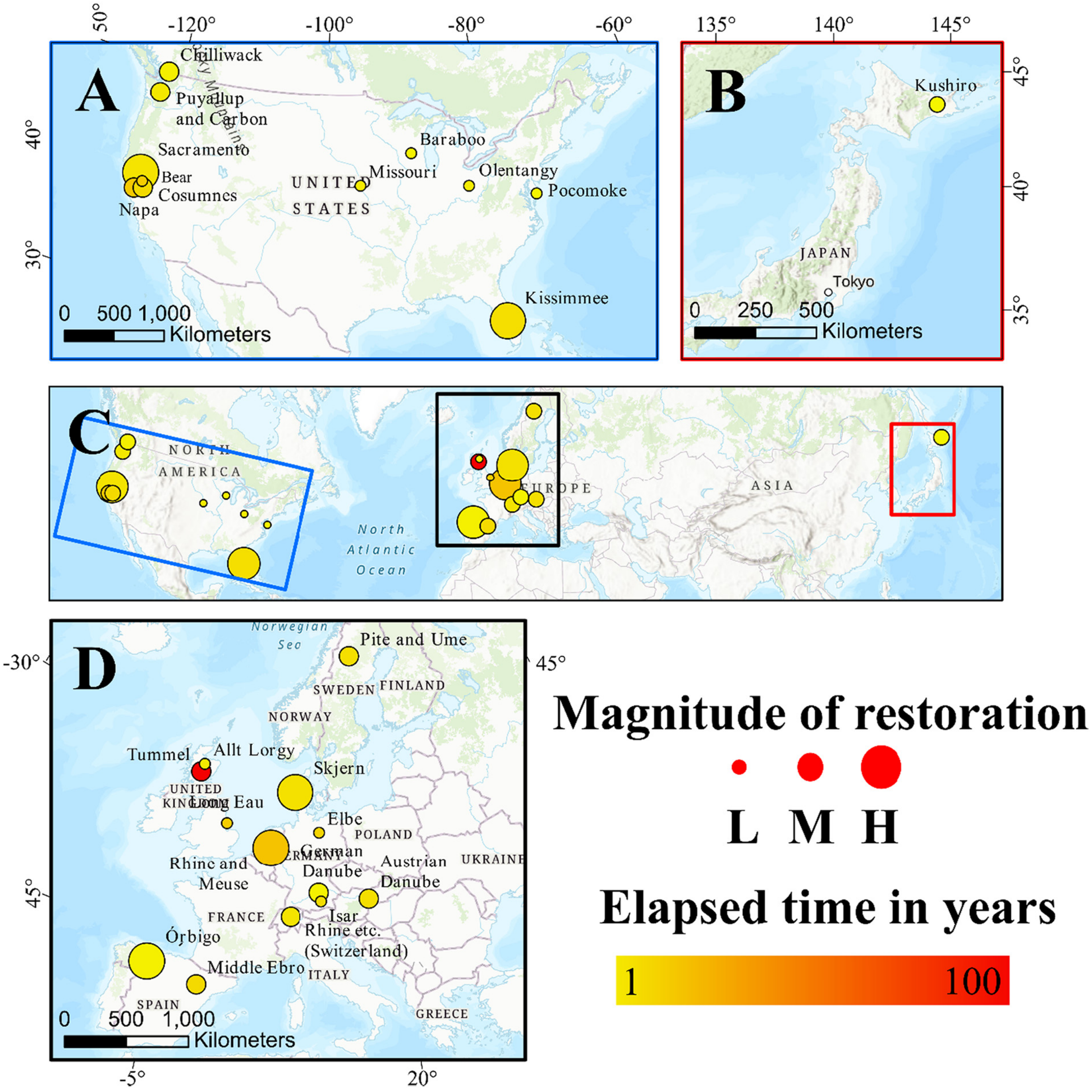

Fig. 3. Selected case study location, magnitude of alteration, and elapsed time between alteration and data collection. (C) Case studies are concentrated in the northern hemisphere in (A) North America, (B) Japan, and (D) Europe. The magnitude of restoration is indicated as Low (alterations made to single levees impacted less than 10 km of river), Medium (alterations to levees impacting between 10 and 100 river km), and High (alterations made to levees impacting more than 100 river km).

3.3. Restoration-scale dilemma

One aspect of this dilemma is the inverse relationship of restoration scale and observation resolution. This issue is illustrated by Ahearn et al. (2006), who were able to record primary productivity and other data at high spatial and temporal resolution in the Cosumnes River floodplain because of the small floodplain area (0.36 km^2). This contrasts with a larger-scale restoration project (~10 km river corridor) where finer features such as boulders or large wood and subdivisions of aquatic habitat were undetectable using remote sensing (Konrad et al., 2008). The need to restore floodplains on a larger scale, discussed in Section 3.1, poses challenges for the need to study floodplain complexity at finer spatial and temporal resolutions (Ahearn et al., 2006). The second component of the dilemma is that small-magnitude restoration, which allows for finer resolution analyses, is commonly impacted by other stressors outside the study area, as discussed above. The Cosumnes River floodplain experienced artificially low inundation rates because of the small floodplain size and fringing artificial levees. Similarly, the performance of levee setback sites for biodiversity across Switzerland was based mostly on proximity to nearly natural sites, which indicates the important role of nearby stressors (Rohde et al., 2005). The literature reviewed here at least provides a way forward given this dilemma, which will not be solved solely through more data, faster computing, better algorithms, and high-resolution remote sensing. Specifically, lessons learned and improved conceptual models developed at small magnitude restoration studies can facilitate more effective restoration at greater spatial scales.

Numerical modeling does have an important role to play in floodplain restoration. The increasing computational power of personal computers makes it more feasible to use 2D and 3D models to simulate the effects of floodplain restoration. Application of the models may still be limited by the need to provide spatially and temporally explicit input and validation data, as well as limitations on what the models simulate. Surface-water hydrologic and hydraulic models coupled with sediment transport models have advanced rapidly in recent years (e.g., Van Manh et al., 2015;

Gilbert and Wilcox, 2020), for example, but models that effectively couple these physical processes with simulations of biogeochemical cycling or species or biotic community dynamics are limited (e.g., Theng et al., 2022). Another limitation of these studies, many of which combine the HEC-RAS hydraulic model with infrastructure, is the potential for HEC-RAS to misestimate inundation extent in built-up areas (Shustikova et al., 2019).

Table 3 lists examples of numerical simulations used to evaluate the effects of levee alteration. Studies listed here include 1D hydraulic models (e.g., Remo et al., 2012), combined hydraulic-sedimentologic models (e.g., Jones et al., 2018), and combined hydraulic-plant growth models (e.g., Ahn et al., 2006). For at least the next few years, conceptual models of interactions among water, sediment, biogeochemical processes, and biotic communities are more likely to be used than numerical models. Conceptual models, like numerical models, can be most effective if they are based on knowledge of multiple, interacting variables and if they are informed by monitoring of restoration effects over timespans relevant to the process of interest (e.g., years to decades for vegetation community response; Shafroth et al., 2010; Kui et al., 2017).

The use of Decision Support Systems (DSS) that can integrate numerical and conceptual versions of parameter response to changes in floodplain-channel connectivity may prove to be particularly useful in the context of floodplain restoration. An example for environmental flows is the DRIFT DSS software developed for integrated flow assessments by King, Brown, and others (King et al., 2004; Brown et al., 2006, 2013), which has now been applied to multiple watersheds in southern Africa. Another example evaluates fish and vegetation habitat availability given different flow scenarios (Passero, 2020). This approach, when combined with the societal designation of acceptable levels of alteration in a floodplain (King and Brown, 2018), explicitly provides a mechanism for including stakeholder perceptions and values. Given the societal context in which river and floodplain restoration occurs, including socioeconomic considerations such as stakeholder perceptions is likely to be critical to efforts to expand the magnitude and spatial extent of floodplain reconnection via modification of artificial levees.

3.4. Unique place-based challenges

This is the simplest way to explain why certain restoration measures are effective at one location but not at another. The nexus of river and floodplain restoration in altering functions and form experiences the same tension that arises in fluvial geomorphology between the need to identify universal physical processes amidst site-based contingency and characteristics (Wohl, 2014). The restoration of floodplain connection on high-gradient bedrock rivers, which are the exception to the more common restoration on lowland alluvial rivers, illustrates this dilemma. Several restoration projects (Puyallup, Chilliwack, and the Pite/Ume Rivers) are distinct for their location along high-gradient bedrock rivers. Two of these experienced almost immediate positive restoration effects over a period of 6 years at the Puyallup River (Konrad et al., 2008) and 1–4 years at the Chilliwack River (Ogston et al., 2015). Levee removal along the Pite and Ume Rivers (Lepori et al., 2005; Helfield et al., 2007, 2012), which had differing levels of success with respect to desired outcomes, illustrates why expectations for restoration projects along similar types of rivers may be disappointed. Riparian vegetation responded quickly to levee removal along the Ume River but slowly along the Pite River (Helfield et al., 2007, 2012). The different vegetation responses are attributed to (i) different substrate at the restoration sites because of differences in glacial history, (ii) the limited elapsed time, which was up to 20 years, (iii) different pre-

Table 3
Selected case studies of simulations to restore floodplains by levee alteration.

Location	Floodplain functions analyzed	Summary	Model type(s)	Reference
Middle Mississippi River, US	Hazard mitigation	Simulation scenarios indicate effectiveness of levee setbacks combined with buy backs given floodplain development and decreased flood stages from levee alteration	1D hydraulic (HEC-RAS & Hazus-MH)	Dierauer et al., 2012; Remo et al., 2012
Wisconsin, River, Wisconsin, US	Enhanced habitat abundance and diversity, enhanced biomass and biodiversity, hazard mitigation	Simulation and field data indicate levee setbacks provide some flood mitigation with little impact to vegetation biodiversity	1D hydraulic (HEC-RAS)	Gergel et al., 2002
Sangamon River, Illinois, US	Fluxes, enhanced spatial heterogeneity of hydrology and biogeochemistry, enhanced habitat abundance and diversity, enhanced biomass and biodiversity	Simulation of different options for levee setbacks or gates on N and P storage and biodiversity involves tradeoffs in N/P storage and biodiversity	2D environmental (CASM)	Bartell et al., 2020
Illinois River, Illinois, US	Fluxes, enhanced habitat abundance and diversity, enhanced biomass and biodiversity	Different approaches involving levees and levee pumping are evaluated to restore floodplains	1D hydraulic; 2D plant growth; UNET	Sparks et al., 1990; Ahn et al., 2006
Illinois River, Illinois, US	Enhanced habitat abundance and diversity, enhanced biomass and biodiversity, hazard mitigation	Simulation of analysis and site selection of tradeoffs between economic costs of setbacks, flood risks, and biodiversity	1D hydraulic (HEC-RAS)	Guida et al., 2016; Remo et al., 2017
Iguacu River, Brazil	Hazard mitigation	Simulation of levee removal to increase flood storage in an urban watershed	pseudo 3D hydrologic-hydraulic (MODCEL)	Miguez et al., 2015
Upper Mid-western, US	Enhanced spatial heterogeneity of hydrology and biogeochemistry	Simulation of levee removal indicates improved nitrate-nitrogen processing in the floodplain	2D nitrogen biogeochemical numerical; 1D hydraulic (HEC-RAS)	Gergel et al., 2005
Lower White River, Washington, US	Fluxes	Simulation indicates improved sediment storage in reconnected floodplain after levee removal or setback	1D hydraulic (HEC-RAS); 2D sedimentologic (AdH)	Jones et al., 2018
Sacramento River, California, US	Enhanced spatial heterogeneity of hydrology and biogeochemistry, enhanced habitat abundance and diversity	Simulation of levee setback impacts to floodplain reworking and connection to cutoffs indicates site-specific thresholds can be used to maximize habitat with minimal cost	2D river channel migration model	Larsen et al., 2006
American River, California, US	Hazard mitigation	Simulation of flood risk from future development and climate	2D hydrologic (HadCM2); 1D hydraulic (HEC-RAS); economic model for climate and urban scenarios	Zhu et al., 2007
White River, California, US	Enhanced habitat abundance and diversity, enhanced biomass and biodiversity, hazard mitigation	Simulation of levee setbacks reduces flood heights and improved salmonid habitat	2D hydraulic (RiverFlo-2D); 3D Stream Tube model; 3D fish foraging and bioenergetics model	Black et al., 2016
San Joaquin River, California, US	Enhanced habitat abundance and diversity, enhanced biomass and biodiversity	Simulations of impacts of levee setbacks, bypasses, and climate projections indicate that successful restoration must include both floodplain reconnection and augmented reservoir releases	2D climate (B1PCM & A2GFDL); 2D hydro-ecologic (HEC-EFM); 1D hydraulic (HEC-RAS)	Matella and Merenlender, 2015

existing vegetation patterns on the Pite River secondary channels and the Ume River primary channels, and (iv) incorrect restoration scale compared to the habitat scale of the target organism (Helfield et al., 2012). Cursory similarities (i.e., high-gradient bedrock streams in northern Sweden, similar artificial levee type and restoration method) fail to explain the differences in riparian vegetation response. Notably, none of the case studies on high-gradient bedrock rivers mention other stressors as a reason for restoration ineffectiveness despite flow regulation for hydropower above the Puyallup site and many kilometers of fringing artificial levees near the Pite/Ume Rivers restoration sites. These case studies illustrate the potential for successful restoration on high-gradient bedrock rivers, but also the need to appreciate site-specific characteristics.

3.5. Context within restoration literature

How do these case studies fit into the wider narratives from river and floodplain restoration literature? With most restoration case studies considered here impacted by flow regulation and impacting less than 2% of river kilometers and disconnected floodplain area in the contiguous U.S., the scale of restoration remains highly limited in spatial extent (e.g., Bernhardt et al., 2005; Wohl et al., 2005). This research (e.g., Tables 1 and 2) indicates that even though most restoration studies focus on single or limited potential benefits from restoration (e.g., Serra-Llobet et al., 2022), the vast majority of floodplain restoration efforts impact multiple floodplain functions. Our short survey of knowledge gaps in understanding floodplain functions and how they are impacted by artificial levees seems to contradict the assertion of Serra-Llobet et al. (2022) that there are no technical challenges to overcome in the context of floodplain management. The gaps that we listed previously are complicated by our poor understanding of transferability (Wohl et al., 2005) and the still-elusive universal approach to restoration (Geist and Hawkins, 2016) as well as our inability to predict and quantify impacts across floodplain functions. For example, in terms of material fluxes, we can quantitatively predict changes to sediment and water fluxes but not particulate or dissolved carbon.

So, what must be done? The breadth and scale of knowledge gaps related to floodplain functions indicate that future transdisciplinary approaches to solve the socio-economic-ecologic problems of humans and floodplains (e.g., Auerswald et al., 2019) must be matched by commensurate efforts along disciplinary lines, many of which cannot immediately be integrated or implemented together. The short length of elapsed time and the uncertainty of restoration outcomes indicate the need for longer periods of monitoring that includes multiple floodplain functions, especially when the project aim is solely for hazard mitigation. With most of the restoration case studies summarized here impacted by flow regulation, future floodplain restoration could effectively target watersheds where both the return of environmental flows and structural modifications to infrastructure (such as artificial levees) are feasible. Future modeling efforts should aim at quantifying responses of floodplain functions to floodplain modifications and integrating response relationships across functional boundaries.

4. Conclusion

Our intent is to explore floodplain functions and how they are impacted by artificial levees. We define five floodplain functions (fluxes, enhancement of spatial heterogeneity of hydrology and biogeochemistry, habitat abundance and diversity, biomass and biodiversity, and hazard mitigation) and selected floodplain restoration case studies that involve alteration to artificial levees. Floodplain functions are highly integrative and based primarily on lateral connectivity between the channel and the floodplain, which is why artificial levees are so harmful to floodplain functions. Case studies are concentrated in North America and Europe on lowland alluvial rivers and generally include data collection within 30 years of restoration. Artificial reconfiguration of floodplain connectivity achieved limited success. Reconnection of channels and floodplains seems more likely than reconfiguration to set floodplains on a trajectory to more fully restore floodplain functions. Case studies highlight the dichotomy between restoration site scale and study resolution, although future case studies will continue to inform conceptual models of restoration and it is critical to continue multi-decadal monitoring of the effects of floodplain restoration. Restoration effectiveness varied by location and highlights the need to apply restoration techniques that are relevant to a specific location. Some of these considerations include the impacts of other stressors (e.g., flow regulation) on connectivity after barrier removal, the site's geologic history, and the scale of restoration required by the target species.

Limitations of this review include searching only English-language journals and the subsequent focus on North America and Europe for restoration. The limited elapsed time between floodplain restoration and analyses is agnostic on whether floodplain functions were actually restored, or if the stage was set for the restoration of functions. Another limitation was our inability to compare restoration aims with floodplain functions analyzed (e.g., Tables 1 and 2).

Our primary recommendations after conducting this review and synthesis include the need to combine floodplain restoration involving artificial levee alteration with restoration of discharge. As pointed out by Wohl et al. (2005), this is difficult due to the cost and regulatory complications but is ultimately critical to restoring diverse floodplain functions. A second recommendation is the need for more multi-year to multi-decadal monitoring that includes quantitative assessments of multiple floodplain functions. Our ability to restore floodplain functions more effectively is constrained by limited understanding of the long-term and integrative effects of existing restoration projects. A third recommendation is to emphasize transdisciplinary research that quantifies, for example, how floodplain hydrologic and sediment connectivity interact with floodplain topography and stratigraphy to influence nitrate or carbon dynamics. Ideally, such research can facilitate integrative numerical models, as exemplified by recent progress in coupling hydraulics and sediment transport in two-dimensional models.

Fundamentally, floodplains are an integral component of rivers that have not received the legal protection or prioritization for restoration accorded to the active channel. We hope that this review of floodplain functions and restoration projects provides an impetus for greater scientific and management focus on floodplains.

CRediT authorship contribution statement

Richard Knox: Conceptualization, Investigation, Writing- Original Draft, Visualization. **Ellen Wohl:** Conceptualization, Writing- Review & Editing, Supervision. **Ryan Morrison:** Conceptualization, Writing- Review and Editing,

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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