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Water Resources Research

REVIEW ARTICLE
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Coupling landscapes and river flows to restore highly modified rivers

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Key Points:
- Channel-floodplain manipulation and environmental flows, themes of river restoration science, converge on restoring biophysical processes
- Opportunities for restoring processes in highly modified rivers are enhanced by coupling channel-floodplain and flow manipulation
- Coupled approaches identify process potential, consider capacity, model alternatives, and evaluate metrics of integration

Supporting Information:
- Supporting Information S1

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Abstract Modifications to landscapes and flow regimes of rivers have altered the function, biodiversity, and productivity of freshwater ecosystems globally. Reestablishing geomorphological and hydrological conditions necessary to sustain ecosystems is a central challenge for restoration within highly altered systems. Meeting this challenge requires simultaneously addressing multiple and interacting stressors within the context of irreversible changes and socio-economic constraints. Traditionally, river restoration approaches either physically change the landscape or channel (channel-floodplain manipulation) or adjust hydrology (environmental flows), and such actions are often independent. We juxtapose these two subfields of river restoration, which have undergone parallel transformations, from goals of reproducing static representations of form and flow regime to goals of reestablishing processes. The parallel transformations have generated shared ideas, which point to benefits of coupling channel-floodplain manipulation and environmental flow actions to achieve process-based goals. Such coupling supports comprehensive river restoration efforts aimed at supporting resilient ecosystems within human dominated landscapes in a nonstationary climate. We identify four elements of coupled approaches for restoring highly modified rivers: (1) identify physical and ecological process potential given interactive effects of altered landscapes and flows; (2) consider capacity for sustaining identified processes under potential future change; (3) model alternatives for coupled restoration actions to support identified processes; and (4) evaluate alternatives using metrics representing integrative effects of coupled actions. We suggest these emergent elements contribute to the development of standard practices for restoring highly modified rivers and encourage an increasing number and quality of coupled applications.

Plain Language Summary Freshwater ecosystems globally have been fundamentally altered and degraded by multiple human modifications of rivers, which have affected the amount and timing of water availability as well as the riverine landscape with which river flows interact. Knowing that it is often impossible or infeasible to completely reverse these impacts, a central challenge for restoring freshwater ecosystems of highly modified rivers is to determine what water management changes and physical habitat restoration actions can be taken to reestablish processes necessary to support ecosystems. These different river restoration approaches have traditionally been considered independently of one another. However, both river restoration subfields have shifted in recent decades from goals of reproducing static representations of channel forms or reference flow regimes to those of reestablishing processes driven by flow-landscape interaction. This shared understanding points to the benefits of coupling channel-floodplain manipulation and water management for a combined added positive impact to ecosystems. Four elements of coupled approaches are identified: (1) identify process potential; (2) consider capacity under potential future change; (3) model alternatives; and (4) evaluate metrics of integrative effects. This commentary supports the development of standard practices for coupled approaches for restoring highly modified rivers.

1. Concepts Behind Restoration of Highly Modified Rivers

Rivers and their freshwater ecosystems have been transformed and continue to undergo profound environmental change as a result of extensive human modification of streamflow, landscape, and climate. More than half of the world's major rivers are regulated by dams (Nilsson et al., 2005), which, along with long histories of levee building, channelization, water abstraction, and land use change, have homogenized the hydrologic, geomorphic, and ecological dynamics driving riverine ecosystem structure and function (Poff et al., 2007; Wohl et al., 2017). Most river systems have been transformed by multiple stressors that impact both landscapes and flows and interact to alter the availability of water in space and time, sediment and

thermal regimes, and disturbance processes (Ward & Stanford, 1995). Such problems are multiplied and intensified by other stressors, such as invasive species or water quality degradation, which may fundamentally alter food webs and erode ecosystem resilience. Global freshwater ecosystem biodiversity is severely compromised as a result (Meybeck, 2003; Vörösmarty et al., 2010). Increasingly, climate change amplifies threats and interacts with other factors of change, demanding proactive and adaptive management strategies (Malmqvist & Rundle, 2002; Palmer et al., 2009). Degradation is particularly pronounced within lowland alluvial floodplain environments, which attract development and accumulate upstream impacts (Naiman et al., 2002). Despite being some of the most diverse and productive ecosystems, freshwater-dependent ecosystems are also among the most impaired worldwide (Dudgeon et al., 2006; Tockner & Stanford, 2002).

With riverine ecosystems increasingly altered by human activities, there is urgent need for realistic definitions of restoration objectives given constraints, including the persistence of nonnative species, development within floodplains, dams regulating rivers, and nonstationary no-analog climates (Palmer et al., 2004). Overly precise conservation and restoration targets—many of which may be unrealistic for highly altered systems—may restrict variability and erode ecosystem resilience (Hiers et al., 2016). Similarly, engineering specific conditions for only some locations or certain ecological functions may come at the expense of supporting the range of processes necessary to sustain the wider ecosystem (Bond et al., 2014; Pittock et al., 2013). As such, there is a need to define restoration actions by their potential to maintain ecological integrity or to support diverse and productive ecosystems that are resilient to change as opposed to specific native species or reference conditions (Hobbs & Harris, 2001; Naiman et al., 2012; Poff, 2017; Rieman et al., 2015; Williams et al., 2015). Though targeting natural flows regimes or historical channel forms may no longer be appropriate in many cases, reinstating physical processes that support desired ecosystem functions may still be feasible. It is therefore necessary to determine the suite of actions that may best address those processes or functions when coupled together, a potentially more challenging task than attempting to reproduce a hydrograph or channel form in isolation of the other.

Over the last several decades, recognition of the many interacting factors affecting riverine ecosystems has led to rapid growth in the science and practice of river restoration. Applications have expanded from small-scale actions in headwater streams to new domains and challenges within larger rivers and their floodplains (Beechie et al., 2009; Gore & Shields, 1995; Schiemer et al., 1999; Sparks, 1995). Though many restoration efforts continue to address single issues at the site-scale, more comprehensive programs now employ a multitude of restoration actions at different scales. Typical restoration measures to encourage more natural geomorphic and hydrologic patterns and processes can be grouped generally into those that directly alter the riverine landscape physically and more locally (e.g., channel redesign, levee removal, riparian plantings)—herein referred to as channel-floodplain manipulation—and those that adjust altered flow regimes (e.g., dam reoperation or removal, regulating diversions)—collectively referred to as environmental flows in the literature (Bernhardt & Palmer, 2011; Hudson, 2002; Jacobson & Berkley, 2011; Palmer et al., 2014). Though not explored here, there is growing emphasis in the scientific literature on addressing ecological limitations (e.g., altered food web dynamics, invasive species, altered biogeochemical processes, and poor water quality) through actions such as invasive species control or nutrient management (Acreman et al., 2014; Bellmore et al., 2017; Lake et al., 2007; Naiman et al., 2012). Also not within the scope of this discussion is the increasingly recognized issue that challenges of river restoration are not only scientific but also social, political, and economic (Eden et al., 2000; Naiman, 2013; Palmer et al., 2014; Rogers, 2006).

Tracking themes emergent from the restoration ecology literature (Hobbs & Harris, 2001; Hobbs & Norton, 1996), the field of river restoration has generally transformed from an early and primary focus on form (e.g., creating river meanders) or definitions of static conditions (e.g., implementing a minimum instream flow) to its current focus on dynamic hydrologic, geomorphic, and ecological processes (Beechie et al., 2010; Kondolf et al., 2006; Palmer et al., 2014; Tharme, 2003; Wohl et al., 2015; Yarnell et al., 2015). This transition accelerated several decades ago, as science established that interaction of variable flow and sediment regimes with heterogeneous landscape patterns produces and maintains diverse conditions in space and time that support ecological diversity and productivity (Gore & Petts, 1989; Junk et al., 1989; Naiman et al., 2002; Petts, 1996; Poff et al., 1997; Ward & Stanford, 1995). There is broad consensus that the recreation of form—the "Field of Dreams" hypothesis of "if you build it, they will come" (Palmer et al., 1997)—does not mean biophysical processes necessary to support ecosystem functions will be reestablished (McDonald et al., 2004). The flow regime is well understood to be a master variable driving riverine and floodplain ecosystems, a

concept solidified in the natural flow regime paradigm of Poff et al. (1997), which has led to management for natural flow variability becoming a central tenet of river restoration (Poff & Matthews, 2013). The ecological significance of flow-landscape interaction emerged in part from the flood pulse concept of Junk et al. (1989), which articulated linkages between physical and ecological processes, ecological implications of a variable flood pulse interacting with complex physical structures, and the critical ecohydrological role of seasonal floodplains in large river systems. Later, Tockner et al. (2000) demonstrated the importance of river-floodplain interaction in relating hydrologic connectivity to species diversity. Hydrologic connectivity and spatiotemporal variability are identified as core restoration objectives (Fausch et al., 2002; Opperman et al., 2010; Ward & Stanford, 1995). However, meeting these restoration objectives, such that they reestablish biophysical processes and related ecosystem functions in environments fundamentally altered by multiple pressures, remains a central scientific challenge (Brewer et al., 2016; Palmer & Bernhardt, 2006).

Along with the shift from form-based to process-based thinking, restoration failures and unintended consequences have led to the recognition that channel-floodplain manipulation or the implementation of environmental flows alone may be insufficient to achieve desired outcomes within heavily engineered and regulated rivers (Arthington et al., 2010; Kondolf, 2011; Palmer et al., 2014; Wohl et al., 2015). The absence of coupled or coordinated planning and implementation of channel-floodplain manipulation and environmental flows in the past has hampered the rehabilitation of highly degraded riverine ecosystems (Arthington et al., 2010; Kondolf et al., 2006; Palmer et al., 2014; Wohl, Lane, & Wilcox, 2015). This paper focuses on the intersection of process-based goals for reestablishing more naturally functioning ecosystems in highly modified rivers. For the purposes of this discussion, we define these rivers as river-floodplain systems degraded by substantial and potentially irreversible landscape alteration and flow regulation or diversions, which tend to be what are considered large (e.g., unregulated mean annual discharge >350 m^3/s) alluvial rivers (in the sense of Jacobson & Galat, 2006; Nilsson et al., 2005; Tockner et al., 2011; Yarnell et al., 2015). We note this discussion is not intended as a comprehensive assessment of current river restoration science. Rather, we limit our scope to scientific perspectives of channel-floodplain manipulation and environmental flows in order to focus on their convergence toward coupled restoration strategies for reestablishing dynamic hydrogeomorphic processes in highly modified rivers. Specifically, we briefly summarize these perspectives and discuss how emphasis on process-based approaches integrates these perspectives and points to the benefits of coordinated restoration actions. To facilitate development of the science and application of concepts in practice, we identify elements for coupled restoration approaches, drawing from examples in the literature.

2. Channel-Floodplain Manipulation and Environmental Flows as Themes Within the River Restoration Literature

River restoration science has expanded rapidly in recent years, with channel-floodplain manipulation and environmental flows as discernable themes, or subfields, within the broader literature. The growth is corroborated by a search of the scientific literature, which suggests a 12.5% median annual increase in the number of papers on river restoration since 1990 (Web of Science search $n = 8{,}583$; Figure S1 in the supporting information; Whipple & Viers, 2019). Search criteria were selected from a diverse set of terms common to the field in an effort to be inclusive (i.e., minimize error of omission), and the search syntax was constructed to reduce returns of nonrelevant papers (i.e., minimize error of commission). However, the resulting bibliometric data set remains subject to these issues (see Text S1 for search details). For general characterization and visualization, papers were classified based on word associations within the title and keywords (see Text S2 for classification details). The interconnectivity of river restoration literature was explored using citation network analysis of the bibliometric data set (Brughmans, 2013). We established a directed network of peer-reviewed journal papers published since 1990, which connected papers cited at least once ($n = 7{,}600$) to highly cited papers (20 or more citations per year; $n = 51$; Text S3).

Figure 1 depicts the network, which shows most highly cited papers to be well connected, with some noticeable patterns. The highly cited papers in the lower center and denser part of the network—many of which specifically focus on advancing the science of environmental flows (e.g., Poff et al., 2010; Richter et al., 1997; Tharme, 2003)—are drawn together by flow-related papers citing them. Many of the highly cited

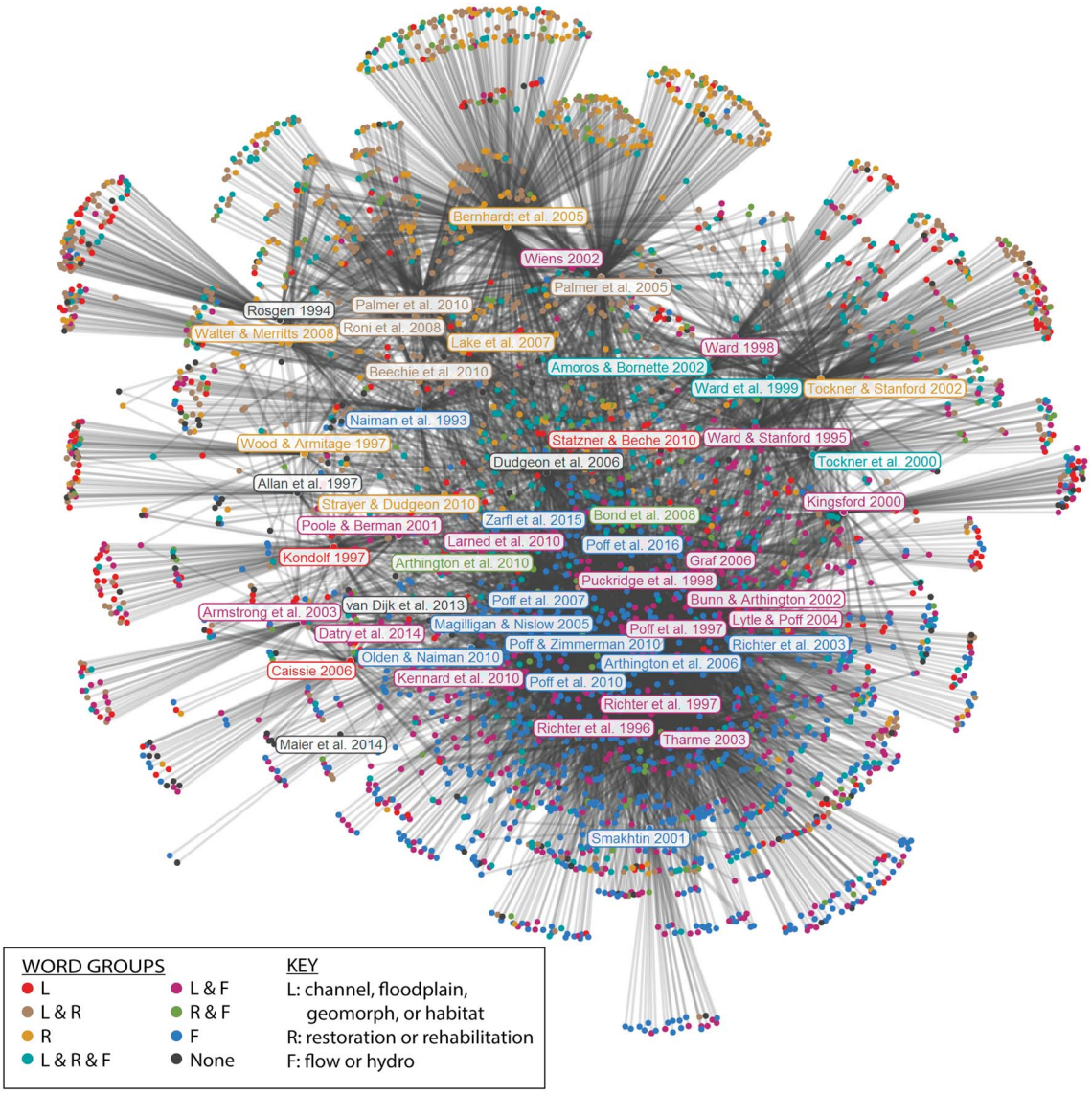

Figure 1. Diagram of directed network of river restoration peer-reviewed journal articles (cited at least once) citing highly cited papers (labeled, defined as papers with at least 20 citations per year) from a Web of Science topic search of river restoration literature (see Text S1 for search terms and criteria). Colors indicate word associations in the title or keywords, grouped as landscape- (L), restoration- (R), and flow-related (F) terms, combined into seven classes (see Text S2 for classification details). Flow-associated papers are clustered around highly cited environmental flow papers, whereas papers assigned to word groups not related to flow are found more at the periphery.

papers addressing aspects of river restoration other than (or more broadly than) environmental flows are pulled more to the periphery, often cited by a diverse pool of papers (including, but not limited to those addressing channel-floodplain manipulation), very few of which are related to flows alone. These highly cited papers include those that present river restoration principles (e.g., Beechie et al., 2010; Palmer et al., 2005; Stanford et al., 1996), review river restoration practice (e.g., Bernhardt et al., 2005), or advance riverine landscape ecology (Figure S2; e.g., Lake et al., 2007; Ward et al., 1999; Wiens, 2002).

This citation network offers a depiction of general patterns observed from reading the literature, though we note this diagram is just one of many ways to view a complex literature (see Text S3 for network details). While bibliometric analysis such as this cannot replace thorough reading of the literature, it can be a useful investigative tool. This approach helps address practical challenges of comprehending what is now a voluminous body of river restoration literature. Detailed review of papers most germane to the subject can thus be supported by exploration of the larger body of work. The core arguments of this paper were developed

based on our careful reading of the literature, with this analysis adding context, corroboration, and illustration of pattern.

Much of the separation between subfields can be attributed to the fact that there are many causes of change in river systems. As noted by Bernhardt and Palmer (2011), geographic locations where water is generally plentiful but highly impacted by land uses (e.g., channelization, nutrient runoff) have historically inspired channel-floodplain manipulation approaches to river restoration (e.g., localized physical habitat restoration), while water scarcity and subsequent infrastructure development to move and store water, typically in arid and semiarid environments and often within agricultural contexts, have catalyzed efforts to better allocate or utilize flows for ecosystems. For example, a suite of responses to repair riverine ecosystems degraded by contaminated urban runoff and loss of riparian forests would be expected to be quite different from those addressing the reduction of flood peaks due to dams. Different scientific disciplines have addressed the variety of context-dependent challenges, as recognized by those encouraging more interdisciplinary river restoration approaches (e.g., Buijse et al., 2002; Nestler et al., 2016; Newson et al., 2012; Palmer & Bernhardt, 2006). Additionally, with many physical changes originating at the reach scale and local institutional management structures, channel-floodplain manipulation responses have often developed with limited geographic scope, in isolation from the larger landscape context (Hobbs & Norton, 1996; Hughes et al., 2001). Conversely, flow alteration typically occurs at a much broader geographic scale such that the scope of environmental flow strategies rarely resolve reach-scale needs (Arthington et al., 2010; Beechie et al., 2010).

Furthermore, river restoration in practice is often disjointed, as management of land and water resources is typically conducted separately by different organizations, at different spatial scales, and/or governed and funded by different policies (Allan et al., 1997; Gumiero et al., 2013; Newson et al., 2012; Poff & Matthews, 2013). This disconnect between need and implementation has long been recognized, with river basin management arising more than three decades ago partly in response to this issue (Downs et al., 1991; Lundqvist et al., 1985). Watershed management plans and restoration programs attempt to address these disconnects by providing a basin-scale context and by identifying suites of promising restoration actions, from site-specific habitat restoration actions to broad water infrastructure and policy reforms. However, a watershed plan alone does not necessarily translate to coordinated restoration efforts. For example, in a review of California river restoration actions, Kondolf et al. (2007) found that although plans were often present, they usually did not substantially influence project outcomes. Observed patterns within the literature may be partly attributable to such institutional and management challenges, and the discussion herein underscores the broader need to recognize and address these issues.

The general patterns in the literature discussed here make sense for a research field like river restoration that encompasses a wide range of issues. At the same time, they also motivate exploration of how the subfields of channel-floodplain manipulation and environmental flows intersect, influence one another, and have been considered jointly in the science and practice of river restoration. To explore the intersection of river restoration perspectives, the following section discusses the shift in the field of river restoration toward process-based principles specifically as it relates to addressing challenges of restoring highly modified rivers.

3. Process-Based Thinking Drives Convergent Perspectives

Some of the earliest efforts (early twentieth century in the United States) to restore rivers and streams focused on improving conditions for fish (Thompson & Stull, 2002), and these activities tended to be associated with remedying local-scale conditions within smaller stream systems (Bernhardt et al., 2005; Roni et al., 2008). Several decades later, as dams regulating rivers in the United States and Europe became pervasive, methods for establishing instream flow needs for fish were developed (Tennant, 1976) and principles for regulated river management were established (Gore & Petts, 1989; Petts, 1996). The environmental regulations of the late 1960s and 1970s increased attention and generated further expansion of river restoration efforts, with fish still the primary focus (Lave et al., 2010). During this period, foundational research in fluvial geomorphology, led primarily by Luna Leopold (Leopold & Maddock, 1953; Wolman & Leopold, 1957), established the role of riverine processes and dynamics in the development and maintenance of channel form and habitat, and thus advanced scientific understanding of the nature and causes of riverine degradation and the scientific basis for river restoration. These origins fostered different emphases within the river

restoration field, and the following sections juxtapose the progression of channel-floodplain manipulation and environmental flows literature through their convergence on process-based approaches.

3.1. Evolving Channel-Floodplain Manipulation Approaches

Traditionally, channel-floodplain manipulation approaches have focused on altering channel morphology to reconfigure the physical structure of a river or stream to match a perceived "natural" form or to provide habitat for a particular species or, more recently, particular ecosystem services (Palmer et al., 2014; Wohl et al., 2005). However, these types of channel-floodplain manipulation approaches—typically prescriptive, engineering oriented, and limited in spatial scope—have been criticized as simplified applications of scientific concepts (Bernhardt et al., 2005; Kondolf, 1998; Lave et al., 2010; Palmer et al., 2014; Wilcock, 1997). Expected benefits of riparian planting may not accrue, for example, when underlying factors of alteration are not addressed, such as land cover change or a declining water table (Giling et al., 2016; Stromberg et al., 2007). Watershed-scale changes affecting hydrogeomorphic regimes or water quality may be unrecognized, inadequately understood, or disregarded as outside the purview of reach-scale restoration projects (Kondolf et al., 2007; Palmer et al., 2014; Roni et al., 2008; Tockner & Stanford, 2002). Kondolf et al. (2006) analyzed restoration trajectories along axes of streamflow variability and connectivity (representing channel-floodplain manipulation-related activities), concluding that restoration actions rarely remedy causes of degradation in part because some actions, such as promoting hydrologic connectivity, are easier —politically and economically—than others. In many cases, causes of degradation are valuable socioeconomic activities, such as flow alteration resulting from irrigation and hydropower, which require extensive infrastructure and investment. Thus, the relatively more costly environmental flow options may incentivize the use of channel-floodplain manipulation alternatives as surrogates for flow restoration (e.g., Rieman et al., 2015). Consequently, many reach-scale efforts do not address the root causes of degradation that can overwhelm such small positive actions, rendering restoration goals unattainable (Beechie et al., 2010; Kondolf et al., 2006; Lake et al., 2007).

Clarification of these restoration limitations has motivated a shift toward process-based principles, including managing for dynamic habitat mosaics that respond to variability (Fryirs & Brierley, 2009; Kondolf et al., 2006; Palmer et al., 2005), planning at the scale of physical and biological processes (Beechie et al., 2010), accounting for local or landscape potential (Beechie et al., 2013), and addressing causes of degradation as well as changes at the watershed scale (Beechie, Richardson, et al., 2013; Palmer et al., 2014; Wohl et al., 2005; Wohl, Lane, & Wilcox, 2015). A central concept is to set restoration objectives and develop actions based on processes rather than a fixed outcome (Beechie et al., 2010; Bernhardt & Palmer, 2011; Wohl et al., 2005). With a focus on how a river works, fluvial geomorphology has become an important contributor to restoration planning (Brierley et al., 2002; Gilvear, 1999). Some of the first process-based approaches were developed for salmonid habitat restoration in the Pacific Northwest (Beechie & Bolton, 1999). Process-oriented actions in large lowland alluvial rivers typically work to restore hydrologic connectivity and floodplain geomorphic processes (Buijse et al., 2002; Florsheim & Mount, 2002; Schiemer et al., 1999; Wohl, Lane, & Wilcox, 2015). From the channel-floodplain manipulation perspective, levee removal, for example, has been shown to restart erosional and depositional processes, which in turn reestablishes complex topography and a mosaic of dynamic habitats important for riparian forest succession and biodiversity (Florsheim & Mount, 2002). Today, process-based principles underlie restoration of rivers and streams globally, at different scales and across a range of objectives.

With regulated rivers, however, simply providing room for the river to reestablish processes may be insufficient (Kondolf, 2011) and may mean missing potential opportunities for ecological improvement (Wohl et al., 2005). In such cases, developing restoration strategies while assuming natural flow and sediment regimes may be inappropriate, yielding unexpected results (Clarke et al., 2003; Kondolf et al., 2006; Wohl, Lane, & Wilcox, 2015). This can occur even if the actions themselves are process motivated, such as levee removal in a highly regulated river that may fail to reintroduce floodplain inundation dynamics known to be important for focal species (Matella & Merenlender, 2015). Simply put, restoring only the morphological side of the equation for dynamic interactions of flow and landscape is unlikely to produce the spatiotemporal variability and complexity of environmental conditions to which ecosystems are adapted.

Understanding hydrogeomorphic processes and how and why they have changed facilitates more effective and efficient restoration strategies (Beechie, Richardson, et al., 2013). Following process-based restoration

protocols can benefit from watershed assessments that describe existing processes, factors of change, and potential limitations (Beechie et al., 2008; Roni et al., 2002). To develop strategic actions, reach-scale actions must be placed within a broader spatial context, from channel to watershed, where processes and impacts occurring at many scales are understood (Fausch et al., 2002). In highly modified rivers, such assessment also helps identify aspects of the system that may be fundamentally altered and restoration actions that may best align with current limitations (Beechie, Richardson, et al., 2013). Further, a landscape-scale perspective is increasingly needed to understand climate change implications and to maintain diverse and productive ecosystems under a range of possible future conditions (Beechie et al., 2013; Williams et al., 2015).

While there is general recognition that returning to some past state in highly modified systems is rarely feasible, working to restore more natural physical and ecological processes within existing constraints can support desired ecosystem functions (Opperman et al., 2010; Stanford et al., 1996). For example, the ecohydrogeomorphic approach of Clarke et al. (2003) involved determining appropriate forms and strategic site selection of projects given altered landscapes and hydrologic regimes. Rohde et al. (2006) accounted for watershed-level impacts by examining physical as well as socio-economic factors affecting floodplain restoration, such as hydrologic alteration, bed load, and flood protection infrastructure. To account for limitations of the highly regulated Rhine River in the Netherlands, planning processes have involved floodplain and channel excavations alongside levee removal to encourage sedimentation and riparian vegetation succession while also increasing flood conveyance capacity (Baptist et al., 2004). In another example, Trush et al. (2000) and Downs et al. (2011), on two different rivers in California, proposed encouraging beneficial processes through downscaling river morphology to match altered flow regimes. These hydrogeomorphic concepts align with Ward and Stanford (1995), who suggested that physical changes can be made to counter the impacts of altered flows.

3.2. Evolving Environmental Flows Approaches

The scientific basis for management of water for ecosystems, widely referred to as environmental flows, has also transitioned from more static definitions (e.g., minimum flow and percent flow) to variable flows that support ecological and geomorphic processes and functions (Arthington et al., 2006). Arising initially in the late 1970s as minimum instream flow targets for fisheries below dams (Tennant, 1976), the environmental flows literature now encompasses a broad array of purposes and approaches (Kennen et al., 2018; Petts, 2009; Tharme, 2003). Typically, environmental flows in practice target individual species requirements, specific landforms or physical habitat types, or a reference hydrograph in the absence of function or process justification (Acreman et al., 2014; Arthington et al., 2006; Yarnell et al., 2015). The shift toward more process-based thinking is represented in the widespread adoption of the natural flow regime paradigm by Poff et al. (1997), which emphasized that ecosystems are adapted to flow dynamics and variability, expressed by flow regime components of magnitude, frequency, duration, timing, and rate of change. Numerous approaches have been developed to apply these principles to achieve more natural flow regimes while also addressing human demands (Tharme, 2003). Many rely on some form of hydrologic analysis to define environmental flow targets that presumably maximize ecological benefits (Bond et al., 2018; Richter et al., 1996, 1997). However, as the natural flow regime is rarely achievable, particularly in highly modified rivers, the resulting compromised flow targets are often criticized for lacking a process-based grounding connected to ecological functions (Arthington et al., 2006; Shenton et al., 2012). Other approaches for establishing flow recommendations, such as the Instream Flow Incremental Methodology and Physical Habitat Simulation technique (Bovee, 1982), address the relationship between flow and habitat (though often limited to in-channel habitat for particular fish life history functions) but generally do not consider the role of dynamics and fluvial geomorphic processes necessary to maintain conditions (Clarke et al., 2003; Petts, 2009).

More holistic approaches to environmental flows, such as Ecological Limits of Hydrologic Alteration (ELOHA; Poff et al., 2010), are increasingly common given their improved capacity to account for multiple ecological and geomorphic objectives and constraints in flow alterations and ecological responses. Developing appropriate and useful flow-ecology relationships for these methods is an important area of research (Arthington et al., 2010; Davies et al., 2014; Poff, 2017). Holistic methods include the "bottom-up" concept of managing for specific flows or components of a flow regime that drive processes supporting desired ecological functions, particularly valuable for prioritizing flow objectives in heavily regulated systems. Such ideas are found in the early Building Block Methodology (King & Louw, 1998), the naturalized

flow regime design of Jacobson and Galat (2008), and more recent emphasis on "functional flows" (Yarnell et al., 2015). Process-based thinking has encouraged the inclusion of geomorphic considerations, such as transport processes and management of the natural sediment regime alongside the natural flow regime (e.g., de Jalón et al., 2017; Kondolf & Wilcock, 1996; Shafroth et al., 2010; Trush et al., 2000; Wohl, Bledsoe, et al., 2015; Yarnell et al., 2015). Prominent examples of geomorphically focused flow objectives exist, such as the high flow experiment protocol for the Colorado River. There, alongside other species-oriented flow requirements, floods released from Glen Canyon Dam have been specifically designed through modeling for their capacity to move sand and thereby meet multiple objectives, including fish habitat (Melis et al., 2015; Schmidt et al., 2001; Wright & Kaplinski, 2011).

Altered riverine landscapes can profoundly influence the effectiveness of environmental flows (Meitzen et al., 2013). However, approaches to setting environmental flows typically do not involve assessments of whether the appropriate landscape exists with which flows can interact. Such an assumption is challenged by myriad changes at multiple scales, including sediment regime alteration, leveeing and channelization of rivers, as well as groundwater extraction, water quality degradation (e.g., thermal regime change), and invasive species (Davies et al., 2014; Wohl, Bledsoe, et al., 2015). Inadequate consideration of these issues is often acknowledged as a limitation in environmental flow studies (e.g., Acreman, Overton, et al., 2014; Brooks et al., 2011; Growns, 2016; King et al., 2010; Reich et al., 2010; Steinfeld & Kingsford, 2013; Thompson et al., 2017). Missing geomorphic components may limit the reestablishment of dynamic physical processes and thus make it difficult to meet ecological objectives. For example, reintroducing high-magnitude, long-duration floods of a more natural flood regime may not produce positive results if the sediment to be moved by the floods is no longer present (Arthington et al., 2010; Wohl, Bledsoe, et al., 2015). Furthermore, reinstating historical flow regimes may in fact be detrimental to some ecosystems (Brewer et al., 2016; Palmer et al., 2014). A study by Tracy-Smith et al. (2012) on Missouri River sandbar habitat showed that natural and environmental flow alternatives were less beneficial than regulated flows within the context of the channelized reach morphology of the river. Spatial and temporal constraints, such as land available for floodplain processes and potential timing and duration of associated flood pulses within modified floodplains, are increasingly recognized as important components of environmental flow assessments (Lake et al., 2007; Opperman et al., 2010; Yarnell et al., 2015).

Researchers have called for growth in environmental flows science that considers how flows interact with fundamentally altered landscapes in developing process-based strategies (Brewer et al., 2016; Dunbar & Acreman, 2001; Poff, 2017). Some have warned that defining a natural flow regime for highly modified rivers is not straightforward, or even possible in some cases (Acreman, Arthington, et al., 2014; Petts, 2009). Very different flow targets may result depending on whether a natural flow regime is some description of a past state or defined for its potential within the existing landscape and/or future climate. Recent conversations suggest that climate nonstationarity and "novel" ecosystems (Hobbs et al., 2009) make it necessary to develop dynamic flow prescriptions defined by process-based links to ecological responses with goals of ecosystem resilience rather than ones based on reference conditions (Acreman, Arthington, et al., 2014; Poff, 2017). Some caution, however, that managing for specific desired functions or services should not be taken too far and recommend a focus on reestablishing naturally variable and dynamic processes (Higgs et al., 2014; Palmer et al., 2014). Poff et al. (2010) stated that a central challenge to environmental flow advancement is including the effects of flow-landscape interactions, and, more recently, Poff (2017) and Thompson et al. (2017) encouraged environmental flow science to adopt a broader approach that considers how other factors of change or environmental variables may mediate relationships between flow and ecology.

4. Why Coupled Approaches to Restore Highly Modified Rivers Make Sense

In highly modified systems with interdependent causes of degradation, considering problems individually may limit potential for restoration success in practice (Arthington et al., 2010; Kondolf et al., 2006; Palmer et al., 2014; Wohl, Lane, & Wilcox, 2015). Developing effective river restoration strategies rests on a process-based and landscape-scale understanding of the system that illuminates connections and interactions between physical processes, anthropogenic alteration, and ecological structure and function (Beechie et al., 2010; Palmer et al., 2014; Wohl et al., 2005). In fundamentally altered systems, it may be found that the most effective means for restoring processes involves altering landscapes and/or flow

regimes in ways that do not reflect historical appearances of one or both aspects (Hobbs & Harris, 2001; Jackson & Pringle, 2010; Meitzen et al., 2013; Nilsson et al., 2007; Stanford et al., 1996).

There is general consensus that greater ecological benefit is achievable when multiple problems are addressed together from a process-oriented perspective. And, just as stressors interact, so do effects of channel-floodplain manipulation and environmental flow actions. Implementation or adjustment to one type of restoration could vastly amplify (or possibly negate) the positive benefits of another restoration action. It follows that restoring processes in highly modified rivers should involve coupled actions of all types, including both channel-floodplain and hydrologic adjustments, that are planned and implemented in a coordinated way to encourage the diverse habitat mosaics and fluvial dynamism upon which ecosystems depend (Arthington et al., 2018; Beechie et al., 2010; Rieman et al., 2015). This has the effect of broadening the spectrum and combinations of alternatives. Although these concepts are well recognized, we suggest that as rivers face increasing pressures and become more intensively managed (Acreman, Overton, et al., 2014; Palmer et al., 2004), there is room for greater attention toward incorporating coupled approaches into the science and practice of managing and restoring these highly modified systems. For example, the potential role of channel-floodplain manipulation activities in affecting outcomes of environmental flow management arises only briefly as part of general recommendations (Arthington et al., 2018) in a recent special issue on managing environmental water (Kennen et al., 2018).

The opportunities afforded by coupled approaches are especially apparent when considering flow releases below dams in conjunction with measures to enhance river-floodplain connectivity within lowland alluvial rivers (Hughes & Rood, 2003; Lake, 2012; Lamouroux et al., 2015; Nilsson et al., 2007), which would address some of the primary degrading forces in large rivers (Gore & Shields, 1995). Figure 2 provides a conceptual example of potential benefits accrued when coupling channel-floodplain manipulation and environmental flow approaches for such a situation. In (a), the current flow regime limits potential from expansion of the active floodplain through levee removal, leading to selected actions (restoration actions 1–8 in inset) including excavation to increase flood frequency and horticultural planting. When only environmental flow actions are considered (restoration actions I–VIII in inset), introduced flood peaks may enhance sediment processes but may have limited ecological benefits due to leveed channels. Coupling channel-floodplain manipulation and environmental flows (c) allows for greater benefits by establishing environmental flows that can take advantage of expanded floodplain area from levee removal. Figure 2 also illustrates that the suite of actions and their magnitudes (e.g., major versus minor alteration to flow releases) selected in coupled approaches might be different than simply combining channel-floodplain manipulation and environmental flow options chosen independently. Fundamental to this integrated concept is that it is not simply the addition of restoration prescriptions but rather development of coordinated strategies that result in greater impact than that summed from individual actions.

5. Elements of Coupled Approaches Are Emergent in the Literature

A growing number of studies apply elements useful for coupling channel-floodplain manipulation and environmental flows to achieve synergistic restoration outcomes in highly modified rivers (Table 1). We identified four emergent elements from these and other studies to encourage development of standard practices for coupled approaches that enhance opportunities for restoring highly modified rivers. These emergent elements are (1) identify physical and ecological process potential given interactive effects of altered landscapes and flows; (2) consider capacity for sustaining identified processes under potential future change; (3) model alternatives for coupled restoration actions to support identified processes; and (4) evaluate alternatives using metrics representing integrative effects of coupled actions. We suggest that applying these elements, which are described in the following sections, enables more effective and efficient restoration practice overall. They align with and can be mechanisms for applying guiding river restoration principles established in the literature, such as establishing clear objectives (Kondolf, 1995), addressing root causes of degradation (Beechie et al., 2010), selecting appropriate restoration methods within existing constraints (Wohl et al., 2005), restoring hydrogeomorphic connections (Yarnell et al., 2015), and establishing self-sustaining and resilient riverine systems (Palmer et al., 2005). We note that these elements augment, as opposed to supplant, existing river restoration frameworks, as is illustrated in Figure 3 where elements are linked to the restoration framework of Skidmore et al. (2013). They can be incorporated into

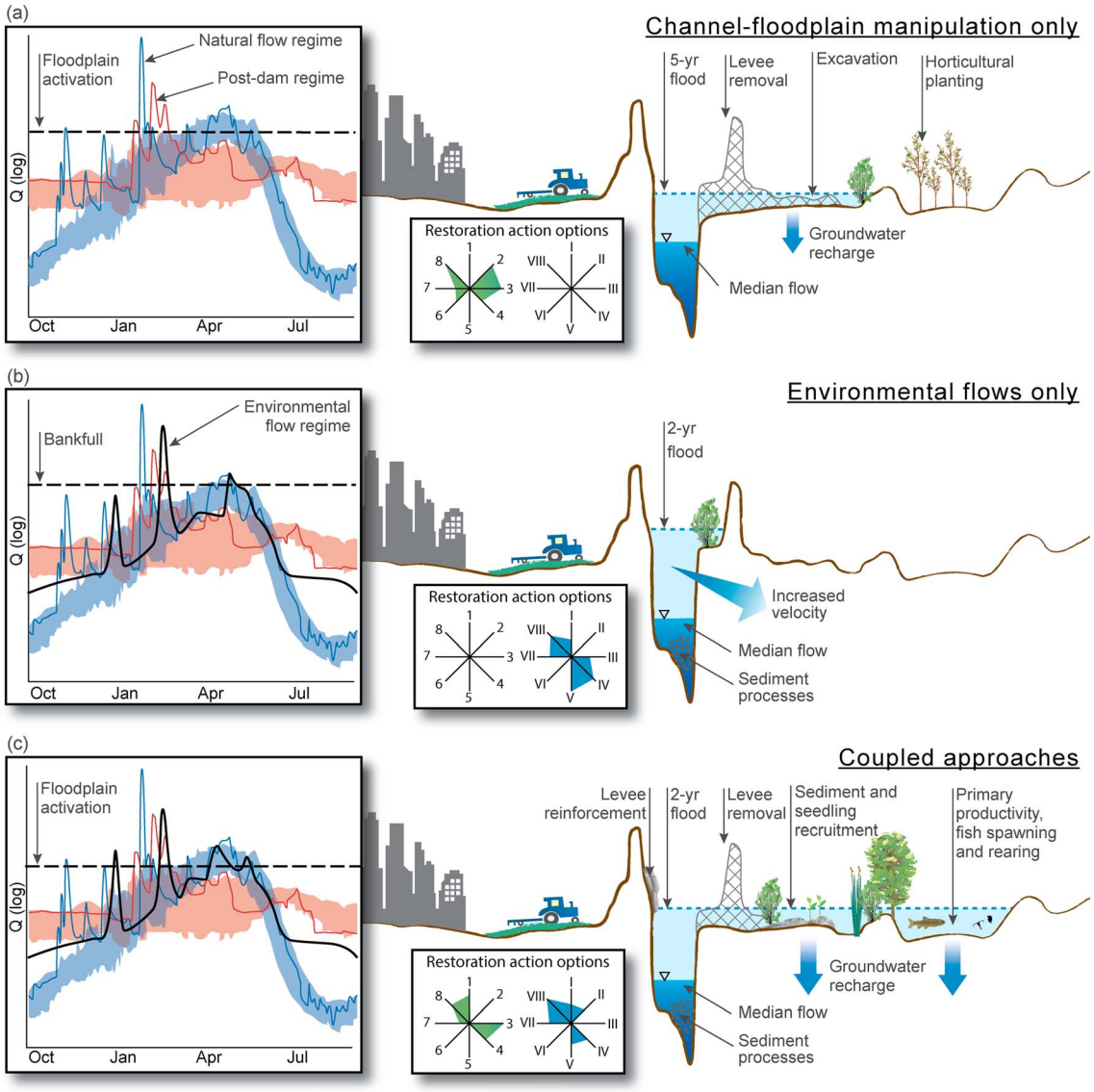

Figure 2. Conceptual graphic illustrating how channel-floodplain manipulation (a) and environmental flows (b) can each accrue certain benefits when applied independently. If coupled (c), different actions may be selected (e.g., excavation in (a) for more frequent inundation, multiple spring pulse flows in (c) for secondary production, lower peak environmental flow needed in (c)) and there is potential for greater benefit than if each were planned and implemented alone. Inset "restoration action options" boxes conceptualize the selection of these different options for each case (1–8 for channel-floodplain manipulation, I–VIII for environmental flows). Inset hydrographs depict a (mostly) natural flow regime (blue) and postdam regime (red) based on hydrographs of years representing median total annual flow volume with shaded 0.25th–0.75th percentile range for a snowmelt-dominated large river in western United States. A hypothetical environmental flow regime is shown in black.

monitoring and adaptive management frameworks as systems respond and evolve over time. While many individual restoration projects—which are often limited in scope, resources, and time—may not be able to address all such elements, even partial incorporation over time will encourage adoption across science, management, and policy arenas.

5.1. Identify Physical and Ecological Process Potential Given Interactive Effects of Altered Landscapes and Flows

The first emergent element of coupling landscapes and river flows for restoring highly modified rivers involves identifying the restoration potential of physical and ecological processes given interacting human-caused stressors. Identifying critical processes and their potential for reestablishment is particularly important, as well as challenging, in highly modified rivers given long histories of change and complex

Table 1
Brief Summaries of Studies That Exemplify Each of Four Identified Elements of Coupled Channel-Floodplain Manipulation and Environmental Flows Approaches

Elements of coupled approaches	Citation	Description
Identify physical and ecological process potential given interactive effects of altered landscapes and flows	Diaz-Redondo et al. (2017)	Examined altered river-floodplain processes over time due to multiple human-induced changes to identify processes to support through restoration for the highly altered Upper Rhine River, EU
	Downs et al. (2011)	Process-based restoration implemented within limitations of altered flow regime
	Fremier et al. (2014)	Examined cumulative impacts of flow alteration and channelization on the Sacramento River, California, United States; revealed that some channel migra tion processes could be reintroduced
	Gilvear et al. (2002)	Developed understanding of multiple interacting hydrologic and geomorphic responses to flow regulation and land use changes along rivers in Scotland, UK, and used this to inform selection of flow- and form-based approaches to support salmonid populations
	Hauer and Lorang (2004)	Considered altered processes due to dams, focusing on reestablishing the shifting habitat mosaic within floodplains of the Upper Snake River, United States, through "normative" flows and habitat protection and restoration
	Jacobson and Berkley (2011)	Floodplain restoration potential evaluated through joint examination of flow regime, geomorphic context, and soils
	Osmundson et al. (2002)	Empirical analyses on the Colorado River, United States, linking altered processes due to flow regulation to ecological response, identifying pathways of ecological degradation
	Paetzold et al. (2008)	Examined interactive effects of flow regime change and channelization on riparian arthropods
	Trush et al. (2000)	Identified river "attributes" reflecting processes for restoring river integrity, with application to the highly altered alluvial Trinity River, California, United States
Consider capacity for sustaining identified processes under potential future change	Battin et al. (2007)	Linked models (climate change, land use, hydrologic, and salmon population) to evaluate effects of potential future conditions, including restoration, on salmon populations
	Beechie, Imaki, et al. (2013)	Evaluated a range of salmon habitat restoration actions for their potential effectiveness under climate change, finding that actions addressing processes (over more static instream habitat restoration measures) were more likely to support long term ecosystem resilience under change; presented as a decision support framework
	Boughton and Pike (2013)	Assessed fish migration impacts under climate change scenarios and quantified potential mitigating effects of floodplain rehabilitation for the Pajaro River, California, United States
	Donley et al. (2012)	Uses climate change scenarios in combination with irrigation water withdrawals and instream flow restoration alternatives to prioritize Columbia River basins based on their sensitivity to restoration
	Fu et al. (2015)	Climate change scenarios combined with altered hydrology (e.g., dams and water diversions); linked to species responses through flood impacts (moves beyond assessing hydrologic metrics)
	Guse et al. (2015)	Examined expected ecological responses of combined effects of climate and land use change using coupled hydrologic-hydrodynamic modeling
	Justice et al. (2017)	Evaluated the potential of riparian restoration and channel modifications to offset projected water temperature impacts of climate change
	Karim et al. (2015)	Relative and combined impacts of climate scenarios and flow regime alteration of dams on floodplain inundation extent, duration, frequency, and connectivity for the Flinders and Gilbert rivers, Australia
	Mantyka-Pringle et al. (2014)	Combined impact of climate change (water temperature) and land use change on fish and macroinvertebrate biodiversity in southeast Queensland, Australia
	Perry et al. (2015)	Riparian restoration measures for their potential to accommodate climate change
	Williams et al. (2015)	In application to improving conditions for trout in the western United States, suggests individual projects can be prioritized via a large scale assessment that includes potential climate change impacts
Model alternatives for coupled restoration actions to support identified processes	Arias-Hidalgo et al. (2013)	Developed decision support system for large-scale wetland management that considered combinations of localized water infrastructure adjustments and land management strategies in application to the Guayas River, Ecuador; used a coupled modeling framework and included socio-economic considerations

Table 1
(continued)

Elements of coupled approaches	Citation	Description
	Beechie et al. (2015)	Combined salmonid habitat quantity and quality restoration measures on the Trinity River, California, were compared against conducting each alone (hydrologic alternatives not considered)
	Bond et al. (2018)	Used state-and-transition models to assess ecological response to different flow scenarios
	Jacobson and Galat (2006)	Modern and historical channel morphology and modern and historical flow regimes of the Lower Missouri River, United States, were combined and compared, illustrating relative importance and interactive effects of different measures
	Matella and Merenlender (2015)	Within a hydrologic connectivity modeling framework, levee setbacks were modeled in conjunction with environmental flow alternatives for the San Joaquin River, California, USA, showing dynamic floodplain processes (and related fish habitat) would be limited without both levee setbacks and environmental flows
	McManamay et al. (2013)	Applied multivariate models to address non-flow variables (e.g., temperature, substrate), which were shown to confound flow-ecology relationships within ELOHA framework for the Tennessee River, USA
	Null et al. (2010)	Improvements to quantity and quality of instream fish habitat on the Shasta River, California, USA, were compared across different combinations of restoration options, including environmental flows and riparian planting
	Shenton et al. (2012)	Supports use of demographic modeling to capture flow-ecology dynamics in evaluating environmental flow alternatives (does not consider channel-floodplain manipulation alternatives)
	Stein et al. (2017)	Assessed, through ELOHA application, expected benthic invertebrate community outcomes as a result of changing flow releases below a dam and applying land use measures to reduce watershed imperviousness; Though cases were evaluated separately, the methods applied could have been easily extend to assess joint impact
	Stewart-Koster et al. (2010)	To address the problem of multiple stressors treated in isolation, restoration options were assessed using Bayesian networks
	Tracy-Smith et al. (2012)	Multiple environmental flow scenarios as well as natural and current hydrology were modeled with current leveed Lower Missouri River, USA; Showed variable outcomes for biota due to the heavily altered river morphology; Recommended that channel rehabilitation measures be considered alongside flow alternatives
Evaluate alternatives using metrics representing integrative effects of coupled actions	Besacier-Monbertrand et al. (2014)	Used macroinvertebrate metrics to evaluate impacts of varying levels of floodplain connectivity for permutations of channel-floodplain and hydrologic restoration measures along the Rhône River, France
	Cienciala and Pasternack (2017)	Floodplain inundation regimes along the lower Yuba River, California, USA, evaluated using metrics relating to inundation extent and duration
	Coleman et al. (2015)	Model-based assessment of multiple metrics representing hydrologic processes as they relate to inundated wetland or floodplain habitat, with application to assessing impacts of channel-floodplain and hydrologic restoration alternatives
	Dolédec et al. (2015)	Compared restoration assessment metrics on the Rhône River, France, finding common bioassessment metrics should be avoided
	Dunbar et al. (2010)	Developed macroinvertebrate LIFE score for use in assessing combined influence of both riverine landscape and hydrologic alteration
	Karim et al. (2012)	Connectivity assessed via extent, timing, and duration metrics, to compare natural and artificial wetlands of the Tully and Murray Rivers, Australia
	McClain et al. (2014)	Hydraulic metrics were found to be useful for developing flow-ecology relationships in an environmental flows assessment for the Mara River Basin in East Africa
	Stone et al. (2017)	Floodplain connectivity assessed using metrics associated with river-floodplain dynamics, such as mass flux, on the Gila River and Rio Grande, New Mexico, United States
	Turner and Stewardson (2014)	Compared hydrologic and hydraulic metrics, finding hydrologic metrics inadequate for capturing flow-ecology relationships due to channel morphology

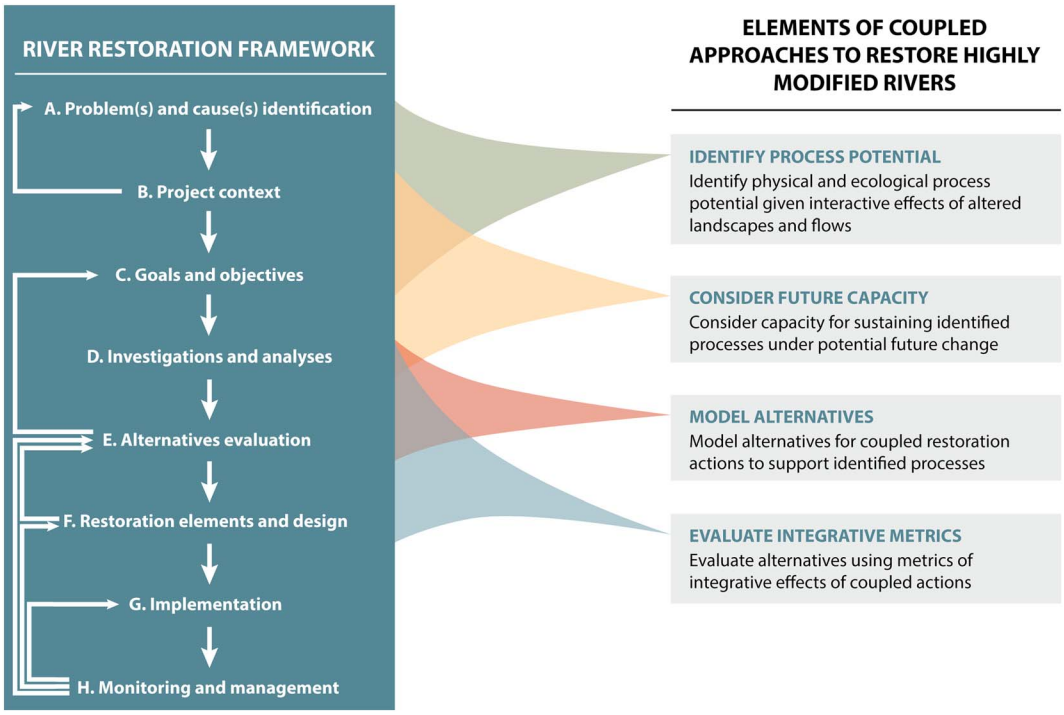

Figure 3. Elements for coupled approaches that coordinate channel-floodplain manipulation and environmental flows to restore highly modified rivers (right column) and their connection to a general river restoration framework (Perry et al., 2015; Skidmore et al., 2013).

biophysical feedbacks (Beechie et al., 2010; Grabowski et al., 2014). While the initial incentive for restoration may be a single perceived cause and effect, identifying potential restoration opportunities in highly modified rivers demands engaging a broader perspective to help illuminate how a particular effect may, in fact, be a product of a suite of interacting stressors overlapping in space and time. This element is especially needed for developing effective coupled approaches as it provides insight into the interdependence of restoration actions and their potential effects and can thus guide selection of restoration alternatives to consider. The larger context of altered landscapes and flows informs realistic assessment of the extent to which identified processes can be reestablished through coupled channel-floodplain manipulation and environmental flows. For individual projects with limited resources, this may take the form of synthesizing existing research and developing conceptual models of drivers, stressors, and responses. An example of the type of research useful to draw upon can be found in Gilvear et al. (2002), which used assessment of interacting hydrologic and geomorphic responses to flow regulation and land use change to help select actions to support salmonid populations. In another example, Diaz-Redondo et al. (2017) identified processes of focus for restoration by reconstructing process-responses to anthropogenic stressors on the highly altered Upper Rhine River. Other studies, such as Osmundson et al. (2002) and Paetzold et al. (2008), have focused on identifying the physical and biological pathways connecting landscape and flow alteration to ecological functions and species response. To encourage strategies focused on processes, Trush et al. (2000) proposed alluvial river "attributes" and suggested resizing channel morphology to establish these attributes within the context of the highly altered flow regime of California's Trinity River. Conceptually, this first emergent element, purposeful identification of process potential within the context of interactive effects of landscape and flow alteration, can be used with an understanding of potential future capacity (the second identified element) to guide selection of alternatives for coupled restoration actions. This first element augments the initial steps in the Skidmore et al. (2013) river restoration framework (A–C: identifying problems, project context, and goals and objectives; see Figure 3).

5.2. Consider Capacity for Sustaining Identified Processes Under Potential Future Change

The second emergent element addresses—given broad scientific and socio-economic uncertainty—questions of how physical and ecological processes may respond, what restoration actions are amenable to

future adaptation, and what the associated ecological adaptive capacity might be to drivers of change (e.g., climate change, land use change, and human responses to change). Confronting these questions entails advancing scientific understanding of mechanisms connecting hydrogeomorphic processes and hydroclimatic change and defining potential ranges of uncertainty in biophysical interactions and ecological responses. Such evaluation is especially important for considering how coupled restoration actions may influence possible trajectories through identified interactions and feedbacks and whether they have potential to expand rather than erode riverine ecosystem resilience. We distinguish this element from the others in order to qualify restoration expectations, encourage development of coupled strategies that are effective across a range of socio-ecological conditions, and recognize the urgent need to understand interacting factors of change (Arthington et al., 2018). The ramifications of climate change are generally expected to further strain already degraded riverine ecosystems (Palmer et al., 2009), though individual or localized effects are variable and continued direct human alteration may be measurably greater than those of hydroclimatic alteration alone (e.g., Rheinheimer & Viers 2014). Hydroclimatic alteration, such as shifts in spring snowmelt or extreme precipitation, directly impact riverine ecosystems and also interact with other anthropogenic stressors and responses in both positive and negative ways, which are often difficult to predict. Thus, future conditions and system feedbacks can alter the effectiveness or feasibility of restoration objectives and activities, which likely requires flexibility or adaptive capacity to introduce new or adjusted measures to meet given river restoration goals (Palmer et al., 2009; Perry et al., 2015; Pittock & Finlayson, 2011). While climate change is the overwhelming focus given broad-ranging potential impacts and substantial uncertainties, other changes such as future land use change or construction of new dams are also necessary to consider. Studying combined effects can help establish an expected range of responses or trajectories from which to consider restoration or management measures (e.g., Donley et al., 2012; Guse et al., 2015; Karim et al., 2015; Mantyka-Pringle et al., 2014). Studies that examine restoration outcomes within the context of future change have provided guidance on prioritizing basins or river reaches for restoration (Battin et al., 2007), quantified relative impact (e.g., Boughton & Pike, 2013; Justice et al., 2017), and prioritized restoration actions based on their capacity to accommodate change (Beechie, Richardson, et al., 2013; Perry et al., 2015; see Table 1). A common theme is that diversified portfolios of large-scale and process-based restoration measures are expected to be beneficial under a wide range of potential future scenarios (Beechie, Richardson, et al., 2013; Perry et al., 2015; Williams et al., 2015). Within the river restoration framework referred to herein, this second emergent element helps establish the restoration context and define goals and also involves investigation into potential interactive effects of restoration actions (B–D, see Figure 3). While it is unrealistic for any single restoration project to consider system capacity under all future conditions and scientific uncertainties, restoration practice can begin to evaluate cumulative effects and trajectories of change more broadly and in turn identify no-regrets approaches toward restoring ecological integrity and resilience in highly modified rivers.

5.3. Model Alternatives for Coupled Restoration Actions to Support Identified Processes

The third emergent element, which contributes to the investigations and analyses and the alternatives evaluation steps of the river restoration framework (D–E; see Figure 3), involves the use of modeling (e.g., hydrologic, hydrodynamic, water quality, and population) to examine joint effects of coupling restoration actions. Understanding gained by the previously described elements informs model development (e.g., what processes should be of particular focus), research questions (e.g., what sets of restoration actions and what ecosystem processes or functions to address), and the selection of realistic or promising alternatives of coupled actions (e.g., what interactive pathways are most relevant). Research studies provide needed insights as well as establish methods and tools from which individual restoration projects can compare modeled alternatives for coupled actions. Scenario-based modeling allows for comparative analysis of coupled restoration actions to identify complementary alternatives (Palmer et al., 2009). Examples can be found in research by Beechie et al. (2015) who used empirical relationships to examine individual and combined salmon habitat restoration actions and Stewart-Koster et al. (2010) who used Bayesian networks to assess interactive effects of restoration actions. Scenarios can help define a range of potential outcomes within the constraints posed by highly modified rivers. Hydraulic modeling can be used to examine potential restoration outcomes by assessing effects of coupled actions on physical processes, which can be subsequently linked to ecological response models (Merenlender & Matella, 2013). Several studies highlighted in Table 1 evaluated coupled restoration actions using a hydraulic modeling

framework. These studies modeled comparisons of expected shallow water habitat under combinations of historical and modern hydrology and channel morphology (Jacobson & Galat, 2006), inundation patterns and potential fish habitat under different levee setback and environmental flow alternatives (Matella & Merenlender, 2015), and instream flow and temperature between riparian vegetation enhancement and environmental flow measures (Null et al., 2010). To determine combined effects of restoration measures acting at different scales, watershed-scale hydrologic modeling can be linked to hydraulic modeling capturing reach-scale processes (Brewer et al., 2016). In one example, a model chain was used to evaluate the relative influence of localized infrastructure and land management on wetland condition (Arias-Hidalgo et al., 2013). Other studies illustrate the benefits of more sophisticated ecological modeling (Bond et al., 2018; Shenton et al., 2012), which can better address interactive effects (e.g., nonflow variables affect flow-ecology relationships; McManamay et al., 2013) and dynamic relationships between process and response. Models and linked modeling are becoming increasingly sophisticated with technological advances in computing power, handling of large data, and new statistical methodologies. Also, modeling capabilities improve as fundamental ecological research informs predictions of ecological response (e.g., Besacier-Monbertrand et al., 2014; Schlatter et al., 2017).

5.4. Evaluate Alternatives Using Metrics Representing Integrative Effects of Coupled Actions

The fourth emergent element involves the use of metrics that represent collective responses—physical and ecological—to coupled channel-floodplain manipulation and environmental flows in order to evaluate alternatives and guide decision-making (framework steps D–F; see Figure 3). Metrics that more explicitly relate to sediment dynamics, hydrologic connectivity, and floodplain inundation patterns and dynamics should enable more effective evaluation of the combined impact of multiple restoration options. Research has shown that hydrologic metrics (i.e., analyzed from a hydrologic time series) may be insufficient indicators of ecological responses to restoration measures and that hydraulic metrics (e.g., depth, velocity, and duration) may be more useful indicators for flow-ecology relationships (e.g., Bond et al., 2014; Kozak et al., 2016; Turner & Stewardson, 2014). Hydraulic metrics have been employed in a number of studies on changing dynamics or processes within floodplain environments, including characterizing inundation regimes (Cienciala & Pasternack, 2017), comparing connectivity of natural and constructed wetlands (Karim et al., 2012) or under natural and regulated flow regimes (Stone et al., 2017), and assessing impacts of restoration alternatives (Coleman et al., 2015). Where possible, modeled alternatives and existing scientific research may allow for the determination of ecological response metrics. Chosen metrics should also enable more effective evaluation of expected ecological response. Studies have shown that macroinvertebrate metrics, for example, can be effective indicators of combined impacts of geomorphic and hydrologic change (Besacier-Monbertrand et al., 2014; Dolédec et al., 2015; Dunbar et al., 2010). Use of taxonomic, phylogenetic, and functional trait metrics—as recently proposed by (van Looy et al., 2019)—and metrics representing ecosystem function (e.g., primary productivity; O'Brien et al., 2016) can help link abiotic outcomes of coupled approaches to expected ecosystem responses. As no single metric can represent complex riverine processes and interactions, multimetric assessments and indices can be used to capture different processes and functions (Einheuser et al., 2012; van Looy et al., 2019). Metric development and selection should be specific to location, as well as restoration goals and objectives.

6. Conclusions

Rivers that have been highly impacted by landscape alteration and flow regulation face mounting and interacting stressors at many scales, which fundamentally alter the processes supporting diverse and productive ecosystems. Repairing the many process components and their interactions within highly modified rivers is a central challenge to riverine ecosystem management and restoration. Overcoming this challenge demands coupling channel-floodplain manipulation and environmental flows, often treated separately in the scientific literature and implemented singularly in practice. While these separate themes persist within the river restoration literature, process-based thinking has led river restoration efforts to better address the role of land-water interactions and dynamics in driving ecological processes. Central to this observation is the convergence on coupled channel-floodplain manipulation and environmental flows approaches for reestablishing complex landscapes that interact with variable flows to sustain riverine and floodplain ecosystems. Based on the literature, we identified four emergent elements for these

types of coupled approaches: (1) identify physical and ecological process potential given interactive effects of altered landscapes and flows; (2) consider capacity for sustaining identified processes under potential future change; (3) model alternatives for coupled restoration actions to support identified processes; and (4) evaluate alternatives using metrics representing integrative effects of coupled actions. These elements should be applied within larger river restoration frameworks and programs that reevaluate outcomes and opportunities as conditions change and that address other practical limitations (e.g., socio-political, institutional, and economic). This discussion is intended to foster scientific consensus concerning coupled channel-floodplain manipulation and environmental flows for restoring highly modified rivers. Establishing the value and practice of coupled approaches to restoration will provide practitioners, managers, and policy makers a stronger basis for strategies that improve riverine ecosystem integrity and resilience.

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