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Biomic river restoration: A new focus for river management

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Abstract

River management based solely on physical science has proven to be unsustainable and unsuccessful, evidenced by the fact that the problems this approach intended to solve (e.g., flood hazards, water scarcity, and channel instability) have not been solved and long-term deterioration in river environments has reduced the capacity of rivers to continue meeting the needs of society. In response, there has been a paradigm shift in management over the past few decades, towards river restoration. But the ecological, morphological, and societal benefits of river restoration have, on the whole, been disappointing. We believe that this stems from the fact that restoration overrelies on the same physical analyses and approaches, with flowing water still regarded as the universally predominant driver of channel form and structural intervention seen as essential to influencing fluvial processes. We argue that if river restoration is to reverse long-standing declines in river functions, it is necessary to recognize the influence of biology on river forms and processes and re-envisage what it means to restore a river. This entails shifting the focus of river restoration from designing and constructing stable channels that mimic natural forms to reconnecting streams within balanced and healthy biomes, and so levering the power of biology to influence river processes. We define this new approach as *biomic river restoration*.

KEYWORDS

anthrome, biogeomorphology, biome, ecosystem engineering, river management, river restoration, working with natural processes

1 | INTRODUCTION

Approaches to river management based exclusively on physical science and engineering analyses were developed and vigorously applied throughout the 20th century but have proven to be unsustainable for two reasons. First, the problems that these approaches were intended to solve (e.g., flood damages and water scarcity) have, demonstrably, not been solved. On the contrary, long-standing and increasing trends in annual expected damages associated with river-related problems are accelerating (Tanoue, Hirabayashi, & Ikeuchi, 2016) and long-term deterioration in river environments and ecosystems has materially reduced the capacity of the world's rivers to continue meeting the needs of society (Vörösmarty et al., 2010).

Towards the end of the 20th century, growing recognition of the limitations of conventional approaches led river scientists to argue for a radical rethink of river management, including steps to first halt, and then reverse, historical trends of degradation and deterioration, and so emerged the practice of river restoration. However, despite efforts to restore thousands of kilometres of impaired channels and massive capital investments, river restoration has underachieved when judged by its own aspirations. The fact is that many, perhaps most, restoration projects have not delivered the hydrological, morphological, ecological, and societal benefits that were anticipated, at least not yet (Geist & Hawkins, 2016; Haase, Hering, Jähnig, Lorenz, & Sundermann, 2013; Palmer, Menninger, & Bernhardt, 2010).

We argue here that the reason for the manifest underperformance of river restoration stems from a lingering overreliance on the same physics-based science that has underpinned river management for centuries. For example, the majority of restoration projects still employ principles of stable channel design developed between the 17th and 20th centuries (Chezy, 1775; Kennedy, 1895; Lacey, 1929). The theory underpinning such physics-based approaches is that redesigning the slope and cross-sectional dimensions of an alluvial (i.e., self-formed) channel, so its capacity to transport sediment just matches the supply from upstream will result in a morphology that is dynamically stable. In this context, dynamic stability occurs when the channel's geometry and dimensions remain unchanged even though sediment passes through it and the channel shifts laterally through time. Where lateral shifting is unacceptable, restoration projects may prevent this using natural, rather than artificial, materials (Kondolf, 2011). Such restoration is not without value. Restoration of a stable channel can increase biodiversity (e.g., Hockendorff et al., 2017), whereas improved aesthetics and accessibility have value in enhancing social engagement with, and valuation of, rivers (e.g., Åberg & Tapsell, 2013). Notwithstanding this, restoration that is strictly physics-based is incomplete and will not reverse declining trends in river environments and ecosystems. Indeed, Auerswald, Moyle, Seibert, and Geist (2019) suggest that continued reliance on engineering approaches will further amplify river hazards such as unnatural flooding, due to system decoupling that has serious, negative socio-economic consequences related to reductions in the aesthetic and recreational values of our waterways.

If some components or functions of a natural stream are sacrificed to enhance others, the river responds by adjusting in ways necessary to regain its lost functions and recover balance, within its catchment and hydrological contexts. Increased capital works and heavy maintenance can prevent such recovery while temporarily continuing valued functions but, as the costs mount up and the river continues to deteriorate functionally, there comes a time when funders question how long the increasingly frequent actions needed to maintain valued functions must continue. The inconvenient answer is *forever*. In short, conventional river management and restoration is unsustainable economically, as well as environmentally.

To reverse long-standing declines in river environments and functions, we propose a paradigm shift in restoration theory to re-envisage "restoration design" and redefine "natural processes." This is now possible, because science at the interfaces among geology, hydrology, and biology has developed sufficiently that, for the first time, we can properly appreciate, and to an extent quantify, the capacity of living organisms to influence river form and process. Rivers are critical components of the biome within which they are situated, where the biome is defined as an area characterised by general similarity in ecosystems comprising plants and animals that are adapted to the regional environment. Biomes are identified through the analysis of geology, physiography, vegetation, climate, soils, land use, wildlife, and hydrology that affect or reflect differences in ecosystem quality and integrity. Changes to river channel form and dynamics can alter the surrounding biome, for example, through lowering of the regional water table, whereas alterations to the biome, such as deforestation or species invasion, can instigate river responses (e.g., Beschta & Ripple, 2009). It follows that reintegrating rivers so they are in sync with their biomes provides a more sustainable basis for restoring rivers.

In our opinion, it is time to start harnessing the power of biogeomorphic agents as "nature's river restorers," replacing stable channel design with a new approach best described as biomic restoration. This can be encapsulated by revising Lane's balance (Lane, 1955) to incorporate the role of the life of the river in controlling the balance of aggradation and degradation (Figure 1).

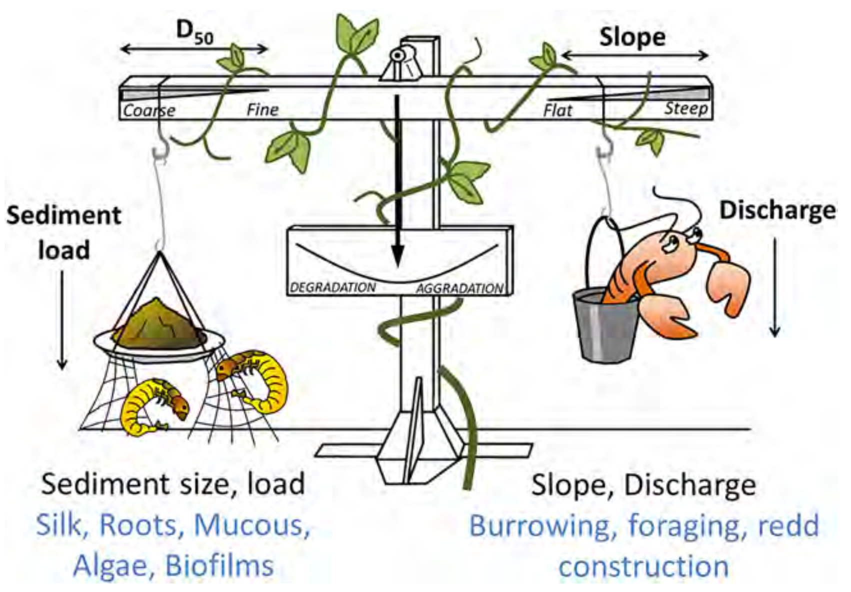

FIGURE 1 Lane's balance (1955) has been used as a visual representation of the engineering paradigm of the equilibrium, stable river channel form for 60 years. It describes how stable channels occur where sediment load and size are balanced by the stream power of the flow. Here, we propose an alteration, which represents the important role that the surrounding ecosystem also has in controlling stable channel form [Colour figure can be viewed at wileyonlinelibrary.com]

2 | THE POWER OF PHYSICS

The focus of river management on manipulating hydrology, hydraulics, and sediment dynamics is understandable because it has long been recognized that the ways in which the flow and sediment regimes interact with bed and bank materials control the form of an alluvial channel (e.g., Chezy, 1775). The prevalence of analyses based on solution of physics-based equations governing water flow and sediment transport remains largely unchallenged, albeit with additional considerations taken into account (Dust & Wohl, 2012). It is now possible to model water flow and sediment transport over long reaches and periods, yet the focus remains on the physics of in-bank flows in single-thread, alluvial channels. This is despite the growing body of evidence that single-thread, meandering channels that inundate their floodplains only occasionally were not prevalent prior to human occupation and disturbance of river catchments and are likely to be the legacy of historical, anthropogenic alterations to catchments and rivers (Brown et al., 2018; Walter & Merritts, 2008). The orthodoxy that single-thread channels are the best restoration target is being challenged. Instead, it is argued that rivers with functional floodplains and adequate sediment supplies may be better served by multichannel, anastomosed morphologies that are fully connected to their floodplain–wetland systems (Castro & Thorne, 2019; Cluer & Thorne, 2014).

If factors other than physical processes influence stable channel form, this should be evident in relations defining stable river morphology, yet most hydraulic geometry equations relate stable channel dimensions to discharge alone, and with high coefficients of determination (Leopold & Maddock, 1953). However, the influence of these other factors emerges when researchers diverge from the physics-focused paradigm. For example, in the United Kingdom, the type, density, and extent of bank vegetation has been shown to be significant, with dynamically stable channels becoming narrower for a given discharge as the strength of bank vegetation increases (Hey & Thorne, 1986). In the Pacific Northwest, research has revealed significant, regional differences in hydraulic geometry relationships, attributable to differences in climate, geology, soils, and vegetation (Figure 2; Castro & Jackson, 2001). However, even in these aberrant cases when river forms have been analysed in a biologic context, the biotic influencers are restricted to large vegetation, rather than the multitude of resident animals considered in the next section.

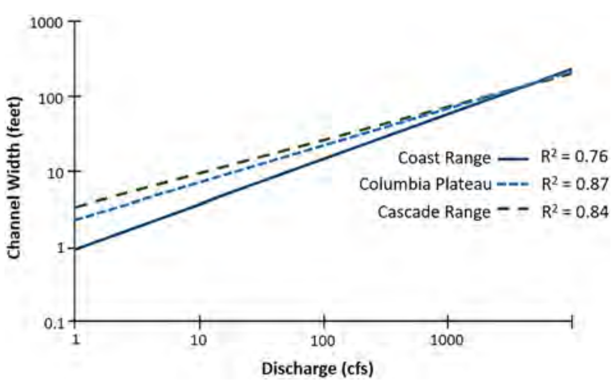

FIGURE 2 Hydraulic geometry relationships for rivers in different Level III Ecoregions in the Pacific Northwest [Colour figure can be viewed at wileyonlinelibrary.com]

3 | THE POWER OF BIOLOGY

3.1 | Small creatures, big impacts

Small animals are rarely incorporated into our treatment of fluvial sediment transport, despite a growing body of work demonstrating the multiple impacts of life in rivers (Albertson & Allen, 2015; Rice, Johnson, & Reid, 2012). For example, hydropsychid caddisfly larvae (*Trichoptera*) spin silk nets that bind together bed grains and, at natural densities, can increase the critical boundary shear stress for entrainment by 33–45% (Johnson, Reid, Rice, & Wood, 2009). Other invertebrates, such as shrimp and insect larvae, winnow fine sediment from between coarser grains when foraging and feeding (Rice et al., 2012). Cyprinid fish and lamprey have been shown to alter the texture, structure, and mobility of river sediments while foraging (Boeker & Geist, 2016; Pledger, Rice, & Millett, 2017), and salmonids have been shown to move approximately half of the annual bedload yield in mountain streams in British Columbia (Figure 3; Hassan et al., 2008).

The contribution of freshwater mussels (Mollusca: Bivalvia: Unionidae, Margaritiferidae) to biogeomorphic processes in streams is seldom fully appreciated. Mussels filter suspended algae, protozoa, bacteria, and organic detritus from the water column, reducing turbidity and capturing nutrients that would otherwise be lost downstream (Lummer, Auerswald, & Geist, 2016; Vaughn, 2018). Mussel aggregations modify near-bed flow environments, promote vertical exchange of water in the hyporheic zone, reduce bed material mobility, alter the transport dynamics of substrate sediments, and influence benthic community composition (Vaughn, 2018). Mussels can also use their muscular foot to burrow into the river substrate. During high-flow events, some species burrow beneath the surface to avoid being washed downstream, which increases substrate heterogeneity,

FIGURE 3 Pink Salmon (*Oncorhynchus gorbuscha*) redds located on a large Fraser River bar downstream of Agassiz, British Columbia. The gravel reach of Fraser River is one of the most productive pink salmon spawning areas in the world (Photo by David Reid, 2012) [Colour figure can be viewed at wileyonlinelibrary.com]

whereas deep burrowers can help compact and stabilize bed sediments (Allen & Vaughn, 2011).

In practice, the effects of small aquatic animals can be difficult to discern because differences in species diversity, distribution, and community composition complicate biogeomorphic impacts on stream forms and processes (Rice et al., 2012). Additionally, the influence of small animals on physical processes is related to environmental conditions through complex feedback loops, resulting in diurnal, seasonal, and interannual variability in biogeomorphic processes and their impacts, especially at temperate latitudes (Rice, Johnson, Mathers, Reeds, & Extence, 2016). Also, biogeomorphic impacts can be life-stage specific and heavily influenced by ecological interactions; for example, hungry stonefly nymphs (*Megarcys signata*) move more fine sand than satiated nymphs (Zanetell & Peckarsky, 1996).

Disrupting these complex and poorly understood interactions is likely to have unintended consequences for river hydrology, geomorphology, and ecology. For example, across North America and Europe, many freshwater mussel species are critically endangered, with populations that have been decimated or locally extirpated, and loss of their filtration functions is believed to have critical implications for river ecosystems (Vaughn, 2018).

3.2 | Bigger creatures, big impacts

Large animals also significantly influence physical processes. For example, large ungulates accessing the river to drink or browse can compact soils, break down banks, and overgraze riparian vegetation, all of which tend to reduce bank stability and accelerate lateral erosion (Beschta & Ripple, 2009; Trimble & Mendel, 1995). Beaver (*Castor canadensis*; *Castor fibre*) have built dams to pool water and regulate water surface elevations since the Eocene, operating through glacial and interglacial periods and adjusting successfully to large, episodic rises and falls in sea level. Beaver create and help to maintain complex floodplain–wetland systems generally referred to as beaver meadows, which support a wide range of aquatic and terrestrial species (Westbrook, Cooper, & Baker, 2011). Beaver were nearly extirpated in North America within a few decades in the 1800s, causing the multiple, local base level controls provided by beaver dams to disappear. Many rivers then incised, abandoning their floodplains and reducing the extent and diversity of wetland habitats at a continental scale (Polvi & Wohl, 2012). When beaver populations began recovering during the late 20th century, it did not go unnoticed by river scientists that many aquatic and wetland habitats and ecosystems also started to recuperate (Pollock, Lewallen, Woodruff, Jordan, & Castro, 2015). Although not a panacea, beaver reintroduction is incorporated to hasten recovery in a growing number of restoration projects, allowing the river restoration community to capitalize on this trophic cascade and potentially providing long-term resilience to future climate or land-use changes by recreating complex river–wetland–floodplain systems (Burchsted, Daniels, Thorson, & Vokoun, 2010).

In this context, Palmer, Ambrose, and Poff (1997) pointed out that the "field of dreams" hypothesis, "build it and they will come," is often unsuccessful: Restorers build suitable physical habitat, but the target biota fail to occupy it. In restoration based on partnering with beaver, perhaps a more apt hypothesis is that "given the opportunity, they will come and build it."

3.3 | Good animals gone bad

The impacts of native organisms on their environments tend to be beneficial to the individuals, their species, and the wider community, including processes surrounding plant succession and facilitation (Corenblit, Tabacchi, Steiger, & Gurnell, 2007). However, perhaps the clearest demonstrations of the power of biology occur when organisms work *outside* their native ranges. Under these circumstances, the impacts of biogeomorphic agents can be devastatingly negative. For example, in their native range, the impacts of signal crayfish (*Pacifastacus leniusculus*) are beneficial, but where invasive, they burrow intensely into river beds and banks, partially reversing fluvial sediment structuring (Johnson, Rice, & Reid, 2011) and significantly increasing fine sediment transport (Harvey et al., 2011). Rice et al. (2016) show that bioturbation by invasive signal crayfish contributed at least 32% to the monthly base flow of suspended sediment load leaving a 233-km^2 catchment in the United Kingdom.

The ability of beaver to manage and maintain key ecological, hydrologic, and geomorphic processes and riverscapes across their native ranges is notable. However, where beaver are introduced into new habitats not adapted to herbivory and lacking predators, the results can be highly detrimental. In 1946, 20 North American beaver (*Castor canadensis*) were deliberately introduced into the *Nothofagus pumilio* forest biome of Tierra del Fuego, southern Patagonia. The beaver population grew quickly and its range expanded accordingly (Pietrek & Fasola, 2014). By 2015, a beaver population estimated to be between 98,000 and 165,000 had colonised nearly all freshwater aquatic and wetland environments, except for large rivers and some extensive, raised bogs (Henn, Anderson, & Pastur, 2016). Negative impacts of these invasive beaver include dams that lead to excessive sedimentation in riparian areas, harvesting of very large numbers of trees, excavation of thousands of cubic metres of peat and mineral sediment to build dams, and drowning of peat-forming mosses and

FIGURE 4 A fen and stream ecosystem after beaver invasion in Tierra del Fuego, southern Patagonia [Colour figure can be viewed at wileyonlinelibrary.com]

sedges in fens that has allowed a massive invasion of exotic plant species (Figure 4; Westbrook, Cooper, & Anderson, 2017). These changes to southern Patagonian river and landscapes have tipped many ecosystems from one stable state to another, perhaps irreversibly (Westbrook et al., 2017).

Invasive species that modify invaded habitats are particularly potent (Crooks, 2002). The impacts of invasive species, especially when coupled with the trampling of bank and bed material by domestic stock, are significant drivers of geomorphic disturbance that have been shown to substantially reduce river channel stability (Rice et al., 2016; Shin-ichiro, Usio, Takamura, & Washitani, 2009). Although underlining the biogeomorphic power of plants and animals, these examples of "good animals gone bad" also illustrate that attempts to harness that power in the context of river restoration must be undertaken with care. The risks associated with restoration that introduces a new species, or reintroduces an extirpated species, are real and significant.

4 | EXPLAINING BIOGEOMORPHIC POWER AND ITS LIMITS

4.1 | Natural evolution

Not only trees and beaver, but most riverine lifeforms, have had millions of years to hone the skills necessary to survive and influence fluvial processes, with the genes and acquired behaviours of the most successful individuals preferentially passed to the next generation (Corenblit et al., 2007). From an evolutionary perspective, plants and animals work to improve their own life chances and those of their species and, in so doing, they drive biogeomorphic processes and influence fluvial processes more strongly than has generally been recognised. We should not be surprised that life in rivers is well adapted to the environments that streams provide, adept at responding to disturbance, and able to adapt to environmental change by maintaining and modifying habitat. This gives disturbed natural systems a self-healing capacity, with the recolonisation and successional processes that follow a major disturbance facilitating recovery of ecological systems (Corenblit et al., 2007).

On Earth, rivers themselves have coevolved and coadapted with riverine organisms since the emergence of life. Sedimentological evidence shows that, on Earth, meandering rivers only became widespread once terrestrial plants with root systems evolved and that, after terrestrial mass extinctions, rivers temporarily reverted back to sheet braiding—until plant life is recovered (Ward, Montgomery, & Smith, 2000). Similarly, in the geological record, the occurrence of sedimentary structures indicative of deposition by anastomosed rivers is related closely to the presence of trees and log jams (Gibling et al., 2014).

4.2 | The significance of biomes and anthromes

The term "biome" refers to a fully integrated climatic, geologic, and ecologic system, typically at or in excess of the river catchment scale. Rivers are keystone components of the biomes within which they exist (Dodds et al., 2014). Two pieces of pioneering research demonstrate the utility of using biomes to inform river science. Castro and Jackson (2001) established the existence of a biomic influence on the stable morphology of rivers in the Pacific Northwest. Grouping rivers by Level III Ecoregion revealed differences in hydraulic geometry relations that were statistically significant, establishing the existence of an "eco-footprint" in river morphology. Simon et al. (2004) grouped rivers by Level III Ecoregion to successfully produce a series of evidence-based, biome-specific Total Maximum Daily Loads suitable for detecting sediment concentrations elevated by anthropogenic activities.

The reality is, however, that few true biomes remain. Development has reshaped large areas of the planet, converting them in various degrees to "anthromes" (Ellis, Goldewijk, Sibert, Lightman, & Ramankutty 2010). These "anthropogenic biomes" mix remnants of predevelopment landscapes and ecosystems with forest, pastoral, and arable monocultures, mineral extraction sites, water resource infrastructure, and constructed industrial, urban, and suburban spaces, all sustained through complex interactions between natural and human systems (Figure 5).

4.3 | Biomic river restoration

The biomic approach recognizes that changes in the landscape reverberate through the catchment's biogeomorphic system, with consequences for fluvial processes and the physical form of the river. Changes could stem from extinction of a native organism or introduction of an invasive species. Extirpation of wolves (*Canus lupus*) in Yellowstone National Park in the 1920s instigated channel instability because of a trophic cascade that led to increased elk (*Cervus canadensis*) abundance and behavioural change, with intensified foraging of riparian willow that destabilized river banks, drove out beaver, and led to river planform metamorphosis from meandering to braided (Beschta & Ripple, 2009). Reintroduction of wolves 70 years later has reversed those changes. Ergo, stable channel form depends not only on "Lane's balance" between the water and sediment regimes but also the balance of species within the ecosystem (Figure 1). A biomic approach, by definition, requires consideration of the catchment context and connectivity of the channel longitudinally, laterally, and vertically. Without floodplain and groundwater connectivity, it is unlikely that a truly sustainable management or restoration solution will be found and, hence, ecological uplift is likely to be more limited than would be the case in a fully connected channel–wetland–floodplain systems (Pander, Knott, Mueller, & Geist, 2019).

"Process-based" river restoration has become a mantra. But it is not enough to base restoration design only on *physical* processes. It is vital that the rivers we restore are resilient to changes in climate, land-use, and river management in a highly uncertain future (Fuller, Gilvear, Thoms, & Death, 2019). Disturbed natural systems have a self-healing capability, because the recolonisation and successional processes that follow a major disturbance facilitate recovery of ecological systems that, in turn, promote recovery of the physical system towards a new, dynamically stable state. In short, biomic rivers are not only responsive to change but also resilient to its adverse impacts.

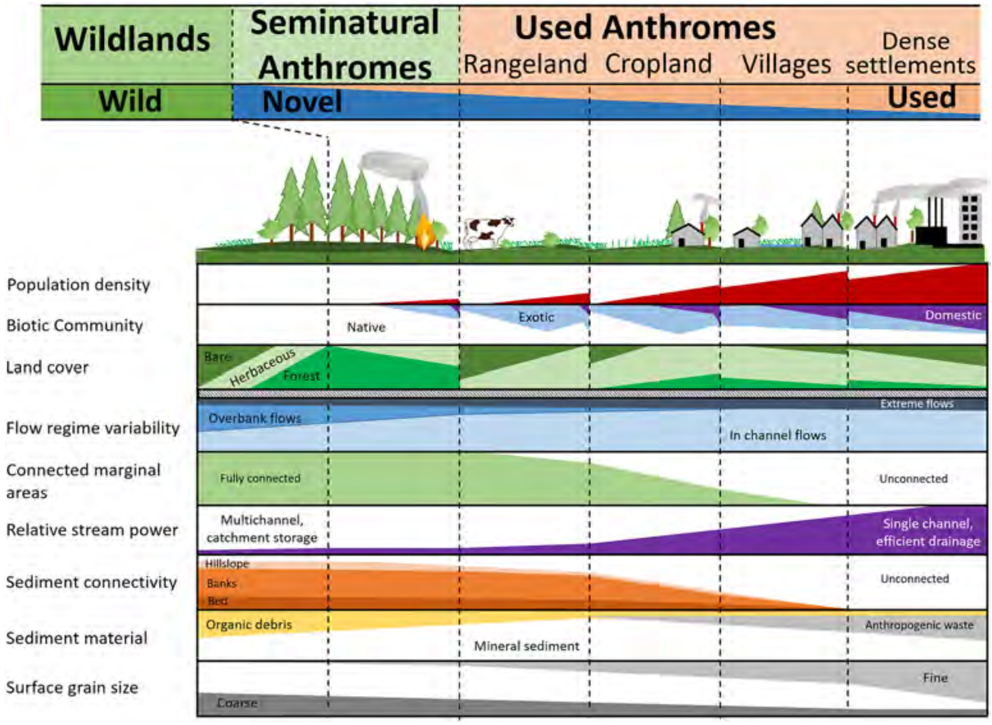

FIGURE 5 Typical stream properties in differing anthromes. Modified from Ellis et al. (2010) [Colour figure can be viewed at wileyonlinelibrary.com]

This requires restoration outcomes that are adaptable not only to changes in the flow and sediment regimes but also to changes in local, catchment, and regional ecosystems. Adaptive capacity is maximized when restoration recreates fluvial and ecological systems that can coevolve, accommodating change no matter how the future unfolds.

5 | WORKING WITH NATURE'S RIVER RESTORERS

5.1 | Requirements for partnership

It is our thesis that restoration design currently remains overreliant on relationships expressing stable channel dimensions as functions of discharge and sediment load with, at best, some allowance for the stabilising effects of live vegetation and/or large wood. We cannot replicate physically what biogeomorphology does organically. We can, for example, mimic beaver dams with “beaver dam analogues” (Bouwes et al., 2016), but we can neither deliver the attentive maintenance provided by beaver nor reproduce the wetland mosaics that result from frequent removal and relocation of structures in beaver dam complexes (Lautz et al., 2019). We would not know how, even with unlimited resources. Beaver are nomadic members of living river systems, with whom people can collaborate but in which people cannot fully participate (Woelfe-Erskine, 2018).

The issue therefore becomes that of empowering the agents responsible for driving and managing biogeomorphology, which requires that we provide the opportunity for plants and animals to do something only they can do: build, maintain, and adaptively manage habitat. For too long, restorers have thought that physical processes build habitat when, in fact, they build landforms. In essence, all our restoration partners need us to do is enable them to turn landforms into habitat. However, in practice, this is challenging because of the degree and extent to which the habitats, morphologies, and biomes of many rivers have deteriorated. For example, where a river flows through a single channel that has been enlarged to contain major flow events, the stream power is likely to be high relative to the “biological power” associated with nature's river restorers. In contrast, where the flow is distributed between multiple channels and mean annual floods are spread across wide floodplains, unit stream power is reduced and the relative influence of biological power increases accordingly (Figure 6; Castro & Thorne, 2019). It is therefore likely that biogeomorphic power and influence are maximized in streams restored to predisturbance configurations that feature multithreaded planforms flowing through wetland–floodplain complexes that are inundated frequently and minimised in streams with large, single-thread channels that inundate their floodplains less often and for shorter periods.

As restoration partners, nature's river restorers have just three key requirements: liveable flow regimes, space in which to live and work, and a reliable food web. It is rarely practical to restore the natural, predisturbance flow regime, and climate change means that the future flow regimes will *in any case* differ from those of the past (Meybeck, 2003). Fortunately, many native species are naturally adapted to tolerate conditions that are highly variable and nonstationary (Bunn & Arthington, 2002). It follows that a liveable flow regime does not necessarily need to replicate the past. What is required is the range and seasonal patterns of instream and overbank events sufficient to meet

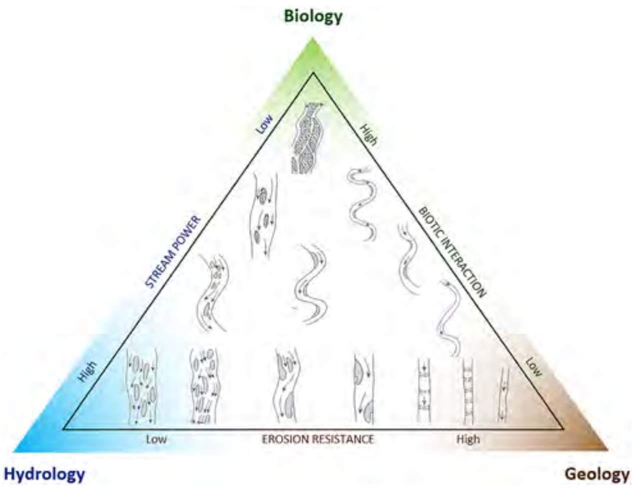

FIGURE 6 The stream evolution triangle (from Castro & Thorne, 2019) [Colour figure can be viewed at wileyonlinelibrary.com]

the life stage requirements of key aquatic, riparian, and floodplain organisms, enabling them to drive biogeomorphic processes (Rood et al., 2005). However, a river's capacity to absorb and recover from extreme events requires giving it not only room to flood but also to erode and deposit sediment, allowing recruitment of trees from eroding banks, and giving opportunities for riparian vegetation to re-establish on new surfaces (Kondolf et al., 2006; Piégay, Darby, Mosselman, & Surian, 2005). Unfortunately, in some settings, expanding the river corridor to provide sufficient width for dynamic geomorphic processes would be socially unacceptable or prohibitively expensive. Hence, although the potential for creation of "self-healing" rivers managed by nature's river restorers is considerable, candidate streams need to have dynamic flow and sediment regimes and be given enough space to accommodate a dynamic, erodible "stream evolution corridor" (Kondolf, 2011).

Even with suitable flows and space, nature's river restorers cannot survive without a functional food web. In this context, consideration should start with the microorganisms that cycle the chemicals, nutrients, and minerals that enable primary production at the bottom of the food web (Mendoza-Lera & Datry, 2017; Montgomery & Biklé, 2015). Clean sediments used to construct and replenish fluvial environments create sterile, abiotic matrices, at least initially, and little work has been done quantifying the time taken for a healthy and vibrant microbiome to develop. Without this microbial ecosystem, higher lifeforms will struggle to thrive in new habitats and the success of restoration projects will be impeded.

5.2 | Multidisciplinary understanding and working

Partnering with nature's river restorers requires a deep understanding of the river and its functions that spans the engineering, physical, and biosciences and extends across scales ranging from micro to macro. Applying biogeomorphic principles and approaches to river restoration has transformative potential, but if undertaken inappropriately, it will be at best ineffective, and at worse detrimental. Biogeomorphology is powerful, but hazardous if mishandled. Harnessing biogeomorphology safely and responsibly requires unprecedented levels of collaboration between river engineers and scientists who share a common appreciation and respect for biogeomorphic systems as being integrated and inseparable. But it is achievable through concerted action to conceive, develop, and implement biomic river restoration that is founded on community values, supported by stakeholder engagement, defined by nature, informed by scientists, and delivered by engineers—all working in partnership with nature's river restorers.

5.3 | Goals and challenges of biomic restoration

Restoration goals and best practice guidelines are widely published (e.g., EPA, 2019; Geist, 2015; Simenstad, Reed, & Ford, 2006) and usually focus on setting achievable goals, encouraging adaptive management, implementing long-term monitoring, and engaging with stakeholders at all stages of the process. These important considerations hold true for biomic restoration, but additional objectives are also significant. First, an assessment of the ecological context is critical because understanding the natural capital available, and its potential utility in restoration, is fundamental to biomic restoration planning and design. To a degree, this already takes place. For example, if beaver are known to be resident in an area, restoration will likely be planned differently than in places where they are absent. However, biomic restoration requires looking beyond any single species to consider the entire ecological community and looking at not only the immediate vicinity of the channel but also to the wider landscape. Second, the identification of methods to maximize the significance of biology relative to purely physical processes becomes important. Where appropriate, this could mean moving away from single-thread channel designs to promoting anastomosed channels, which divide and spread the flow laterally, reducing unit stream power and therefore increasing the relative significance of "biological power" (Castro & Thorne, 2019). Third, any process-based restoration should allow biological processes, in due course, to "take over channel maintenance" and for the restored area to fully reintegrate within its fluvial and catchment contexts, without the need for continued human interventions. Identifying where, how, and when this can be achieved is a significant exercise, and it must be acknowledged that this outcome may not be achievable for some sites and catchment contexts—at least not anytime soon.

There are, indeed, circumstances and constraints that make a biomic approach infeasible. For example, there may be no marginal room to accommodate a channel migration zone, no opportunities to improve connectivity, irrecoverably poor water quality, or the channel may be located within a densely built and populated anthrome. Accepting this, applying biomic principles in such situations could still yield material benefits and, even in these settings, valuable habitat can be recreated. However, it is also important to acknowledge that in areas where physics-based engineering science dominates restoration practice, post-restoration maintenance and adaptive management will always be required and the resulting channels will never develop the recuperative capacity that characterizes a natural stream. In short, purely physics-based restoration cannot be truly sustainable.

6 | CONCLUSIONS

Given that plants and animals work to improve their own life chances and those of their offspring, we should not be surprised that riverine life is both well-adapted to the environments that streams provide and adept at maintaining, enhancing, and repairing river habitats. Partnering with nature's river restorers should reduce project costs compared with those incurred when consultants and contractors go it alone. High hourly rates for skilled river restoration consultants limit inputs to a few person-days on all but the most lavishly funded projects. Nature's river restorers work constantly and without pay. However, unless a river is being truly rewilded, the involvement of suitably qualified, restoration design engineers remains vital. Ultimately, an appreciation of the human context, as well as the ecological and hydromorphological contexts, is necessary. Many river catchments are located in whole, or in part, in unnatural anthromes. Therefore, the river, as an integrator of catchment conditions, cannot be returned to nature. Many river channels are heavily modified and confined or have regulated flow regimes. These rivers work hard in the service of humankind and they will not be relieved of that duty anytime soon. Finding sustainable management solutions for these blue-collar, “working streams” is challenging but also important and worthwhile. Working streams may never again be pristine, but they and the ecosystem services they provide can be restored to be robust, reliable, valued, and resilient to changes in their hydro-climatic and socio-economic futures that are not just uncertain but unknowable. In short, even if we cannot give them back an unbounded stream evolution corridor, there will be a good return on the investment if we give them as much liveable space as their service to society allows.

Restoring the adaptive capacity necessary to ensure ecosystem service provision that is both acceptable and reliable requires a deep understanding of the surrounding anthrome, so that the catchment is able to meet changing needs of all the organisms that support, and benefit from, the river. This encompasses all types of organisms from the smallest to the largest and from the simplest to the most complex. Management and restoration projects that perpetuate the physics-based orthodoxies of stable channel design that balances the flows of water with sediment load represent a form of hubris that, alone, will not reverse long-standing and accelerating declines in aquatic life and river functioning.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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