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COMMENTARY

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Key Points:

- A river floodplain is an integrative physical, chemical, biological system and a key component of a river corridor
- Contemporary societal perceptions and regulatory frameworks do not reflect this scientific consensus

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Conceptualizing River Floodplains

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Abstract Geologic, geomorphic, hydrologic, ecological, and biogeochemical conceptual models of river floodplains developed since the mid-20th century led to the current conceptualization of floodplains as integrative systems that store and transform diverse materials, provide a source of material that can be transported downstream, and function as ecosystems. Scientific recognition of floodplains as a critical component of river corridors is not, however, matched by societal perceptions and legal or regulatory frameworks, which typically treat the active channel and floodplain as separate entities. The development of an integrative scientific understanding of floodplains is reviewed here, along with five primary challenges to progress in understanding and managing floodplains. These challenges involve: integrating thinking, data collection, modeling, and prediction across disciplines in a manner that facilitates the work of practitioners and regulators; scaling across time and space; measuring and predicting feedbacks and nonlinear interactions; measuring and predicting resilience and resistance of floodplains and river corridors to natural and human-induced disturbances; and effectively communicating social and technical uncertainties in river management.

Plain Language Summary River floodplains are integrative ecosystems in which diverse processes operate together to maintain river health. Floodplains are as critical to river health as the channel itself, yet floodplains lack the legal protections afforded to river channels in many countries.

1. Introduction

Most nations have a legal framework to protect river channels and associated water resources. In the United States, for example, the federal government has jurisdiction over the active channel below the ordinary high water mark (Wohl et al., 2016) and the Clean Water Act protects water quality (Walsh & Ward, 2022). Other components of the river corridor, such as the floodplain, typically lack such protection and are under private ownership (Tarlock & Albrecht, 2018), although relatively recent legislation in the European Union, such as the Water Framework Directive (2000) and the Floods Directive (2007), facilitate floodplain protection and restoration (Hein et al., 2016). The continuing lack of legal protection for floodplains in many politicial jurisdictions may reflect a fundamental difference in perceptions of floodplains between river scientists and others. I distinguish here between river scientists, practitioners and regulators, and the general public, although overlaps can exist between these groups. River scientists are those who are engaged in basic and applied research on rivers. Practitioners are those who manipulate rivers to enhance desired characteristics. Practitioners and manipulation in this context ranges from non-governmental organizations and environmental consultants who are striving to increase river resilience to disturbance associated with changing climate (e.g., Dadson et al., 2017; Norman et al., 2022; Skidmore & Wheaton, 2022), to engineers attempting to decrease flood hazards or improve water quality using more traditional infrastructure approaches (e.g., Islam et al., 2024; Wenger, 2015). Regulators are those in various levels of government who oversee activities of practitioners and the general public as these activities affect rivers.

A floodplain can be defined in diverse ways. Some definitions are based on inundation frequency in a regulatory context (e.g., FEMA, 2023), such as the "100-year floodplain" that has a 0.01 probability of being inundated in any year. Other definitions are based on geomorphic processes that create and maintain the floodplain (e.g., Nanson & Croke, 1992). Ecologists might define a floodplain as a wetland that oscillates between terrestrial and aquatic phases (Junk, 1997). Here, I define a floodplain as a relatively flat alluvial surface adjacent to the channel that is inundated at least periodically by flows of the contemporary hydrologic regime and is composed of river-deposited sediment (Wohl, 2021). The lateral limits of floodplain inundation are governed by a combination of flood discharge magnitude relative to the conveyance of the active channel(s), natural topographic features such as valley walls and terraces, and human-built features such as dikes or embankments.

The floodplain is an integral part of the river corridor, which includes the active channel(s), the adjacent floodplain, and the underlying hyporheic zone (Harvey & Gooseff, 2015). The consensus among river scientists is that a river corridor is an integrated system in which process, form, and function of the active channel, floodplain, and hyporheic zone strongly influence each other (Fausch et al., 2002; Han et al., 2022; Torgersen et al., 2022; Ward & Packman, 2019). Integration in this context refers to (a) exchanges of materials and organisms among the river corridor components of channel, floodplain, and hyporheic zone and (b) interactions among physical (water, sediment) and chemical (solutes) materials and processes, and organisms. Exchanges of materials and organisms occur along the three primary dimensions of longitudinal (upstream-downstream), lateral (channel-floodplain), and vertical (surface-subsurface) (Ward, 1989). Examples of physical-chemical-biological interactions include: woody riparian vegetation that both germinates in response to water and sediment dynamics but then also influences those dynamics by creating flow resistance and altering substrate erosional resistance (Bywater-Reyes et al., 2022; Corenblit et al., 2015); fishes such as salmon that modify the grain-size distribution and sediment transport within channels in the process of creating spawning redds (Hassan et al., 2008); elephants and hippos that, in using floodplain habitats during the dry season, create pathways and wallows that then concentrate overbank flows on floodplains and facilitate the formation of incised, secondary channels (McCarthy et al., 1998); and channels in which algal growth contributes substantially to travertine accumulation and the formation of step-pool channel morphology (Fuller et al., 2011).

Artificially disconnecting any of the components of the river corridor, such as with human-built levees that disconnect the floodplain and channel, alters process and form within the river corridor in ways that can reduce ecosystem services (Knox et al., 2022). Human-built levees, for example, can reduce peak flow attenuation (Heine & Pinter, 2012), biological uptake of nutrients (Gordon et al., 2020; Kang & Stanley, 2005), and habitat, biomass, and biodiversity in the river corridor (Roni et al., 2019; van Rees et al., 2024). Scientific understanding of integration within the river corridor is commonly not reflected, however, in legal frameworks governing river management or use of riverine resources (e.g., Colvin et al., 2019; Doyle & Bernhardt, 2011; Nadeau & Rains, 2007), which tend to focus on the active channel and largely ignore the floodplain and hyporheic zone. The primary objective of this commentary is to briefly review how scientists from diverse disciplines have conceptualized floodplains through time as a means of providing insight into the development of the current, integrative scientific view of floodplains.

2. Conceptualizations of Floodplains

2.1. Traditional Perceptions of Floodplains

People have conceptualized floodplains in diverse ways for millennia. Prior to the 20th century, floodplains were mostly viewed in utilitarian contexts as areas for human use (i.e., crops, grazing, cities) or areas that should be disconnected from the active channel to facilitate conveyance in the active channel for flood control, navigation, or waste disposal (e.g., Alexander et al., 2012; Andreadis et al., 2022; Tockner & Stanford, 2002).

By the mid-20th century, diverse individuals had recognized the potential importance of floodplain wetlands as habitat for fishes, birds, and other animals (Bragg & Smith, 1943; Herre, 1940) and geologists and geomorphologists had recognized the sediment storage function of floodplains (e.g., Russell, 1898). Formal scientific conceptualizations of floodplains as a fundamental component of river corridors, however, primarily began during the second half of the 20th century (Figure 1).

2.2. Scientific Conceptual Models of Floodplains

Recognition of characteristic patterns of sediment movement between the active channel and floodplain (Wolman & Leopold, 1957) led to conceptualizations of sediment architecture in floodplains (Allen, 1965; Miall, 1987) and floodplain morphology and relative stability (Nanson & Croke, 1992). Analogous recognition of high levels of biomass and biodiversity (Ward et al., 1999) tied to regular longitudinal, lateral, and vertical movements of materials and organisms within river corridors (Baxter et al., 2005; Junk et al., 1989; Ward, 1989) and to the dual nature of floodplains as alternately terrestrial and submerged by flowing or standing water (McClain et al., 2003), led to conceptualizations of the importance of periodic natural disturbances such as floods in structuring river corridor ecosystems (Arscott et al., 2002). Hydrological simulations capable of modeling lateral and vertical exchanges of moving water facilitated recognition of floodplains as sources of infiltration for hyporheic and

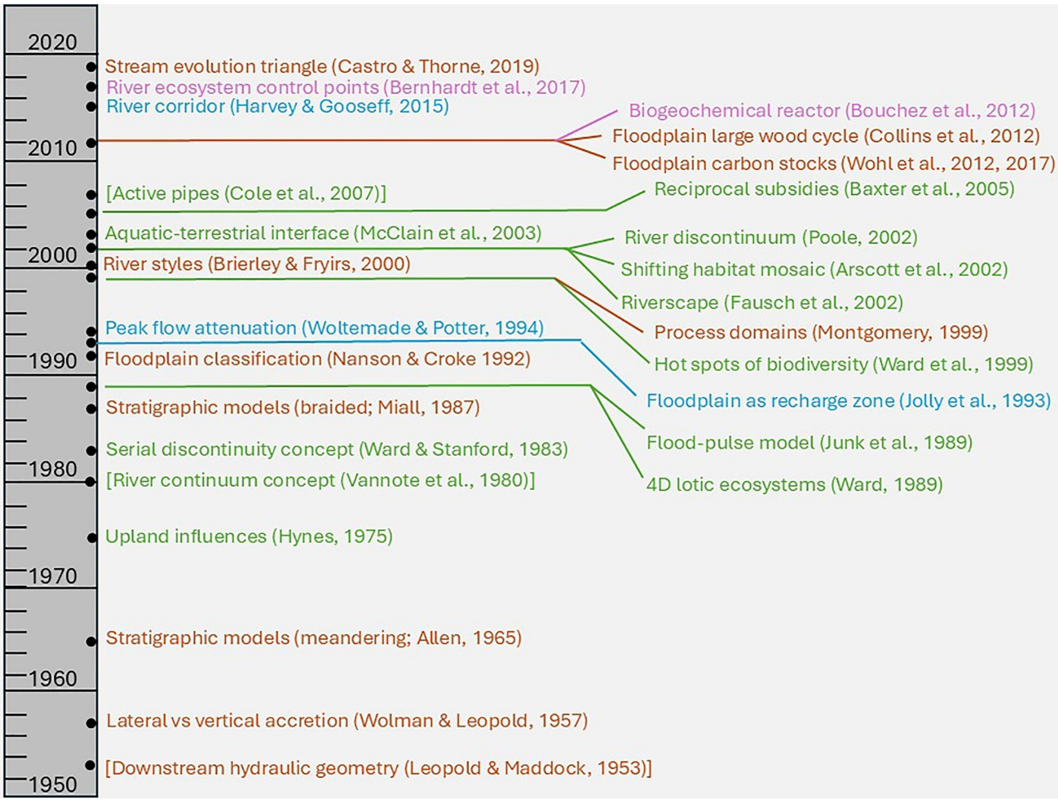

Figure 1. Conceptualizations of floodplains in the context of hydrology (blue), sedimentology and geomorphology (brown), biogeochemistry (magenta), and ecology (green). Primary reference is listed after each descriptive phrase. References in brackets indicate conceptualizations focused on the active channel. Material for this figure came partly from Wymore et al. (2023).

groundwater (Jolly et al., 1993) and as areas particularly effective at attenuating peak flows (Lininger & Latrubesse, 2016; Woltemade & Potter, 1994).

A river corridor can be considered at the scale of a reach—defined here as a continuous length of river corridor with consistent geometry and linear downstream increases in drainage area—which may be tens of meters long in a headwaters river and tens of kilometers long in a large, lowland river (6th or larger stream order). Initial conceptualizations of natural (rather than engineered) rivers focused mainly on the active channel and emphasized gradual longitudinal trends (e.g., downstream hydraulic geoemetry, Leopold & Maddock, 1953, or the river continuum concept, Vannote et al., 1980). Recognition of distinct spatial changes in form, process, and function at reach boundaries led to the serial discontinuity concept (Ward & Stanford, 1983) and subsequently the river discontinuum (Poole, 2002), geomorphic process domains (Montgomery, 1999), and river styles (Brierley & Fryirs, 2000). The serial discontinuity concept focused on longitudinal changes in riverine structure and function (e.g., river water temperature, aquatic species abundance, substrate size) associated with dams, with a focus on the active channel. Subsequent iterations of this conceptual model expanded to include channel-floodplain connectivity (Ward & Stanford, 1995). Geomorphic process domains emphasized longitudinal discontinuities in disturbance regimes such as floods and mass movements and associated longitudinal variation in valley gradient and channel planform (Montgomery, 1999). This concept grew out of reach-scale classifications focused on the active channel based on longitudinal changes in predominant bedform type (Montgomery & Buffington, 1997). The geomorphic process domain concept was subsequently applied to longitudinal variation in sediment dynamics (Wohl, 2010), riparian communities (Polvi et al., 2011), and riverine ecosystems (Bellmore & Baxter, 2014). Analogously, river styles uses longitudinal changes in channel planform, bedforms, bed substrate, floodplain morphology, and floodplain vegetation to distinguish individual river reaches (Brierley & Fryirs, 2000).

Quantification of biogeochemical processes and nutrient stocks revealed that river corridors significantly influence global carbon cycles via gaseous emissions (Cole et al., 2007) and storage of organic carbon in floodplain biota and soils (Wohl et al., 2012, 2017). Spatial and temporal heterogeneity of fluxes within floodplains creates a biogeochemical reactor (Appling et al., 2014; Bouchez et al., 2012) with diverse types of biogeochemical control points (Bernhardt et al., 2017). Floodplain wetlands and lakes play a critical role in nutrient dynamics (Wollheim et al., 2018).

Floodplain process and form reflect complex, nonlinear interactions among materials and living organisms from microbial communities to woody floodplain vegetation and animals (Castro & Thorne, 2019; Collins et al., 2012). These interactions occur within the context of the river corridor (Harvey & Gooseff, 2015) or riverscape (Fausch et al., 2002), which emphasizes both three-dimensional exchanges within river corridors and exchanges with the adjacent uplands (Baxter et al., 2005), as initially articulated by Hynes (1975).

2.3. Contemporary Science of Floodplains

Synthesizing the conceptual models in Figure 1 suggests that floodplains are integrative systems that (a) store and biogeochemically transform surface and subsurface water, solutes, sediment, particulate organic matter, and large wood (Appling et al., 2014; Bhowmik & Stall, 1979; Tockner et al., 1999; Wohl, 2020), (b) provide a source of material that can be transported downstream (Dunne et al., 1998; Moustakidis et al., 2024; Robertson et al., 1999), and (c) function as ecosystems (Bayley, 1995; Petsch et al., 2023). Catchment-to reach-scale biophysical templates of floodplains are governed by climate and geology (Annis et al., 2022; Gibling, 2006; Hynes, 1975; Notebaert & Piégay, 2013). Within these templates, interactions and feedbacks create nonlinear configurations and dynamics (e.g., Camporeale et al., 2013; Chen et al., 2020; Collins et al., 2012). The resulting spatial and temporal heterogeneity and 3D connectivity within catchments, river networks, and reach-scale river corridors are fundamental components of floodplain process and form (Heiler et al., 1995; Stoffers et al., 2022).

The effects of large wood on river corridor process and form provide an example of interactions within a template set by climate and geology. A logjam spanning the active channel can create a backwater and downstream scour pool in a laterally confined valley but these effects are likely to be relatively transient because of the inability of the logjam to withstand the hydraulic force of large floods (Wohl, 2011). Less resistant bedrock or glacial history can result in wider valley segments along the same river. Logjams that form in these segments are likely to be more persistent (Wohl & Iskin, 2022; Wohl & Scamardo, 2021) and to create channel avulsion, an anastomosing channel planform, and a more diverse floodplain forest (Collins et al., 2012; Livers et al., 2018).

The effects of temporal variations in magnitude and frequency of floods provide another example of nonlinear interactions within the template of climate and geology. Numerous studies from drylands in the western United States indicate that a multi-decadal decrease in flood magnitude and frequency can correspond to aggradation in the type of incised channels known as arroyos (Aby, 2017; Graf, 1983) and to gradual encroachment by woody riparian vegetation, channel narrowing, and development of a single, sinuous channel in unincised, sand-bed channels (Friedman & Lee, 2002; Jaquette et al., 2005). When flood magnitude and frequency increase, channel incision occurs in arroyos (Webb, 1987). Previously vegetated, meandering channels may assume a braided planform with minimal woody riparian vegetation (Friedman et al., 1996).

The alternate river corridor states of beaver meadows and elk grasslands provide a third example of nonlinear interactions from the northern hemisphere. Within relatively wide river corridors in small-to medium-sized rivers (peak flow stage less than ~3 m above channel bed), beavers (*Castor* spp.) can create numerous dams and a network of canals (Grudzinski et al., 2020; Larsen et al., 2021). The resulting beaver meadow (Ives, 1942; Polvi & Wohl, 2012), has high lateral and vertical connectivity, limited longitudinal connectivity, a high floodplain water table and abundant standing water and floodplain wetlands, an anastomosing channel planform, and high primary productivity and litterfall from floodplain plants (Westbrook et al., 2006). The organic-rich, saturated soil forms a carbon sink (Laurel & Wohl, 2019; Wohl et al., 2012) and the high lateral and vertical connectivity and enhanced hyporheic exchange flows promote nutrient uptake (Naiman et al., 1994). When beaver disappear and the dams fall into disrepair, peak flows are more likely to concentrate in a single channel that incises, the floodplain water table and primary productivity decline, and the river corridor has lower rates of carbon storage and nutrient uptake, even though the basic template set by climate and geology has not necessarily changed.

2.4. Challenges for Progress in Understanding and Managing Floodplains

At least five challenges exist for progress in understanding and managing floodplains within the context described above. Each of these involves both understanding and research foci in the context of basic science, but also applied science as used by river practitioners and regulators.

1. The first challenge involves integrating thinking, data collection, modeling, and prediction across disciplines in a manner that facilitates the work of practitioners and regulators. River scientists working in hydrology, hydraulics, and sediment transport, for example, have made great progress in 2D numerical models that couple hydraulics and transport of sand-sized and finer sediment during the past few decades (Vowinckel, 2021). Models commonly used by those in the practitioner and regulatory communities, however, tend to treat floodplains as static, impermeable surfaces rather than permeable surfaces that are topographically and stratigraphically dynamic during a single flood and that have evolving feedbacks among hydraulics, topography, and vegetation-induced hydraulic roughness (Bates, 2022; Wohl, 2021).
   Prediction across disciplines here refers to quantifying interactions between processes occurring in river corridors that are traditionally the focus of different disciplines. Effective prediction of nitrate concentrations, for example, will likely require integrating across knowledge from biogeochemistry (nitrogen dynamics), hydrology (solute supply and transport), aquatic and riparian ecology (biological uptake of nutrients), and geomorphology (spatial heterogeneity of the river corridor that facilitates lateral and vertical connectivity) (Li et al., 2021; Wollheim et al., 2018). Numerical models that include limited sets of feedbacks are being actively developed by the research community. Examples come from simulations of vegetation and river morphodynamics (sediment transport, channel planform, channel migration, floodplain topography) (Kleinhans et al., 2018; van Oorschot et al., 2016); biogeomorphic interactions in the context of dam construction and climate change (van Oorschot et al., 2018) or dam removal (van Oorschot et al., 2022); and river habitat diversity in relation to flow regime (Nones, 2019). However, there remains a need to both expand the types of feedbacks simulated in these models, as in the example of nitrate concentrations, and to make the use of models and potential predictive understanding more accessible to practitioner and regulatory communities.
2. A second challenge is that of scaling across time and space. Floodplain processes are inherently multiscale and the use of spatially varying data in distributed models can facilitate simulation and prediction with higher resolution than lumped models. However, process nonlinearity, temporal and spatial scale dependence, system observability and heterogeneity, and parameter equifinality create substantial challenges to distributed modeling (Fatichi et al., 2016). Analogously, simulating the biochemophysical interactions in floodplains is necessary, but coupling additional processes and components to models increases the parameter space and the number of constraints on the system response (Fatichi et al., 2016). Most studies involving direct measurements of river process and form focus on relatively small spatial scales and short temporal scales. The resulting insights can diverge significantly from observations over larger spatial and longer temporal scales and can be constrained by the specific characteristics of the measurement site (e.g., Li et al., 2021). Both direct observations and model simulations suggest nonlinearities in process and form within rivers that make scaling considerations critically important. Examples include biogeochemical ecosystem control points at which reactants accumulate until a threshold is overcome (Bernhardt et al., 2017); river beads of lower lateral confinement in mountain rivers that are disproportionately important for biomass and biodiversity (Bellmore & Baxter, 2014; Hauer et al., 2016; Wohl et al., 2018) or floodplain-groundwater exchange (Schulz et al., 2024); and threshold amounts of downed, dead wood in the river corridor that trigger changes in channel mobility and planform (Collins et al., 2012; Wohl, 2011), spatial heterogeneity and associated habitat, biomass, and biodiversity (Venarsky et al., 2018). The research community is increasingly emphasizing the need for catchment-scale models and predictions of the cumulative effects of reach-scale management actions (e.g., Follett et al., 2024; Li et al., 2021; Wymore et al., 2023), but such models and predictions remain a substantial challenge.
3. Measuring and predicting feedbacks and nonlinear interactions constitutes a third primary challenge to understanding floodplains. Floodplain vegetation response to changing hydrologic conditions, for example, differs with the character of the flood (Thapa et al., 2016). Floods initiate a feedback in the form of an adaptive cycle in which the details of floodplain inundation drive vegetation productivity through adaptive cycles rather than simple presence/absence states of water. Vegetation productivity then influences spatial extent and density of vegetation and hydraulic roughness and floodplain inundation (Thapa et al., 2016). More generally, conventional flood prediction relies on static channel geometries, yet changes in flow, sediment supply, and

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vegetation alter the geometry and flood conveyance of river corridors, such that flood inundation extent and frequency can be amplified or attenuated in unexpected ways (Call et al., 2017). Feedbacks among water, sediment, and floodplain topography, hydraulic roughness, and floodplain biota can alter floodplain surface complexity (Scown et al., 2016), attenuation of downstream fluxes (Wohl et al., 2022), and surface-subsurface hydrologic and biogeochemical exchanges (Gambill et al., 2025) at timespans from the duration of a single flood to multiple floods. These interactions can occur over timespans that are longer than the duration of many focused measurement campaigns (Laudon & Sponseller, 2018; Liu et al., 2021) and effective characterization of the feedbacks can require measurement of multiple parameters from the sub-meter scale to at least the reach-scale (e.g., Gomez-Velez et al., 2015; Tiwari et al., 2017).

4. Measuring and predicting resilience and resistance of floodplains and river corridors to natural (e.g., wildfires, floods) and human-induced (e.g., chemical spills) disturbances presents another primary challenge to integrative scientific understanding of floodplains. Resilience is used in many different contexts and defined in different ways (Thoms et al., 2018; Wohl, 2024). There is little consensus on how to measure or predict river resilience (Thoms & Fuller, 2024; Wohl et al., 2024), yet resilience—if defined as the ability of a system to recover function after disturbance—is particularly important given the current situation of changing regimes of flow, sediment, large wood, and solutes, as well as changing climate, biotic communities, and human alterations of catchments, river networks, and individual river reaches (Flores et al., 2017; Hulse & Gregory, 2004; Karpack et al., 2020). Examples of how resilience has been characterized include: transient sediment storage in headwater river corridors following a major disturbance such as wildfire, with the headwater storage attenuating downstream sediment pulses (Triantafillou & Wohl, 2024); persistence of organisms during and after disturbances (Van Looy et al., 2019); persistence of the functionality of river restoration measures (Tullos et al., 2021); recovery or persistence of morphodynamic processes that maintain riverine morphology following disturbance (Hoitink et al., 2020); and sufficient space within the river corridor (i.e., the absence of bank stabilization or human-built levees) to allow the system to physically adjust to changes in water and sediment inputs (Biron et al., 2014). It seems unlikely that a single set of resilience metrics will ever be sufficiently broadly applicable to the diversity of the world's rivers but developing suites of metrics for different types of river forms and functions would be helpful.
5. Finally, our understanding of river ecosystems is inevitably limited by the complexity of the system. This creates uncertainties in basic understanding because of lack of information as well as inherent random variation (Warmink et al., 2017) and these uncertainties can be difficult to translate into practice in the context of river management. Both social and technical uncertainties occur in river management (Warmink et al., 2017). Technical uncertainties can include system complexity and limited understanding of interactions among multiple variables in floodplains, as well as natural and historical range of variability versus future novel states in the context of changing climate and land use (Duxbury et al., 2024; Francis, 2014; Judd et al., 2023). Technical uncertainties are at the heart of the first four challenges outlined above. Although machine learning is increasingly applied to reduce uncertainty of prediction (e.g., Sharafati et al., 2020), being able to effectively communicate uncertainty to nonscientists remains a fundamental challenge (Gustafson & Rice, 2020). Social uncertainties can derive from different perspectives and framings of an issue such as river restoration or flood control, from cognitive bias, and from ambiguity resulting from confusion among stakeholders due to the presence of multiple, valid, and sometimes conflicting interpretation (Van den Hoek et al., 2014; Warmink et al., 2017; Weick et al., 2005). Social uncertainties lie beyond the expertise of most river scientists and will require collaboration with people from social sciences and the humanities if the understanding of contemporary river scientists is to be effectively communicated to others.

3. Conclusions

Of equal importance to the challenges for scientific progress in understanding floodplains is the challenge of translating the integrative perspective of contemporary river science into integrative river management and legal protection for the entire river corridor. As conceptualizations of a river as a river corridor or riverscape are increasingly adopted by river practitioners and regulators, this should facilitate legal recognition of the need to protect rivers beyond the active channel within the constraints created by existing land ownership and floodplain disconnection. Communicating to the general public the ideas that (a) a river includes the floodplain and hyporheic zone, as well as the active channel, and (b) river form, process, and function rely on physical, chemical, and biological processes that human communities are challenged to understand and manipulate without unintended negative consequences, remain important challenges for river scientists.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

No data were created for this paper.

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