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Towards biogeomorphic river restoration: Vegetation as a critical driver of physical habitat

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Abstract

The current focus of river restoration on flow and sediment transfer without proper consideration of vegetation as a key structuring agent, beyond its stabilising effect, is too simplistic. We contend that vegetation has an essential role in shaping the physical fluvial environment and should be considered equally alongside hydrogeomorphic processes in restoration projects. In support, we introduce engineer plants as important controls, along with flowing water and transported sediments, on the morphodynamics of river systems and associated physical habitat development. The effect of vegetation on channel planform is then summarised, the influence of vegetation on hydrogeomorphic connectivity is outlined, and then the role of vegetation in landform development and habitat provision, as encapsulated in the fluvial biogeomorphic succession model, is described. We then present examples demonstrating how vegetation has contributed to the recovery of degraded rivers through

biogeomorphic processes. Finally, we advance the concept of biogeomorphic river restoration by proposing principles to support a closer synthesis of the component sciences and list key areas for practitioners to focus on. Vegetation succession has a significance that goes beyond its physical structure or influence on sediment stability. In many river settings, it is central to channel evolution. The coupled assembly of plant communities and fluvial landforms affect the development of spatially and temporally dynamic habitat through biogeomorphic interactions. Restoration approaches that do not fully consider this dynamic may fail to anticipate river behaviour and recovery trajectories.

Keywords

Connectivity, habitat recovery, hydrogeomorphology, riparian vegetation, riverscape, succession

1 Introduction

Rivers incorporate the active wet channel(s), hyporheic zone, riparian zone and floodplain, and are variously referred to as the river corridor, river landscape or riverscape (Fausch et al., 2002; Ward, 1989). Human activities have altered the riverscape over millennia to such an extent that most rivers now exist in anthropogenic landscapes (Brown et al., 2018). In many watersheds, this is reflected by multiple physical alterations, including impoundment and flow regulation, channelisation, sediment mining and land cover change. The scale of these pressures means that many rivers are ecologically degraded and require habitat restoration to support their biological communities (Feld et al., 2011; Palmer et al., 2007). Ultimately, most river restoration projects aim to enhance biodiversity and ecological function by improving habitat conditions. Restoration measures typically involve manipulation of the active channel bed, bank profile, adjacent riparian areas and floodplains, and the water, sediment and solute inputs to rivers to improve hydrologic, geomorphic and/or ecological processes, to restabilise lost or degraded system components (Wohl et al., 2015). Initially, restoration approaches sought to engineer specific habitat structures that were considered necessary for certain target species (e.g. salmonids), but this often resulted in unnaturally static conditions with little scope for channel evolution (Wohl et al., 2005). As river restoration practice evolved, it was recognised that riverscapes are not in a static state reflecting fixed conditions, but rather, fluctuate in response to changes in system drivers and this dynamism is central to habitat creation, maintenance and renewal (Ward et al., 2002). This led to calls for more holistic approaches to river management (Newson & Large, 2006; Palmer & Allan, 2006; Ward et al., 2001), and for a restoration approach focused on the reestablishment of naturalised rates and magnitudes of the hydrogeomorphic, chemical and ecological processes that support river ecosystems (Beechie et al., 2008). Moreover, usage of the term 'riverscape' has proliferated in recognition of the interconnectedness of the watershed in terms of physicochemical, ecological processes and human influence. This also reflects the requirement for a more integrated field of enquiry to inform management approaches (Allan, 2004; Amoros & Bornette, 2002; Haslam, 2008).

In practice, this meant that many restoration projects approached rivers as bottom-up, hierarchal systems with hydrology driving channel morphology through its effect on sediment processes and this interaction shaping the physical habitat template for river biota. By applying

this bottom-up perspective to restoration projects, stream functions are classed into a hierarchy of categories (**Figure 1**) in which high-level functions are supported by lower-level functions. Level 1 (hydrology) underpins all other functions, whereas level 5 (biology) depends on all other functions (Harman et al., 2012; Speed et al., 2016). The pyramid shows the primary direction of cause-and-effect relationships structuring the river system and the assumption that addressing deficiencies in underlying hydrologic and geomorphic processes will also address deficits in biodiversity and ecological function. Fundamental to this approach is matching the slope and cross-sectional dimensions of the target (alluvial) channel with its capacity to transport sediment from upstream to downstream. The presumption is that when this relationship is balanced, it will result in a channel morphology that is in dynamic equilibrium and will replicate key physical habitats (e.g. eddies, pools, riffles, undercut banks, alluvial bars), even as the channel migrates laterally over time.

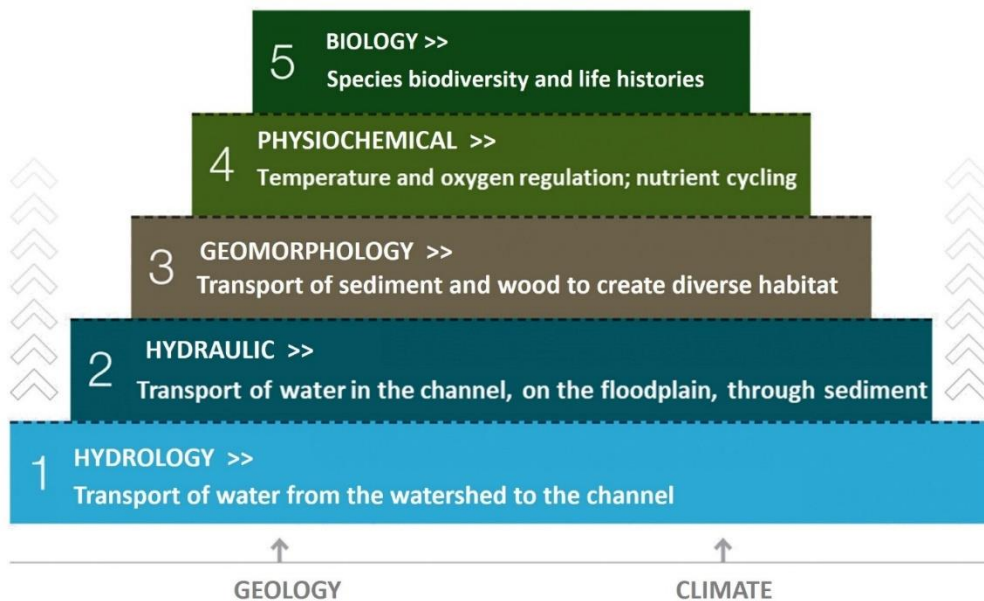


Figure 1. Stream functions pyramid framework. *Source:* Adapted from Harman et al. (2012).

The same construct has led to significant gains in understanding river hydrosystems, including the spatial distribution of geomorphic units/habitat features and energy pathways, as rivers and their biota are shaped by a changing gradient of physical conditions from their headwaters to mouth (Frissell et al., 1986; Hawkins et al., 1993; Poole, 2002; Townsend, 1996; Vannote et al., 1980). For example, the flow regime, its central role in erosion, sediment transport and deposition processes, and how natural flow disturbance is key to maintaining habitat diversity in the riverscape (Poff et al., 1997; Ward et al., 2002). Through further investigation, a greater awareness of the linkages between hydrogeomorphic and ecological processes in shaping fluvial habitat has grown (Fausch et al., 2002) and biota are now considered important drivers of physical change in their own right (Moore, 2006). In this paradigm, initially the interaction of hydrogeomorphic and ecological components was largely conceptualised as independent. In one direction, hydrogeomorphic processes and landforms shape the habitat and related distribution of biota. Conversely, in the other direction, biota modify hydrogeomorphic processes and landforms. Increasingly, researchers view interactions between hydrogeomorphic and ecological components as more circular and developmentally intertwined (Johnson et al., 2020; Polvi et al., 2020), but this understanding has been slow to permeate restoration approaches on the ground (Brierley & Fryirs, 2022). At present,

vegetation is largely used to manage erosion, for example, in bio-engineering techniques that seek to stabilise banks, but rarely consider the temporal dimension of ecological succession that may follow or its implications for habitat evolution. Correspondingly, restoration projects continue to be dominated by the geomorphic and engineering sciences, with physics as the driver and biology as the product.

Yet this stream functions pyramid framework on its own is insufficient to encapsulate the influence of biology on hydrology and geomorphology (and, to a lesser extent, geology), and on overall habitat provision. Substantial evidence that organisms influence hydrology and geomorphology exists, specifically regarding the ability of vegetation (Gurnell, 2014) and animals (Jones et al., 1994; Rice, 2021; Wright, 2002) to modify flow velocities and sediment deposition and transport, thus, challenging the hierarchical nature of the stream functions pyramid framework (Fisher et al., 2007). Beavers are, perhaps, the best known 'engineer species' and modify river systems through canal excavation, woody debris augmentation and dam building with wide ranging impacts on hydrology, sediment transport and morphodynamics (Brazier et al., 2021). Johnson et al. (2020) describe the diverse effect of biota, mostly animals in this case, from small (macroinvertebrates, shellfish) to moderate (fish) and the large (beavers and ungulates) sized on the river environment through their effect on hydrology, geomorphology and other biota. Furthermore, they contend that current restoration failure to sufficiently consider the role of biology on the function and form of rivers is a major cause of the underperformance in many projects.

Concomitantly, we assert that river structuring forces are not always bottom-up, with abiotic processes the overriding driver of ecological systems, but often bi-directional and variable depending on time and system attributes. As plants are typically the dominant land cover, we focus on vegetation as a fundamental control of fluvial morphodynamics in many river settings through its effect on hydrology (frequency and magnitude of river discharge, hydraulics) and geomorphology (the related erosion, transport and deposition of sediment), moderated by sediment supply and valley gradient. We argue that vegetation dynamics are a key agent in structuring the physical environment and should be considered equally alongside hydrogeomorphic processes in restoration projects. The presence of vegetation in river systems has several roles in shaping physical habitat for biota, including:

- Regulation of run-off: hillslope and floodplain vegetation acts as a control on hydrological run-off and associated sediment transport into river channels from the surrounding valley (Jencso et al., 2010; Tabacchi et al., 2000).
- Altered flow dynamics: plants and large fallen dead wood influence flow patterns. They may obstruct and/or deflect flow, creating areas of slower and faster water, side channels or complex hydraulic conditions that enhance habitat heterogeneity and diversity (Cornacchia et al., 2018; Tsujimoto, 1999).
- Bank cohesiveness: riparian vegetation contributes to channel stability by anchoring sediment and resisting bank erosion (Camporeale et al., 2013; Perucca et al., 2007).
- Landform development: riparian and channel vegetation can obstruct water flow, allowing sediment to settle and be retained, leading to the creation of pioneer landforms/habitats such as bars, islands, backwaters and, in the longer term, floodplain features such as scroll bars and oxbow lakes (Corenblit et al., 2015; Corenblit et al., 2007).

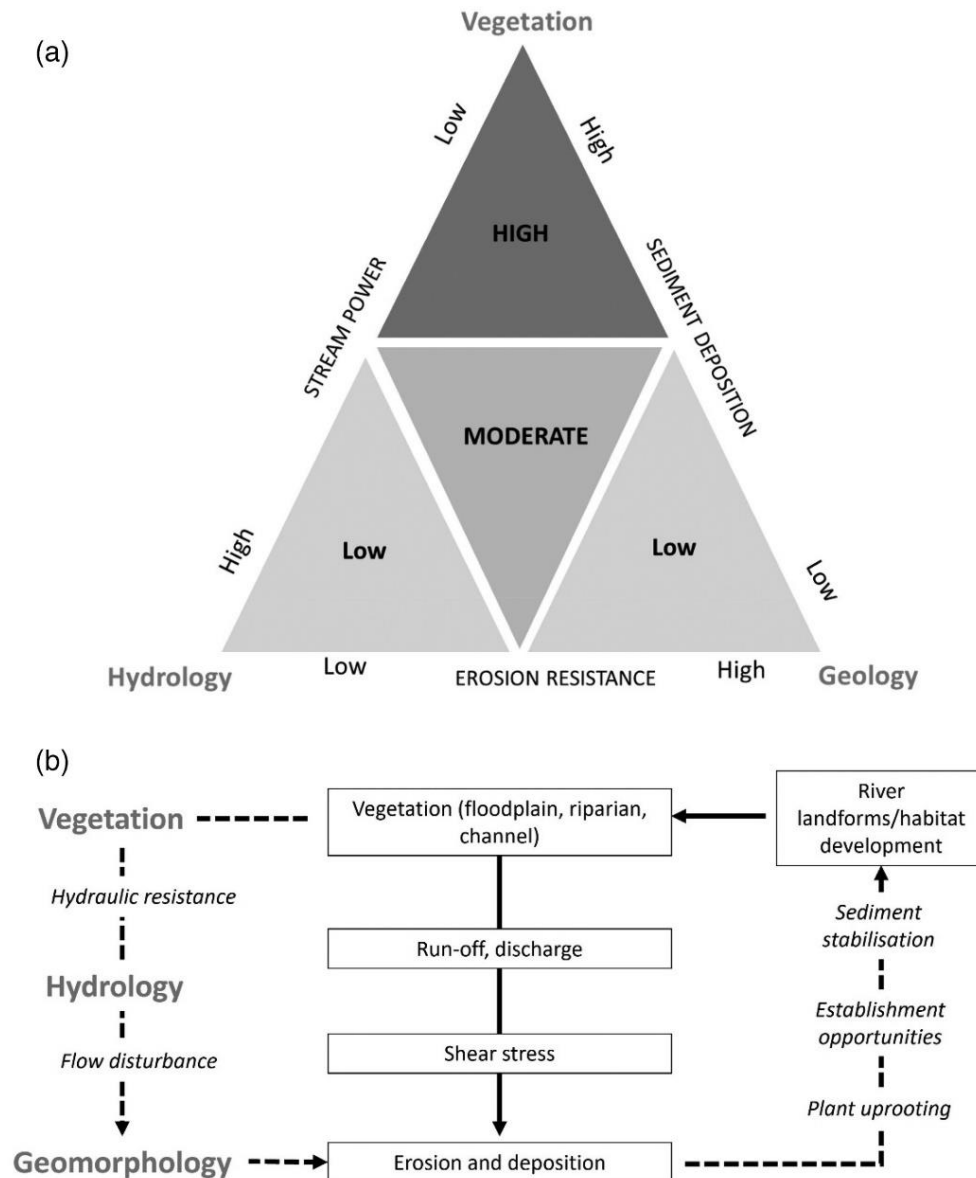


Figure 2. A biogeomorphic framework conceptualising: (a) the strength of control (grey shaded triangles) vegetation exerts on sediment deposition (interception and stabilisation) relative to the influence of geology (erosion resistance) and/or hydrology (stream power) on sediment supply and transport (*sensu* Castro & Thorne, 2019); (b) vegetation as a control (solid line) on hydrogeomorphic processes that influence landform development and habitat provision in rivers. In a feedback loop (broken line), flow disturbance can destroy vegetation patches through scour but also provide establishment opportunities for plants on newly eroded/deposited substrate. Vegetation moderates flow disturbance through obstruction (hydraulic resistance) and by anchoring sediment in its roots which facilitates landform/habitat development.

Researchers increasingly recognise the need for biogeomorphic frameworks that conceptualise the influence of biota on sediment transport and geomorphic structure. Hence, fluvial biogeomorphology represents an integration of river ecology, fluvial geomorphology, geology and hydrology (**Figure 2a**) with a focus on the role of interactions and feedback between hydrogeomorphic and vegetation processes in structuring rivers (Castro & Thorne, 2019; Hughes, 1997; Thoms & Parsons, 2002). Since the hydrogeomorphic conditions are significantly influenced by ecological plant succession, any efforts towards river restoration must realise the nature of this relationship to derive a long-term benefit (O'Brain et al., 2022).

This entails shifting the focus of river restoration from flow and sediment processes to also harnessing the power of biology to influence river processes and habitat provision (**Figure 2b**). To support better integration of vegetation processes into river restoration planning and practice, we first establish the basis for plants as river engineers from an applied perspective. Elaborating on this, the role of vegetation in river planform development is reviewed because common practice in restoration design is to consider analogue or near natural/reference river planform in relation to future channel design (Brown et al., 2018; Nardini & Conte, 2021; Newson & Large, 2006). Hydrogeomorphic connectivity (defined here as the degree to which a system facilitates the transfer of water, sediment and organic matter through itself), another key focus of contemporary restoration is then discussed concerning the influence vegetation exerts on this system property at different scales. We then consider feedbacks between hydrogeomorphic processes and vegetation in directing channel evolution and how these biogeomorphic feedbacks are fundamental to the provision of spatially diverse and temporally dynamic habitats in the riverscape. Case study examples demonstrating how biogeomorphic processes have contributed to habitat recovery in degraded rivers are also presented to support our thesis. Finally, we examine how vegetation dynamics can be better integrated into river restoration and outline principles to help set goals for river restoration approaches that incorporate biogeomorphic processes.

2 Plants as river engineers

In the absence of human interventions, river channels adjust their size and shape in response to interactions amongst flowing water, transported sediment and colonising plants within the river channel and margins, all of which are affected by local climate (Corenblit et al., 2011; Corenblit et al., 2007; Gurnell, 2014; Gurnell et al., 2012). These interactions and the relative importance of the contributing processes regulate vegetation growth and successional phases and related habitat turnover in rivers. Some plant species act as physical ecosystem engineers (*sensu* Jones et al., 1994) and species sharing this function occur across a range of river settings. Engineer plant species typically refers to those that initially colonise bare riverine sediments, and then retain and reinforce fine sediments, organic matter and nutrients to build landforms that provide a variety of physical habitats (for a review, see Polvi & Sarneel, 2018). In this way, engineer riparian (e.g. Tabacchi et al., 2019) and aquatic (e.g. Gurnell et al., 2012; O'Briain et al., 2022; O'Hare et al., 2016) plants play a central role in the fluvial biogeomorphic succession (FBS) process (Corenblit et al., 2007), where their impact on progressive landform development facilitates both, their own growth and the colonisation of the habitats they create by other plant species and biota. The term engineer plant species may include not only pioneers but also secondary species that establish later when conditions are suitable, and they may also have a pronounced effect on river morphodynamics. For example, species typically regarded as aquatic may initiate embryonic landform development on the channel margins, only to be replaced by riparian species as the landform aggrades above the water line and the biogeomorphic succession process evolves further.

In higher-energy and more frequently disturbed reaches such as those found in the middle sections of rivers, flow-resistant woody species such as *Salix* spp., *Alnus* spp. and *Populus* spp. inhabiting the riparian zone are important engineers. In lower-energy reaches, macrophytes are typically abundant and may act as ecosystem engineers (Gurnell et al., 2016;

O'Briain et al., 2017; O'Hare et al., 2016). These engineers can affect ecological succession dynamics by creating and modifying habitats and facilitating colonisation by other plant species (and biota) in river reaches where sufficient sediment supply exists for landform building and related physical habitat creation. The presence, type and abundance of engineer plant species in a river corridor may determine whether river morphology is dominated by disturbance-related landforms associated mainly with hydrogeomorphic processes (e.g. flood disturbance and sediment mobilisation), or by biogeomorphic landforms (e.g. islands, backwaters, strip levees, bank levees and oxbow lakes), linked to the effects and response of the engineer plant species (Corenblit et al., 2011). In river systems where vegetation dynamics are tightly coupled with flow and landform processes, plants may be the dominant control on river planform.

3 Vegetation as a control on planform

River restoration projects often start with efforts to establish the historic planform and related reference conditions. Insights from this exercise provide managers with a tool to determine a restoration target state that bridges the gap between near-natural conditions and future planform potential in the contemporary setting. Reconstructions of historical planform morphology can provide important insights into channel processes, alterations to those processes by humans and legacy effects impacting current planform. For example, sediment legacy supplies need to be accounted for to determine the feasibility of a restored planform and its long-term sustainability.

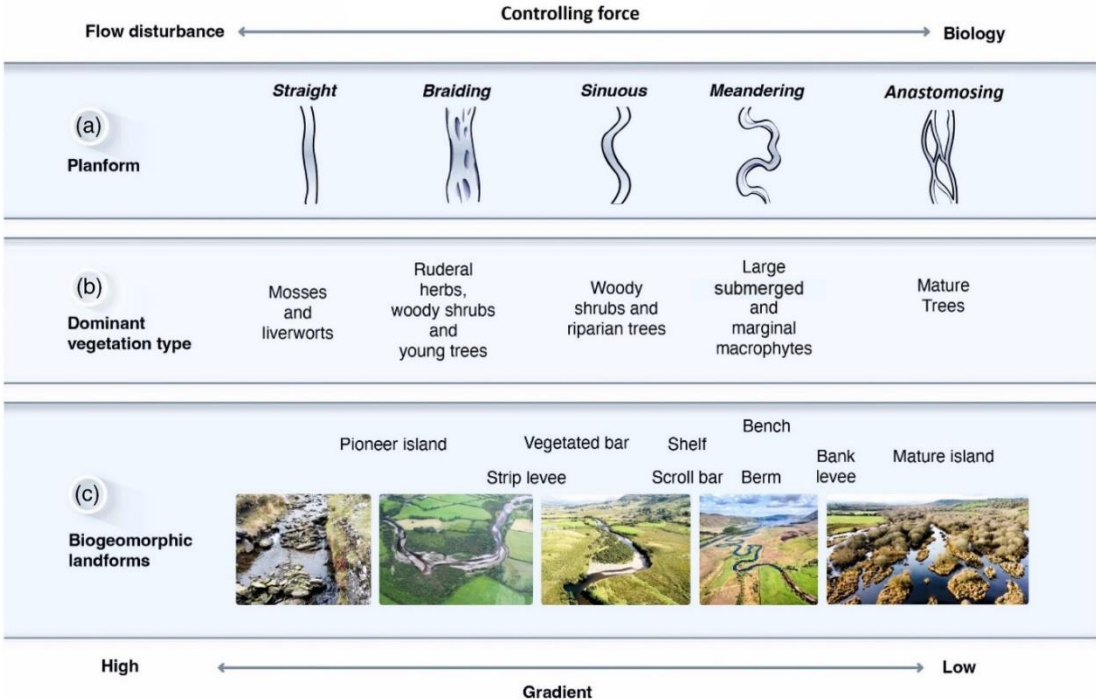


Figure 3. (a) Illustration of classical river planform types and the dominant controlling force on channel morphology and evolution depending on valley location. (b) The dominant vegetation types found in or by each channel planform. (c) Typical biogeomorphic landforms that emerge from interactions and feedbacks between hydrogeomorphic processes and vegetation dynamics to influence the overall planform (images are from rivers in west and southwest of Ireland).

Important physical variables such as gradient and discharge vary along the length of a river from its headwaters to sea, resulting in channel adjustments as patterns of erosion, sediment loading, transport and storage vary to generate relatively predictable planform configurations (Schumm, 1985). Whilst flow disturbance and sediment transport may be the dominant drivers of channel form in steep upland sections, it is apparent that biogeomorphic processes, and plants as biological agents, are the dominant drivers for several planform types in lower-energy settings (Polvi & Wohl, 2013), where erosional forces are reduced, and the presence of plants increase resistance to flow disturbance. As an example, **Figure 3** shows changes to planform (or typologies) as gradient and associated vegetation communities transition from upland to downstream locations along a river course.

3.1 *Straight channels*

In straight, downcutting channels, typically found in uplands, flood frequency and high shear stress are the dominant controls on channel form. Here, low-growing, streamlined plant species such as aquatic mosses have evolved to cope with high shear stress (O'Hare, 2015). However, as flow disturbance becomes more benign in lower river sections, plants increase in abundance and size and may assert considerable control over channel morphology (Gurnell, 2014).

3.2 *Braiding channels*

Braiding channels occur in a wide range of environments associated with moderate to high-energy, coarse-bedded rivers and where the influence of riparian vegetation on bank stability is limited. Braiding channels form progressively by channel migration and avulsion, leading to dynamic turnover of the multi-thread channels and bar patterns. Establishment of woody species such as *Salix* spp. and *Populus* spp. on gravel bars can lead to the development of pioneer islands and associated multi-thread channel patterns. Once these plants establish in the active channel, they trap sediment and other plant propagules as they grow, leading to enlargement of the landform and, potentially, to larger islands where they may merge with similar pioneer features to form larger post-pioneer and mature islands (Gurnell et al., 2001). These woody plants resist moderate flood events and continue to grow until they are buried by either excessive deposition or scoured by a high-magnitude flood disturbance, and thus, the bar-forming process starts over.

3.3 *Sinuuous and meandering channels*

Moving downstream, from braiding to increasingly sinuous planforms, riparian vegetation plays a key role in meander dynamics through its effect on bank erodibility. Laboratory and field studies demonstrate that woody riparian vegetation sufficiently increases stream-bank cohesion, overbank roughness and the associated sediment aggradation to cause braiding channels to transition to a meandering or anastomosing river planform (Braudrick et al., 2009; Nadler & Schumm, 1981). Some authors have contended that vegetation is so crucial to meander dynamics that meandering rivers may have been very rare before the evolution of land plants (Ielpi et al., 2022). In that sense, riverbank stability is essential to forming and developing sustained channel meanders (for a review, see McMahon & Davies, 2018). In particular, the root system of riparian trees and shrubs may greatly influence meander

dynamics by conferring higher erosion resistance on vegetated compared to unvegetated riverbanks, leading to bank areas with higher or lower soil erodibility depending on root density and depth (Camporeale et al., 2013; Perucca et al., 2007).

In the flat lowlands, where flow disturbance is least, macrophytes usually achieve their greatest biomass by developing large leaf surface area for greater photosynthesis and rooting in fine nutrient-rich sediments. In this low gradient, depositing environment, macrophyte stands can exert considerable control on channel morphology (Larsen, 2019). Species such as bur-reed (*Sparganium erectum*) (Gurnell et al., 2013; O'Hare et al., 2012) and fool's watercress (*Helosciadium nodiflorum*) (O'Briain et al., 2017; O'Briain et al., 2022) induce sidebar formation by establishing and trapping fine sediment and propagules of other species on the channel margins, and thus embryonic patches increase into more extensive stands. This process is central for initiating channel adjustments, including narrowing and aggradation.

3.4 Anastomosing channels

Finally, anastomosing channels overlaid by floodplain forests in humid biomes may best demonstrate the coupled assembly of plant communities, fluvial landforms and ecosystem evolution over longtime scales. Anastomosing channels can be differentiated from braiding channels, in which the latter have flows separated by bars within shallow, unstable channels, and the former, in which relatively deeper individual channels are separated by stabilised vegetated bars and islands that exist over longer periods. In these biogeomorphic systems, riparian tree root complexes maintain island stability by resisting erosion and vertically aggrading sediment, and the addition of large wood drives the formation of new channel patterns through obstruction and diversion (Francis et al., 2008; Makaske, 2001; Nanson & Knighton, 1996). Anastomosing rivers may be formed by avulsions or flow diversions that cause the formation of new channels on the floodplain. At other locations, large fallen wood originating from mature islands may lead to channel infilling and island enlargement where it creates debris dams and living vegetation subsequently establishes to further trap and stabilise sediments.

4 Hydrogeomorphic connectivity

Having previously established the important role of vegetation in the planform development, this section provides greater detail on the mechanistic influence of plants on hydrogeomorphic connectivity and its implications for habitat provision within the riverscape. In fluvial hydrosystems, water, sediment and organic matter are connected across lateral, longitudinal and vertical dimensions that span spatial and temporal scales. Vegetation intersects with geology and topography to regulate the extent of hydrologic and geomorphic connectivity across scales. The resultant interactions produce a mosaic of nested connections and associated processes operating in the riverscape that support a variety of habitats and associated biological communities (Frissell et al., 1986; Wiens, 2002) (**Figure 4**).

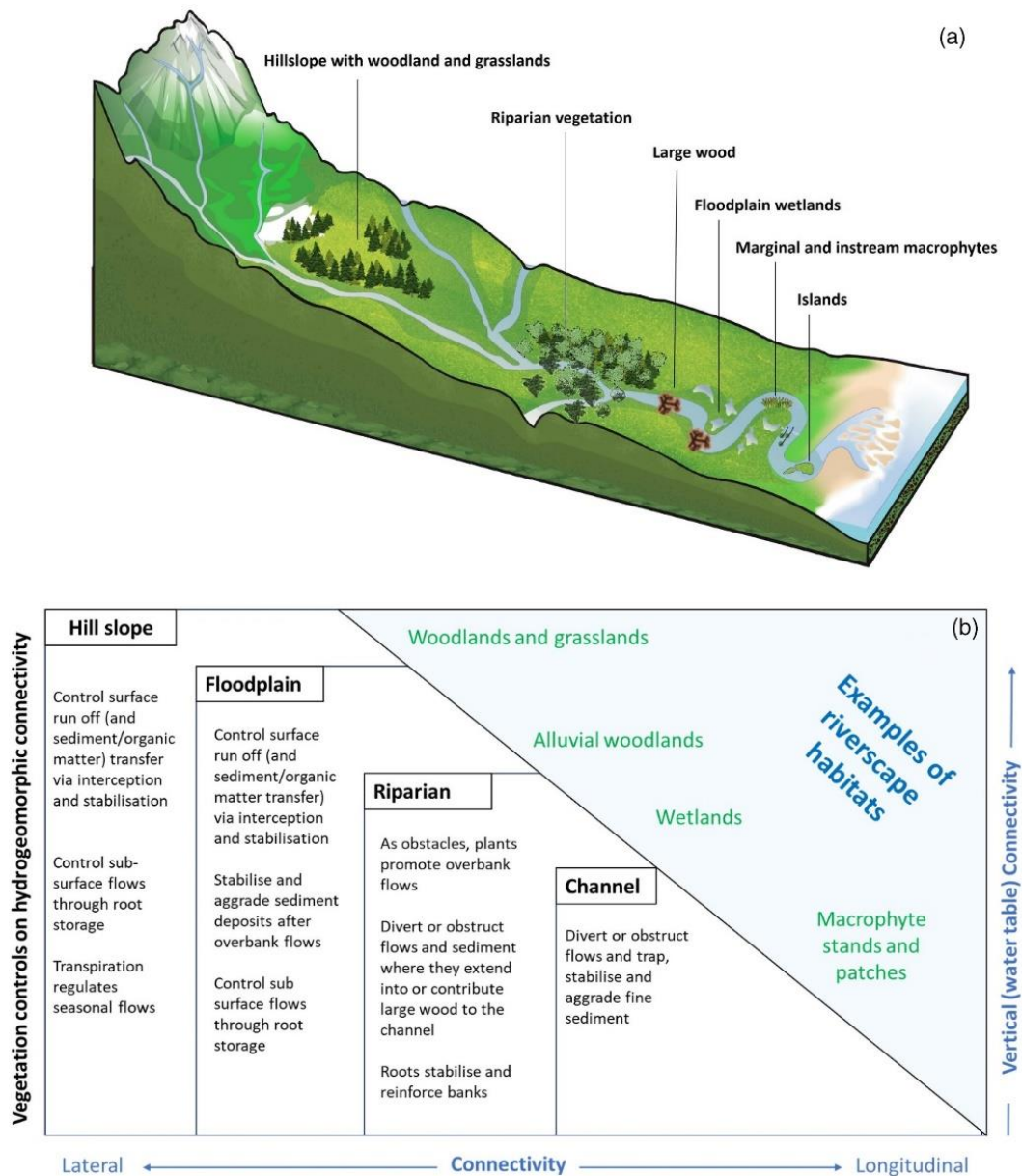


Figure 4. (a) Illustration of vegetation features/habitats interacting with hydrogeomorphic connectivity in a river catchment. (b) Control mechanisms of vegetation on hydrogeomorphic connectivity at different locations in the catchment (black text), associated vegetated habitat features (green text) and the three dimensions of spatial connectivity (blue text).

4.1 Hydrological connectivity

The transmission of water and nutrients, on which biota depend, is dependent on hydrological connectivity within a system because hydrological processes are critical to nutrient transfer between the land surface and river channel (Covino, 2017; Jencso et al., 2010; Wang et al., 2023). Review studies generally agree that stream flow generation is shaped by vegetation land cover and that different vegetation types reflect different patterns in hydrological connectivity (Bormann et al., 2009; Wei et al., 2013). Broadly, current research shows that forest cover, compared to grassland, may reduce average catchment discharge because of (i) increased rainfall interception, (ii) increased transpiration, (iii) reduced soil moisture and (vi) increased permeability of soils (e.g. Andréassian, 2004; Brown et al., 2005). In catchments

located in the mid-eastern (Jencso & McGlynn, 2011) and north-western United States (Emanuel et al., 2014), where seasonal run-off from snowmelt is a primary driver of hydrological variability, both studies found coniferous woodland vegetation to be a significant control on hydrological connectivity. Specifically, Jencso & McGlynn (2011) reported that vegetation land cover was an important determinant of annual streamflow during high run-off events and between events through transpiration processes. Similarly, Emanuel et al. (2014) reported that vegetation density interacted with other variables, such as topography, to create variable hydrological connectivity between hillslope, riparian and stream areas with transpiration having a pronounced seasonal effect.

At a more local scale, riparian vegetation affects hydrological processes in several ways (for a review, see Tabacchi et al., 2000). The main impacts include changes to discharge and control of run-off via root storage and evapotranspiration; promotion of overbank flow by stems, branches and leaves where they act as obstacles; diversion and slowing of flows by log jams; change in the infiltration rate of flood waters and rainfall by leaf litter; increase of substrate porosity by root penetration; the concentration of rainfall by leaves, branches and stems. In relation to macrophytes, they can be very abundant in lowland rivers. In these systems, discharge and flow velocity influence macrophyte colonisation and expansion. However, macrophyte stands can strongly modify flow patterns once established through flow obstruction, deflection and sediment stabilisation (Biggs et al., 2018; Cotton et al., 2006; Janauer et al., 2013).

4.2 *Sediment connectivity*

In a given catchment, multiple sediment sources exist, and sediment transfer occurs through coupled relationships within lateral, longitudinal and vertical dimensions of connectivity. For example, sediment transfer takes place on hillslopes, “between hillslopes and channels (lateral transfer in a slope-channel coupling), between floodplain and channel (bank erosion, floodplain deposition: lateral and vertical accretion) and within channels (longitudinal connectivity associated with downstream sediment transport)” (Fuller & Death, 2018). Hydrogeomorphic connectivity means that sediment loads generated by hydrological and associated erosion events are effectively transferred through the system. The process affects bank erosion, bar development at the local scale and related phenomena at the landscape scale, for example channel migration across the valley floor. During high-magnitude flow events, it may also generate avulsions and mass movement (e.g. hillslope collapse) that contribute to geomorphic diversity.

Sediment connectivity enabled by hydrological disturbance events (i.e. flooding) enhances ecological connectivity and biodiversity by promoting a diversity of geomorphic features. In-channel features (e.g. riffles, pools, side bars), meander loops, side channels, braids, backwaters and floodplain features such as scroll bars, abandoned meanders and wetlands can also be considered as a mosaic of habitat patches, ecotones and successional stages inhabited by different aquatic and terrestrial biological communities (Ward & Wiens, 2001). However, under certain conditions, high hydrogeomorphic connectivity can be potentially detrimental to fauna and flora. For example, high flows and related sediment mobility can directly damage habitat and/or biota through scour and abrasion and intolerable levels of suspended sediment that impair respiratory function, partial or complete burial or sediment

dumping on reproduction/spawning sites (Hastie et al., 2001; Newcombe & MacDonald, 1991). Indirectly, excessive habitat turnover resulting from high hydrogeomorphic connectivity can degrade biological communities by limiting (spatially and temporally) habitat quality and abundance. For example, Madej and Ozaki (2009) documented channel recovery in a coastal Californian river after several large floods in the 1960s–1970s. Vegetation loss associated with intensive logging and road building prior to the floods was responsible for reducing structural resistance, leading to extensive mass movement and high levels of channel aggradation that contributed to extensive geomorphic change. Sediment impacts have persisted for several decades and consequently have reduced the quality and availability of aquatic habitats for anadromous salmonids and retarded population recovery.

In other examples highlighting the role plants play in regulating hydrogeomorphic connectivity and rates of flux, the effects of floodplain and riparian vegetation on system stability have been a subject of research for some time (Andreoli et al., 2020; Eaton & Giles, 2009; Millar, 2000; Zhu et al., 2022). As previously stated, the presence of plants affects lateral geomorphic connectivity by regulating floodplain/bank stability and erosion rates by increasing mechanical resistance to flow disturbance. In a broad geographic study, Ielpi and Lapôtre (2020) investigated vegetation impacts on meandering rates in 483 unvegetated rivers in arid regions and 500 heavily vegetated river meanders in cold, temperate and tropical regions worldwide. Channel migration rates were, on average, 10-fold slower where vegetation was present. The observed slowdown in migration rate was not related to any physical attributes of the river systems, such as channel width, riverbed slope, catchment size or confinement within a valley, but attributed to plants as a dominant control on erosion. This example emphasises the key role of plants in affecting channel patterns at a landscape scale, and the resilience of these landscapes to fluvial disturbance.

Whereas the above example highlights the critical role of plants in regulating lateral hydrogeomorphic connectivity (hillslope, floodplain, riparian and bank areas), aquatic and riparian vegetation is also crucial in moderating longitudinal connectivity. In low-energy rivers, aquatic macrophyte growth and senescence are intimately linked to sediment retention and loss (Jones, Collins, et al., 2012; Wilkes et al., 2019). Gurnell and Bertoldi (2022) estimated fine sediment retention by vegetation across the active channels of three gravel-bed river types (near-straight, meandering and braiding). Vegetation retained nearly all fine sediments found on the bed surface of these active channels, increasing from 78% in the lowest energy to 100% in the highest energy river reaches. In shallow, low-energy streams where macrophytes can grow abundantly, plants will greatly influence the functioning of the ecosystem, at least at the reach scale. Under these conditions, macrophytes, not only trap and stabilise sediment, but also function as a link between bed sediments and the water column. The uptake and temporary storage of nutrients by the plants and the retention of fine sediments within dense plant stands, means that macrophytes in rivers not only affect sediment transport and hydraulics, but are an integral component of nutrient dynamics (Clarke, 2002; Licci et al., 2022), which is critical to the ecological function of rivers.

5 Fluvial biogeomorphic succession

Fluvial biogeomorphic succession refers to the progressive changes in vegetation and geomorphic features over time in response to river dynamics and ecological processes (Corenblit et al., 2007). **Figure 5** conceptualises a distinct cycle of destruction of fluvial landforms by flood events, and their regeneration via engineer plant species that stabilise sediment during the subsequent biogeomorphic succession process. Plants generate biogeomorphic feedbacks when they reach a critical density threshold. Eventually, as landform development proceeds, vegetated patches aggrade above the water flow and away from flow disturbance, ecological processes become dominant in the stabilisation phase. Flood events of varying intensity may reset the process at different phases to begin the renewal process.

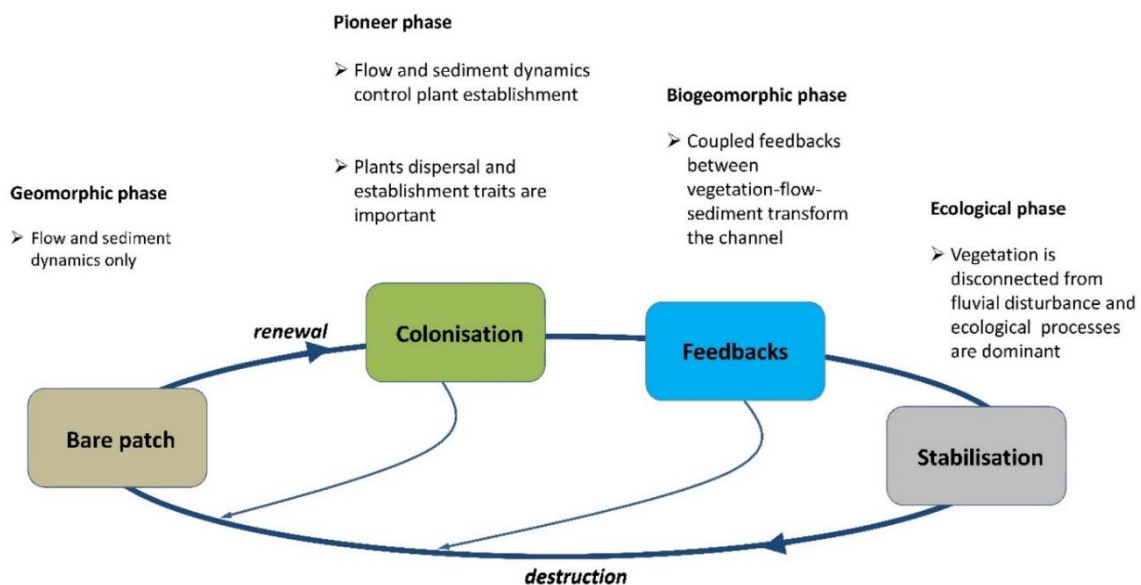


Figure 5. Fluvial biogeomorphic succession of rivers. *Source:* Adapted from Corenblit et al. (2007).

Pioneer plants colonise bare substrate patches that are created by fluvial disturbance, where they further trap and aggrade sediments in their canopy and roots. This biogeomorphic succession promotes landform development. This process has ecological implications as landform development affects the very nature of the physical habitat template. For instance, altered hydraulics through flow obstruction or deflection, sediment sorting and related channel morphology may all be mediated by vegetation establishment and its influence on rates of erosion and deposition shape physical habitat (Gurnell, 2014; Gurnell & Petts, 2006). It is important to note that the specific trajectory and pace of fluvial biogeomorphic succession can vary depending on factors such as hydrology, sediment availability, disturbance regimes, vegetation species and types and biotic interactions. Understanding these processes is crucial for effective river restoration and management, as it allows for the implementation of strategies that support the natural progression of vegetation and geomorphic features. By shifting the focus from static patterns to dynamic processes along river networks and incorporating ecological processes alongside flow and sediment processes as a third system driver, advances can be made to understand the interactions and feedbacks at the nexus of habitat creation.

6 Examples of biogeomorphic processes in river restoration

This section provides case study examples demonstrating how biogeomorphic processes have contributed to the recovery of degraded rivers. The examples show the potential for a broad application of biogeomorphology in river restoration as they represent a variety of river settings and spatiotemporal scales alongside common anthropogenic pressures and constraints that can limit management options.

6.1 *Recovery of low energy channelised streams following the establishment of macrophyte species (Ireland)*

The biogeomorphic recovery period in a gravel bed lowland stream was documented over an 8-year study following the cessation of cyclical dredging and persistent livestock grazing (O'Briain et al., 2017; O'Briain et al., 2022). A review of historical maps from 1829 to 1841 showed that the Stonyford River previously flowed through wetlands and was liable to bank overtopping during high-flow events. Channelisation was undertaken in the 1960s to promote land drainage and facilitate land use change to present-day grazing pastures. This process, together with cyclical maintenance, generated an over-deepened and widened channel with homogenous morphology and high fine sediment deposition on the bed.

Following cessation of dredging and exclusion of livestock from the channel, initiation of more natural vegetation dynamics and interactions with hydrogeomorphic processes occurred quickly to affect a biogeomorphic response. Over the years, the authors documented physical habitat recovery from uniform to more structurally complex habitat. Higher-level channel patterns, including landform development on the margins and promotion of a secondary sinuous channel, emerged from localised interactions and selection processes acting at lower levels, that is, plant establishment, sediment trapping and subsequent succession (**Figure 6**). Physical habitat recovery was reflected in greater water depth and substrate diversity characterised by increasing substrate coarseness with higher and more diverse flow velocities. The observed recovery trajectory was analogous to the phases described in the FBS model (Corenblit et al., 2007; Gurnell et al., 2012). Engineer plant species colonised and initiated pioneer landform development on the channel margins. As the landforms aggraded above the flowing channel, they are increasingly disconnected from flow disturbance, indicated by replacement of aquatic plant species by wetland species in this example. Notably, very high macrophyte abundance created a lag in physical recovery evident after the stream became clogged with vegetation (**Figure 6**, in year 2017) before a more complex pseudo-meander form arose, indicating that recovery trajectories may be non-linear in naturally variable river systems and may require more time to affect change, in contrast to more interventionist approaches to habitat restoration.



Figure 6. Time series (2013–2020) of photographs at two locations (top and bottom) in the Stonyford River, illustrating biogeomorphic trajectory from disturbed to recovering (from left to right) over the study period. Note progressive pioneer landform development on the channel margins.

6.2 Recovery of low energy channelised streams following establishment of woody riparian species (Tennessee, USA)

Hupp (1992) is amongst the earliest investigations reporting biogeomorphic recovery driven by woody vegetation establishment and bank accretion. The study documented morphodynamic responses following channelisation in 15 low-energy sand bed streams in a watershed. Return time to a pre-channelisation state was estimated at ≈ 65 years. Typically, as part of the channelisation process, all aquatic and riparian vegetation was removed during the construction of the engineered channel, creating conditions for secondary succession. The author's description of revegetation post-channelisation and the process of biogeomorphic recovery is summarised as follows. Establishment of vegetation on bank slopes and sediment accretion acted together to increase bank cohesiveness as roots of woody plant species acted to aggrade and stabilise sediment. The engineer plant species comprised a mix of woody, fast-growing riparian species (e.g. *Salix* spp.) adapted to flow disturbance and sediment burial, conditions prevalent at the land–water interface. Presence of these species on channel banks and slopes also reduced flow velocities locally during high-flow events, which further enhanced sediment deposition. Increasing bank slope accretion and vegetation on inside bends prompted point-bar development and concomitant vegetation expansion. Correspondingly, point bar expansion increased flow deflection towards the opposite bank, accelerating bank erosion on the outside bend, and ultimately increasing channel sinuosity as meanders developed. Recovery was characterised as a return to a meandering planform, associated point bar features and diverse bank vegetation that extended from the bank top and down the bank slope.

6.3 Post-mining recovery in a moderate energy river (Wales)

Dawson et al. (2022) investigated changes to river planform caused by metal mining, followed by a century of post-mining recovery from 1880 onwards, and the subsequent biogeomorphic impact of common gorse (*Ulex europaeus*) establishment in the floodplain from the late 20th century onwards. The study describes how erosive flood events affected a shift from a pre-mining meandering to a post-mining braiding planform in the absence of stabilising floodplain vegetation because of heavy metal contamination of soils. The authors then propose that a later reduction in grazing pressure by rabbits and subsequent establishment of extensive areas of *U. europaeus* initiated a relatively rapid process of floodplain and bar stabilisation. Channel pattern has responded by returning to a meandering planform (**Figure 7**) as colonisation of point bars by *U. europaeus* has enhanced sediment accretion. Correspondingly, amplified erosion of outer bends resulting from flow deflection by point bar features has increased lateral space for further bar enlargement through a process of 'bar-push' and 'bank-pull' that promotes meander development (Allmendinger et al., 2005; Parker et al., 2011; Zen et al., 2017), similar to the process described by Hupp (1992) (Section 6.2).

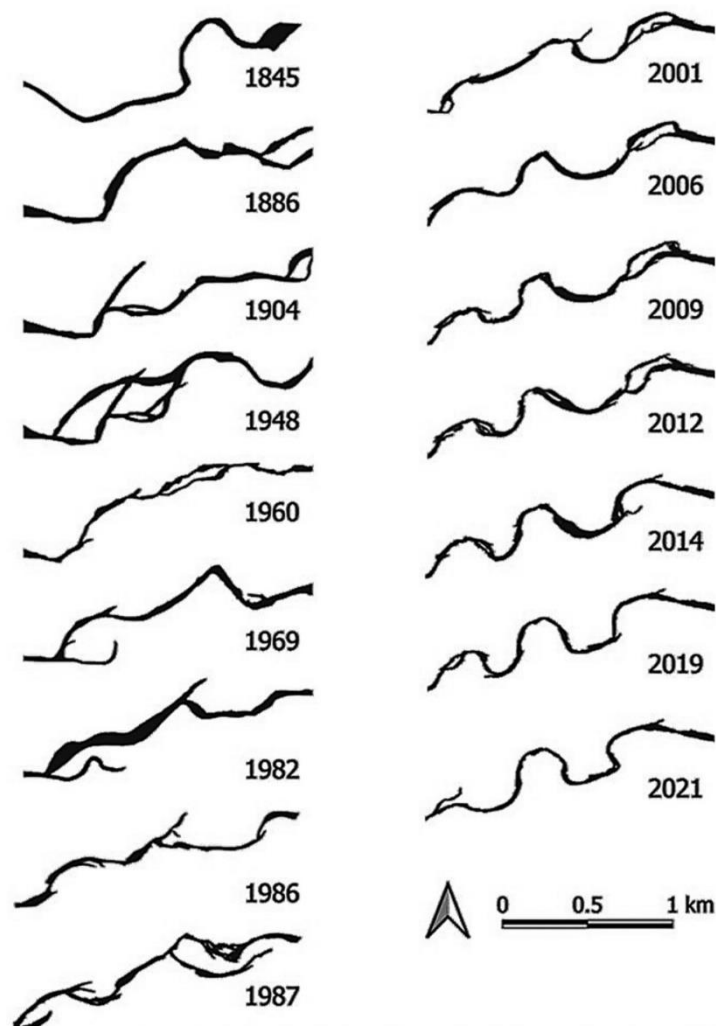


Figure 7. Planform of the River Ystwyth during mining operations (up to circa 1880), post-mining recovery (1886–1887) and following common gorse (*U. europaeus*) establishment (late 20th century–2021). *Source:* Re-drawn from Dawson et al. (2022).

6.4 Moderate-high energy river altered by channelisation, gravel abstraction and flow regulation (France)

Corenblit et al. (2020) have shown on the moderate-high energy Isère River (France) that feedbacks between hydrogeomorphic processes and riparian vegetation play a pivotal role in shaping the landscape and guiding vegetation succession within a channelised river corridor constrained by embankments, resulting in a predominantly straightened course. Over three decades, from the early 1970s to the late 1990s, dynamic alternate bars within the river channel were colonised gradually by riparian species, notably poplars and willows (**Figure 8**). This provided an opportunity to analyse the reciprocal adjustments between fluvial landforms and vegetation, transitioning from bare gravel bars to fully developed upland forests. The spatiotemporal arrangement of vegetated bars within the constrained river channel was a result of the constructive and stabilising effects of vegetation, as well as interactions amongst bars of varying age, size and mobility.

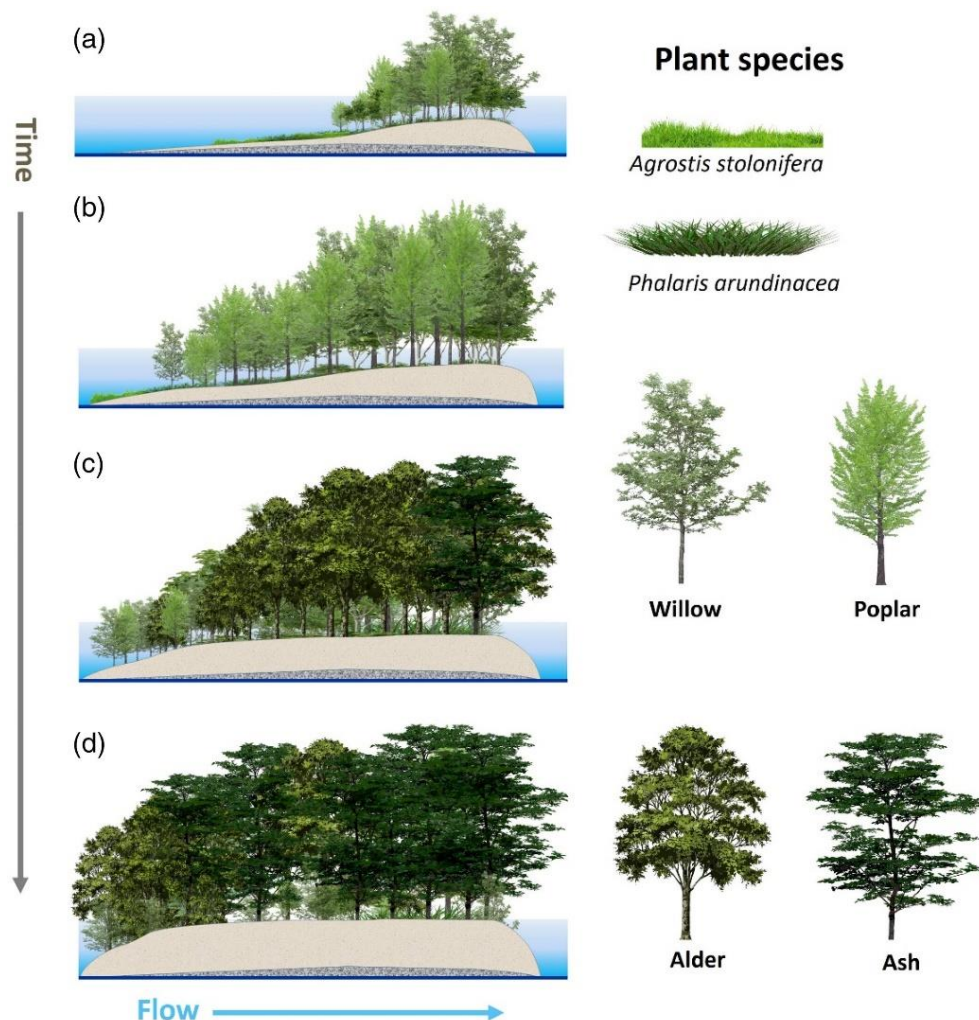


Figure 8. A simplified spatiotemporal representation of biogeomorphic succession occurring on alternate channel bars and its subsequent effect on landform development in the Isère River, France. Initial colonisation by pioneer grasses and riparian tree species (willow and poplar) of lateral bars has contributed to vertical aggradation and stabilisation of sediment over time and facilitated establishment of other tree species (alder and ash) that have further enhanced this process. *Source:* Adapted from Corenblit et al. (2020).

Analysis revealed strong positive feedback between sedimentary dynamics and vegetation succession, ultimately forming stabilised and raised vegetated bars. These dynamics align with the FBS model, as previously described by the authors (Corenblit et al., 2007). Due to the channelisation and confinement of the Isère River within embankments, its ability to naturally adapt its channel plan geometry is constrained. However, even within this highly impacted context, vegetation operated within the artificial confines. Notably, the process of vegetated bars accreting within this channel resulted in the manifestation of fluvial biogeomorphic habitat features in the landscape. The vegetated bars represent structurally complex habitat elements in the riverscape. Their evolution over a relatively short period of time illustrates the important role of biogeomorphic interactions in landform development and associated habitat provision.

6.5 Recovery of a channelised stream in a highly urbanised area (Spain)

The Manzanares River in the city of Madrid (Central Spain) was channelised between the 1910s and 1960s. The channel was transformed into a fixed rectangular concrete form, and a series of retention gates were built to maintain constant water levels. For these reasons, the river was categorised as a heavily modified river due to the presence of multiple pressures such as bank modifications, flow regulation, water pollution and related ecological degradation (Díaz-Redondo et al., 2022). In 2016, a programme to renaturalise the urban river section was initiated by adopting a process-based restoration approach (Magdaleno, 2017). This mainly involved opening the water retention gates. Although the flow regime continued to be subject to regulation, permanent opening of the gates and the introduction of deflectors diversified flow dynamics and promoted more natural sediment transport and deposition (D'Orey et al., 2023). A substantial recovery of habitat heterogeneity was detected over a short time-frame (Díaz-Redondo et al., 2022). Small islands and lateral sand bars developed in depositional areas along the riverbed (**Figure 9**). The pioneer landforms were rapidly colonised by riparian species, mainly willows and poplars, that started trapping new sediments, causing the islands and bars to multiply in number and size, and generating a more biodiverse river environment (Díaz-Redondo et al., 2022; Magdaleno, 2017). In addition, an improvement in water quality parameters has been recorded.



Figure 9. The Manzanares River post restoration. Development of pioneer landforms and their colonisation by herbaceous species. The islands and bars have enlarged and stabilised as pioneer woody species (willows and poplars) established later and trapped more sediment (Image credit: ©ReviveMadrid (left) and Centro Ibérico de Restauración Fluvial (right)).

7 Integrating vegetation processes into river restoration

Alongside physical scientists, landscape ecologists have invoked dynamic constructs such as the fluvial riverscape to describe river ecosystems (Poole, 2002; Ward et al., 2002; Wiens, 2002). Synthesis of ideas is not accidental; fluvial processes shape the physical habitat template against which river ecosystems operate. Ecologists and physical scientists have continued to describe the complex interplay between fluvial and ecosystem processes with several conceptual advances. Prominent examples include the hierarchical framework for stream habitat classification (Frissell et al., 1986); the river continuum concept (Vannote et al., 1980); the ecological significance of flow disturbance (Junk et al., 1989; Poff et al., 1997); hierarchical patch dynamics (Poole, 2002); hydrogeomorphology as a physical science basis to inform stream ecology (Poole, 2010) and biogeomorphic succession (Corenblit et al., 2007; Gurnell et al., 2001) as key mechanisms explaining spatiotemporal patterns of landforms and communities organisation in the riverscape. Each of these has contributed to the hydrological and geomorphological underpinnings of river ecology, and increasingly, the influence of biota on the habitat-landform complex. Full integration of the biogeomorphic dimension of rivers is now necessary to capture the suite of river processes that support the long-term provision of habitat.

Tellingly, changes in river patterns caused by human activities are often associated with enforced changes to vegetation within river catchments (Gurnell et al., 2009). For example, deforestation has caused some formerly braiding European rivers to shift to single-thread patterns and resulted in pronounced re-alignment of rivers in Australia and North America (Williams et al., 2014). The current focus on flow and sediment transfer without proper consideration of vegetation as a key structuring agent, beyond its stabilising effect, is too restrictive for sustainable restoration. In essence, this is because the prerequisites for its use: universality and simple causality, seldom apply in natural systems where biota and their abiotic environment are characterised by multiple causalities across space and time. The contemporary view in river restoration practice is that a planform design can be maintained given the appropriate sediment supply, and biota will use associated geomorphic features as habitats. This perspective is too simplistic. As established, biota often interact with hydrogeomorphic processes to initiate and affect the direction of channel evolution. Forced planform change through engineering measures and subsequent flow-sediment dynamics may not be successful or socially acceptable if the spatiotemporal biotic processes controlling planform are not accounted for. For instance, in low-energy rivers, cessation of dredging as part of restoration measures can lead to choking of the channel by aquatic vegetation, and vegetation colonisation and associated expansion of sidebars can increase lateral instability through flow deflection to the opposite bank. As another example, restoration projects returning single-thread channels to historical braiding planforms must account for longer-term succession dynamics, including riparian vegetation establishment and encroachment. Riparian species may not only enhance accretion and/or bank stability but also vertical incision rather than the desired instability necessary for temporary bar formation in braiding systems.

7.1 Principles for biogeomorphic river restoration

Here, we propose principles to support a closer synthesis of the hydrogeomorphic and ecological sciences to advance the concept of biogeomorphic river restoration, but first, the

role of plants in biogeomorphic processes can be briefly summarised as follows: (i) biostabilisation – the stabilisation of sediment as well as the opposite effect, that is, bioerosion due to mortality of individual plants or vertical incision caused by increased bank strength; (ii) bioconstruction – aggradation of mobile sediment, leading to landform development; (iii) the regulation of soil/sediment moisture regime through physiological processes (e.g. transpiration) and the creation of preferential flow pathways, for example, through root system growth in the subsurface; (iv) surface flow routing, like through the formation of physical obstructions that deflect the flow, for example, as a result of bioconstruction. Moreover, plants established on bare sediment or embryonic landforms facilitate the expansion and complexity of landforms and habitats. The restoration strategy, therefore, becomes one that encourages the propagation of the biological agents that are integral to biogeomorphic processes. With this knowledge, five principles incorporating the biogeomorphic dimension of vegetation are outlined for consideration in restoration projects.

- Vegetation constitutes an important control on the hydrogeomorphic processes of rivers and related habitat provision. Restoration of natural vegetation dynamics can facilitate naturalised rates of hydrological and sediment flux. Therefore, restoration interventions should assess whether vegetation dynamics are natural or can be reinstated as part of a holistic strategy to address system deviation.
- When planning river restoration projects, the starting point typically involves establishing how far the location has departed from the historical planform and the potential to reestablish those conditions. Given the importance of vegetation in some planforms, this part of the planning process should consider likely vegetation communities under undisturbed conditions, not just the physical form. Since altered rivers often lack comparative pristine locations, historical analyses of the river system and likely vegetative land cover can produce valuable reference data for reconstructing the character of the riverine system prior to alteration, including the (semi) natural vegetation components.
- Channel evolution and associated landform development are linked to biogeomorphic trajectories. Thus, restoration planning should identify where and when these processes can be encouraged. Such an approach should consider specified river typologies and associated vegetation types and seek to operationalise pathways for appropriate engineer plant species to establish via the phases (Geomorphic, Pioneer, Biogeomorphic and Ecological phase) conceptualised in the FBS model (Corenblit et al., 2007). For vegetation, with reference to engineer plant species, this requires a propagule source and suitable conditions for establishment and expansion as the river evolves in the long term. Restoration that adopts biogeomorphic approaches will have a goal of creating plant populations that establish, survive and successfully reproduce, so that they can influence system function and persist in the long term. A propagule source to establish the engineer species expected in a given river setting may not always be available in degraded or highly altered river systems. For example, many landscapes have been made virtually treeless by tree harvesting, conversion of land to agriculture and ongoing heavy grazing that retards plant establishment. In these instances, propagules may need to be introduced through, for example, translocation of plant seeds or planting of material sourced from a regional pool. As important as providing a propagule source is affording establishment locations, both spatially and temporally. This may require enclosures to

exclude grazers whilst plants establish or creating appropriate features, for example, channel bars, to provide establishment sites.

- Unless restoration practices are holistic and consider biogeomorphic trajectories, they may fail to understand recovery processes when working towards an eventual planform and the behaviour of a river. Vegetation-induced sediment accretion and/or stability influence channel evolution, but this is not linear. It depends on the traits of the plant species and the spatial and temporal strength of the feedbacks with hydrogeomorphic processes in determining the direction and magnitude of biogeomorphic change. This means that the nature of the three-way flow-sediment-vegetation relationship must be considered over short, medium and long-time frames for realistic targets to be set at the start of any project.
- Plants can act as agents of recovery, with recolonisation and successional processes facilitating improvement in degraded river ecosystems. Process-based restoration should encourage ecological processes and their biological agents to take a central role in habitat maintenance, without the need for regular human interventions. Biota has evolved to improve their survivorship and, in so doing, they drive biogeomorphic processes and can influence fluvial processes strongly. It is no coincidence that plants are well adapted to the fluvial environment, are adept at responding to disturbance, and can adjust to environmental change by maintaining and modifying habitat.

7.2 *Key focus areas for biogeomorphic restoration*

Biogeomorphic processes can be extended to existing river restoration frameworks, for example, the natural flow regime (Palmer & Ruhi, 2019; Poff et al., 1997) or process-based restoration (Beechie et al., 2010) to better link the hydrogeomorphic and biological structure of rivers interacting over temporal and spatial scales. Key biogeomorphic phenomena for river managers to focus on include:

- Retention of fine sediments: macrophytes have a primary role in trapping and regulating fine sediment transport, which is critical to the ecological function of rivers.
- Woody vegetation establishment: their root systems aggrade sediment and/or strengthen bars and banks and their canopy structure creates complex habitats for other organisms.
- Engineer plant species: their establishment in disturbed or newly formed channels and their role in embryonic landform/habitat development.
- Channel evolution and biogeomorphic trajectories: the biogeomorphic template on which landforms/habitat develop is constantly undergoing change depending on the strength of interactions with the flow and sediment regime. The growth and development of vegetation influence the river's dynamics, leading to changes in channel morphology. In particular, the presence of vegetation can both retard and promote lateral erosion, resulting in the formation of meanders and bank slope vegetation.
- Resilience: rivers support a mosaic of habitats that are spatially and temporally resilient because their dynamism supports turnover and renewal. This is not a one-way process, with hydrogeomorphology as the creator and biology as the response. The feedbacks between plants and hydrogeomorphic processes change with rates of colonisation, growth and mortality, which, in turn, affects channel patterns through its influence on erodibility and sediment movement. In this sense, whilst every river is unique, the form

of rivers and their characteristic vegetation community patterns are repeated across space because physical disturbance acts as a filter on species establishment and plants act as a control on fluvial disturbance. This means that re-establishing natural vegetation dynamics can aid geomorphic function, with recolonisation and successional processes facilitating habitat recovery of degraded river ecosystems.

The key focus areas listed above and the principles for biogeomorphic river restoration outlined in Section 7.1, inherently, require continued investigation to assess their efficacy and refine their application. Despite recent advances in conceptualising the processes and feedbacks between hydrogeomorphology and ecology and their role in shaping the river environment, studies that quantify the rate of interactions in a field setting remain scarce. As described in Section 4.2, Gurnell and Bertoldi (2022) focused on the contribution of vegetation to in-stream fine sediment storage in rivers with different planforms and found that nearly all fine sediment was retained by vegetation occupying the active channel. Excess fine sediment delivery and mobilisation caused by human activities negatively affects stream biota, for example, by impacting respiratory function, smothering breeding sites on the riverbed (Jones, Murphy, et al., 2012; Kemp et al., 2011) and blocking the interstitial spaces so important to hyporheic exchange (Magliozzi et al., 2018; Wharton et al., 2017). Better understanding of controls on fine sediment dynamics is potentially very important to managing the ecological and geomorphic function of rivers. The effect of vegetation is likely to change depending on vegetation type and abundance, successional stage and hydrogeomorphic setting. The nature and generality of this fine sediment-vegetation relationship should be explored and quantified further to support its possible integration into river restoration practice.

River restoration is implemented in systems previously altered by human activities. These alterations typically result in changes to energy fluxes and delivery of material in the system. The rate at which organisms engineer their environment may be accelerated or retarded relative to more pristine rivers, depending on the nature of the modifications. Applied studies (O'Briain et al., 2022; O'Hare et al., 2012) report some macrophyte species as establishing extensive stands that exert a strong engineering influence in modified lowland rivers. Their dominant presence in the cross section may lead to 'choking' in heavily managed (channelised) rivers as a response to reduced shear stress associated with artificial channel widening. However, biogeomorphic recovery of degraded rivers is complex and may follow a non-linear trajectory, where long-term trends are overlaid on shorter-term phases. Following cessation of cyclical removal of channel vegetation (by humans) in the same system and a longer period (6 years) for channel adjustments, O'Briain et al. (2022) reported evolution of a more natural meandering planform, characterised by improved depth and flow diversity, and sediment sorting related to spatial patterning of macrophyte patches (see Section 6.1). Channel evolution provided insights into the nature of biogeomorphic trajectories, the requisite time frames required for system recovery to initiate and the length of monitoring period necessary to capture these responses. Applied research is needed across different river settings to confirm how universal the reported response is, and the timeframes involved for different system types to support the application of engineer plant species in restoration projects.

Although not explicitly covered here, the establishment of invasive alien plant species (IAPS), and the potential loss, replacement or displacement of native plant species by IAPS can potentially alter biogeomorphic phenomena (Fei et al., 2014). Moreover, climate change

related modifications of habitat as a response to alterations in temperature and precipitation patterns will affect the distribution of some riverine species (Rogers et al., 2020). Weakening of climatic thresholds that previously constrained the geographic range of IAPS may provide opportunities for their expansion (Gervais et al., 2020) and weaken competition from those native species negatively impacted by climate disturbance. Such a scenario represents a potential double jeopardy for river systems since many IAPS readily colonise and establish in naturally disturbed river corridors and these are likely to experience greater physical disruption as climate change accelerates. Under heavy establishment facilitated by climate disturbance, it is proposed that IAPS could significantly alter landform and ecosystem development at the reach scale (O'Briain et al., 2023). This aspect of alien invasions deserves greater examination in invasive species research and river management science, since river restoration is often implemented at the reach scale. Fluvial biogeomorphology with its holistic view of rivers provides a useful framework within which to consider the potential impacts of IAPS on physical habitat in general, how it may manifest under climate change, and its consideration in restoration approaches.

8 Conclusions

Understanding the mechanisms that contribute to physical habitat diversity is critical because river restoration relies heavily upon the manipulation of channel structure (e.g. sediment patterns, channel dimensions) as a means of managing ecosystem function. Some plant species act as ecosystem engineers by intercepting and stabilising riverine sediments and organic material. This interaction with hydrogeomorphic processes contributes to the development of land-forming sequences and a variety of physical habitats. Concomitantly, biogeomorphic succession processes serve a crucial role in determining channel planform amongst braiding, meandering and anastomosing types by increasing bar, bank and floodplain stability, and the probability of avulsions through large wood delivery in the case of anastomosing channels.

Hillslope, floodplain, riparian and aquatic vegetation all play a role in regulating the timing and magnitude of flood events and the transfer of sediment and organic material through the system. Flood disturbance may partially or completely destroy existing habitats but also provides fresh opportunities for ecological processes and the biological activity that follows during lower flow conditions. Colonisation by plants after flood disturbance and subsequent expansion of vegetation patches percolate through the river ecosystem. Ecological succession on the margins and banks of rivers influences local sediment characteristics (e.g. particle size distributions and cohesion) and hydraulics (flow obstruction and deflection). The same process drives population growth of animals (insects, fish) and other plant species by stimulating landform and associated physical habitat development. These interactions are responsible for the coupled assembly of plant communities, river landforms and ecosystem development. Incorporation of biogeomorphic processes into river restoration planning and target setting is now required for a more complete approach to long-term provision of habitat in degraded systems. In general, we recommend that river restoration strategies should encourage propagation of the biological agents that are integral to biogeomorphic processes in moderate-low energy valley settings, and the maintenance of physical habitat across spatial and temporal scales.

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Conflict of interest statement

The authors declare no conflicts of interest.

Data availability statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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References

- Allan, J. D. (2004). Landscapes and riverscapes: The influence of land use on stream ecosystems. *Annual Review of Ecology, Evolution, and Systematics*, 35, 257–284.
- Allmendinger, N. E., Pizzuto, J. E., Potter, N., Jr., Johnson, T. E., & Hession, W. C. (2005). The influence of riparian vegetation on stream width, eastern Pennsylvania, USA. *Geological Society of America Bulletin*, 117(1–2), 229–243.
- Amoros, C., & Bornette, G. (2002). Connectivity and biocomplexity in waterbodies of riverine floodplains. *Freshwater Biology*, 47(4), 761–776.
- Andréassian, V. (2004). Waters and forests: From historical controversy to scientific debate. *Journal of Hydrology*, 291(1–2), 1–27.
- Andreoli, A., Chiaradia, E. A., Cislighi, A., Bischetti, G. B., & Comiti, F. (2020). Roots reinforcement by riparian trees in restored rivers. *Geomorphology*, 370, 107389.
- Beechie, T., Pess, G., Roni, P., & Giannico, G. (2008). Setting river restoration priorities: A review of approaches and a general protocol for identifying and prioritizing actions. *North American Journal of Fisheries Management*, 28(3), 891–905.

- Beechie, T. J., Sear, D. A., Olden, J. D., Pess, G. R., Buffington, J. M., Moir, H., Roni, P., & Pollock, M. M. (2010). Process-based principles for restoring river ecosystems. *Bioscience*, 60(3), 209–222.
- Biggs, H. J., Nikora, V. I., Gibbins, C. N., Fraser, S., Green, D. R., Papadopoulos, K., & Hicks, D. M. (2018). Coupling unmanned aerial vehicle (UAV) and hydraulic surveys to study the geometry and spatial distribution of aquatic macrophytes. *Journal of Ecohydraulics*, 3, 45–58.
- Bormann, H., Breuer, L., Gräff, T., Huisman, J. A., & Croke, B. (2009). Assessing the impact of land use change on hydrology by ensemble modelling (LUCHEM) IV: Model sensitivity to data aggregation and spatial (re-)distribution. *Advances in Water Resources*, 32, 171–192.
- Braudrick, C. A., Dietrich, W. E., Leverich, G. T., & Sklar, L. S. (2009). Experimental evidence for the conditions necessary to sustain meandering in coarse-bedded rivers. *Proceedings of the National Academy of Sciences*, 106(40), 16936–16941.
- Brazier, R. E., Puttock, A., Graham, H. A., Auster, R. E., Davies, K. H., & Brown, C. M. (2021). Beaver: Nature's ecosystem engineers. *Wiley Interdisciplinary Reviews: Water*, 8(1), e1494.
- Brierley, G., & Fryirs, K. (2022). Truths of the riverscape: Moving beyond command-and-control to geomorphologically informed nature-based river management. *Geoscience Letters*, 9(1), 1–26.
- Brown, A. E., Zhang, L., McMahon, T. A., Western, A. W., & Vertessy, R. A. (2005). A review of paired catchment studies for determining changes in water yield resulting from alterations in vegetation. *Journal of Hydrology*, 310(1–4), 28–61.
- Brown, A. G., Lespez, L., Sear, D. A., Macaire, J. J., Houben, P., Klimek, K., Brazier, R. E., Van Oost, K., & Pears, B. (2018). Natural vs anthropogenic streams in Europe: History, ecology and implications for restoration, river-rewilding and riverine ecosystem services. *Earth-Science Reviews*, 180, 185–205.
- Camporeale, C., Perucca, E., Ridolfi, L., & Gurnell, A. M. (2013). Modeling the interactions between river morphodynamics and riparian vegetation. *Reviews of Geophysics*, 51(3), 379–414.
- Castro, J. M., & Thorne, C. R. (2019). The stream evolution triangle: Integrating geology, hydrology, and biology. *River Research and Applications*, 35(4), 315–326.
- Clarke, S. J. (2002). Vegetation growth in rivers: Influences upon sediment and nutrient dynamics. *Progress in Physical Geography*, 26(2), 159–172.
- Corenblit, D., Baas, A. C., Bornette, G., Darrozes, J., Delmotte, S., Francis, R. A., Gurnell, A. M., Julien, F., Naiman, R. J., & Steiger, J. (2011). Feedbacks between geomorphology and biota controlling Earth surface processes and landforms: A review of foundation concepts and current understandings. *Earth-Science Reviews*, 106(3–4), 307–331.
- Corenblit, D., Davies, N. S., Steiger, J., Gibling, M. R., & Bornette, G. (2015). Considering river structure and stability in the light of evolution: Feedbacks between riparian vegetation and hydrogeomorphology. *Earth Surface Processes and Landforms*, 40(2), 189–207.

- Corenblit, D., Tabacchi, E., Steiger, J., & Gurnell, A. M. (2007). Reciprocal interactions and adjustments between fluvial landforms and vegetation dynamics in river corridors: A review of complementary approaches. *Earth-Science Reviews*, 84(1–2), 56–86.
- Corenblit, D., Vautier, F., González, E., & Steiger, J. (2020). Formation and dynamics of vegetated fluvial landforms follow the biogeomorphological succession model in a channelized river. *Earth Surface Processes and Landforms*, 45(9), 2020–2035.
- Cornacchia, L., Van De Koppel, J., van der Wal, D., Wharton, G., Puijalon, S., & Bouma, T. J. (2018). Landscapes of facilitation: How self-organized patchiness of aquatic macrophytes promotes diversity in streams. *Ecology*, 99(4), 832–847.
- Cotton, J. A., Wharton, G., Bass, J. A. B., Heppell, C. M., & Wotton, R. S. (2006). The effects of seasonal changes to in-stream vegetation cover on patterns of flow and accumulation of sediment. *Geomorphology*, 77(3–4), 320–334.
- Covino, T. (2017). Hydrologic connectivity as a framework for understanding biogeochemical flux through watersheds and along fluvial networks. *Geomorphology*, 277, 133–144.
- Dawson, M., Gurnell, A., & Lewin, J. (2022). Biogeomorphic recovery of a river reach affected by mining. *Earth Surface Processes and Landforms*, 47(15), 3497–3514.
- Díaz-Redondo, M., Marchamalo, M., Morcillo, F., & King, J. J. (2022). Naturalising a heavily modified urban river: Initial habitat evolution in the Manzanares River (Madrid, Spain). *River Research and Applications*, 38, 727–737.
- D'Orey, A., Aragão, N., Smaniotto-Costa, C., & Duarte, T. (2023). A review of urban river restoration projects. Practices and challenges. In C. Smaniotto-Costa & N. Aragão (Eds.), *Understanding and transforming the territory new approaches and perspectives* (Vol. 5, pp. 113–157). Lusófona University Press.
- Eaton, B. C., & Giles, T. R. (2009). Assessing the effect of vegetation-related bank strength on channel morphology and stability in gravel-bed streams using numerical models. *Earth Surface Processes and Landforms*, 34(5), 712–724.
- Emanuel, R. E., Hazen, A. G., McGlynn, B. L., & Jencso, K. G. (2014). Vegetation and topographic influences on the connectivity of shallow groundwater between hillslopes and streams. *Ecohydrology*, 7(2), 887–895.
- Fausch, K. D., Torgersen, C. E., Baxter, C. V., & Li, H. W. (2002). Landscapes to riverscapes: Bridging the gap between research and conservation of stream fishes: A continuous view of the river is needed to understand how processes interacting among scales set the context for stream fishes and their habitat. *Bioscience*, 52(6), 483–498.
- Fei, S., Phillips, J., & Shouse, M. (2014). Biogeomorphic impacts of invasive species. *Annual Review of Ecology, Evolution, and Systematics*, 45, 69–87.
- Feld, C. K., Birk, S., Bradley, D. C., Hering, D., Kail, J., Marzin, A., Melcher, A., Nemitz, D., Pedersen, M. L., Pletterbauer, F., Pont, D., Verdonschot, P. F. M., & Friberg, N. (2011). From natural to degraded rivers and back again: A test of restoration ecology theory and practice. In *Advances in ecological research* (Vol. 44, pp. 119–209). Academic Press.

- Fisher, S. G., Heffernan, J. B., Sponseller, R. A., & Welter, J. R. (2007). Functional ecomorphology: Feedbacks between form and function in fluvial landscape ecosystems. *Geomorphology*, 89, 84–96.
- Francis, R. A., Petts, G. E., & Gurnell, A. M. (2008). Wood as a driver of past landscape change along river corridors. *Earth Surface Processes and Landforms*, 33(10), 1622–1626.
- Frissell, C. A., Liss, W. J., Warren, C. E., & Hurley, M. D. (1986). A hierarchical framework for stream habitat classification: Viewing streams in a watershed context. *Environmental Management*, 10, 199–214.
- Fuller, I. C., & Death, R. G. (2018). The science of connected ecosystems: What is the role of catchment-scale connectivity for healthy river ecology? *Land Degradation & Development*, 29(5), 1413–1426.
- Gervais, J. A., Kovach, R., Sepulveda, A., Al-Chokhachy, R., Giersch, J. J., & Muhlfeld, C. C. (2020). Climate-induced expansions of invasive species in the Pacific northwest, North America: A synthesis of observations and projections. *Biological Invasions*, 22(7), 2163–2183.
- Gurnell, A. (2014). Plants as river system engineers. *Earth Surface Processes and Landforms*, 39(1), 4–25.
- Gurnell, A., & Petts, G. (2006). Trees as riparian engineers: The Tagliamento River, Italy. *Earth Surface Processes and Landforms*, 31(12), 1558–1574.
- Gurnell, A., Surian, N., & Zanoni, L. (2009). Multi-thread river channels: A perspective on changing European alpine river systems. *Aquatic Sciences*, 71(3), 253–265.
- Gurnell, A. M., & Bertoldi, W. (2022). The impact of plants on fine sediment storage within the active channels of gravel-bed rivers: A preliminary assessment. *Hydrological Processes*, 36(7), e14637.
- Gurnell, A. M., Bertoldi, W., & Corenblit, D. (2012). Changing river channels: The roles of hydrological processes, plants and pioneer fluvial landforms in humid temperate, mixed load, gravel bed rivers. *Earth-Science Reviews*, 111(1–2), 129–141.
- Gurnell, A. M., Corenblit, D., García de Jalón, D., González del Tánago, M., Grabowski, R. C., O'Hare, M. T., & Szweczyk, M. (2016). A conceptual model of vegetation–hydrogeomorphology interactions within river corridors. *River Research and Applications*, 32(2), 142–163.
- Gurnell, A. M., O'Hare, M. T., O'Hare, J. M., Scarlett, P., & Liffen, T. M. (2013). The geomorphological context and impact of the linear emergent macrophyte, *Sparganium erectum* L.: A statistical analysis of observations from British rivers. *Earth Surface Processes and Landforms*, 38(15), 1869–1880.
- Gurnell, A. M., Petts, G. E., Hannah, D. M., Smith, B. P., Edwards, P. J., Kollmann, J., Ward, J. V., & Tockner, K. (2001). Riparian vegetation and island formation along the gravel-bed Fiume Tagliamento, Italy. *Earth Surface Processes and Landforms*, 26(1), 31–62.
- Harman, W., Starr, R., Carter, M., Tweedy, K., Clemmons, M., Suggs, K., & Miller, C. (2012). *A function-based framework for stream assessment and restoration projects*. US Environmental Protection Agency (EPA), Office of Wetlands, Oceans, and Watersheds.

- Haslam, S. M. (2008). *The riverscape and the river* (p. 404). Cambridge University Press.
- Hastie, L. C., Boon, P. J., Young, M. R., & Way, S. (2001). The effects of a major flood on an endangered freshwater mussel population. *Biological Conservation*, 98(1), 107–115.
- Hawkins, C. P., Kershner, J. L., Bisson, P. A., Bryant, M. D., Decker, L. M., Gregory, S. V., McCullough, D. A., Overton, C. K., Reeves, G. H., Steedman, R. J., & Young, M. K. (1993). A hierarchical approach to classifying stream habitat features. *Fisheries*, 18(6), 3–12.
- Hughes, F. M. (1997). Floodplain biogeomorphology. *Progress in Physical Geography*, 21(4), 501–529.
- Hupp, C. R. (1992). Riparian vegetation recovery patterns following stream channelization: A geomorphic perspective. *Ecology*, 73(4), 1209–1226.
- Ielpi, A., & Lapôtre, M. G. (2020). A tenfold slowdown in river meander migration driven by plant life. *Nature Geoscience*, 13(1), 82–86.
- Ielpi, A., Lapôtre, M. G., Gibling, M. R., & Boyce, C. K. (2022). The impact of vegetation on meandering rivers. *Nature Reviews Earth and Environment*, 3(3), 165–178.
- Janauer, G. A., Schmidt-Mumm, U., & Reckendorfer, W. (2013). Ecohydraulics and aquatic macrophytes: Assessing the relationship in river floodplains. In I. Maddock, A. Harby, P. Kemp & P. Wood (Eds.), *Ecohydraulics: An Integrated Approach* (pp. 245–259). John Wiley & Sons.
- Jencso, K. G., & McGlynn, B. L. (2011). Hierarchical controls on runoff generation: Topographically driven hydrologic connectivity, geology, and vegetation. *Water Resources Research*, 47(11), W11527.
- Jencso, K. G., McGlynn, B. L., Gooseff, M. N., Bencala, K. E., & Wondzell, S. M. (2010). Hillslope hydrologic connectivity controls riparian groundwater turnover: Implications of catchment structure for riparian buffering and stream water sources. *Water Resources Research*, 46(10), W10524.
- Johnson, M. F., Thorne, C. R., Castro, J. M., Kondolf, G. M., Mazzacano, C. S., Rood, S. B., & Westbrook, C. (2020). Biomic river restoration: A new focus for river management. *River Research and Applications*, 36(1), 3–12.
- Jones, C. G., Lawton, J. H., & Shachak, M. (1994). Organisms as ecosystem engineers. *Oikos*, 69, 373–386.
- Jones, J. I., Collins, A. L., Naden, P. S., & Sear, D. A. (2012). The relationship between fine sediment and macrophytes in rivers. *River Research and Applications*, 28(7), 1006–1018.
- Jones, J. I., Murphy, J. F., Collins, A. L., Sear, D. A., Naden, P. S., & Armitage, P. D. (2012). The impact of fine sediment on macro-invertebrates. *River Research and Applications*, 28(8), 1055–1071.
- Junk, W. J., Bayley, P. B., & Sparks, R. E. (1989). The flood-pulse concept in river floodplain systems. In D. P. Dodge (Ed.), *Proceedings of the International Large River Symposium (LARS) Canadian Journal of Fisheries and Aquatic Sciences. Special Publication* (Vol. 106, pp. 110–127).

- Kemp, P., Sear, D., Collins, A., Naden, P., & Jones, I. (2011). The impacts of fine sediment on riverine fish. *Hydrological Processes*, 25(11), 1800–1821.
- Larsen, L. G. (2019). Multiscale flow-vegetation-sediment feedbacks in low-gradient landscapes. *Geomorphology*, 334, 165–193.
- Licci, S., Marmonier, P., Wharton, G., Delolme, C., Mermillod-Blondin, F., Simon, L., Vallier, F., Bourma, T. J., & Puijalon, S. (2022). Scale-dependent effects of vegetation on flow velocity and biogeochemical conditions in aquatic systems. *Science of the Total Environment*, 883, 155123.
- Madej, M. A., & Ozaki, V. (2009). Persistence of effects of high sediment loading in a salmon-bearing river, northern California. *Management and restoration of fluvial systems with broad historical changes and human impacts: Geological Society of America Special Paper*, 451, 43–55.
- Magliozzi, C., Grabowski, R. C., Packman, A. I., & Krause, S. (2018). Toward a conceptual framework of hyporheic exchange across spatial scales. *Hydrology and Earth System Sciences*, 22(12), 6163–6185.
- Magdaleno, F. (2017). Aesthetic vs. functional restoration of urban and peri-urban rivers: the Manzanares River in Madrid (Spain). *CSE Journal - City Safety Energy*, 1, 48–59.
- Makaske, B. (2001). Anastomosing rivers: A review of their classification, origin and sedimentary products. *Earth-Science Reviews*, 53(3–4), 149–196.
- McMahon, W. J., & Davies, N. S. (2018). The shortage of geological evidence for pre-vegetation meandering rivers. In M. Ghinassi, L. Colombera, N. P. Mountney, A. J. H. Reesink (Eds.), *Fluvial meanders and their sedimentary products in the rock record (IAS SP 48)* (pp. 119–148). John Wiley & Sons.
- Millar, R. G. (2000). Influence of bank vegetation on alluvial channel patterns. *Water Resources Research*, 36(4), 1109–1118.
- Moore, J. W. (2006). Animal ecosystem engineers in streams. *Bioscience*, 56(3), 237–246.
- Nadler, C. T., & Schumm, S. A. (1981). Metamorphosis of South Platte and Arkansas Rivers, eastern Colorado. *Physical Geography*, 2(2), 95–115.
- Nanson, G. C., & Knighton, A. D. (1996). Anabranching rivers: Their cause, character and classification. *Earth Surface Processes and Landforms*, 21(3), 217–239.
- Nardini, A. G. C., & Conte, G. (2021). River management & restoration: What river do we wish for. *Water*, 13(10), 1336.
- Newcombe, C. P., & MacDonald, D. D. (1991). Effects of suspended sediments on aquatic ecosystems. *North American Journal of Fisheries Management*, 11(1), 72–82.
- Newson, M. D., & Large, A. R. (2006). 'Natural' rivers, hydromorphological quality and river restoration: A challenging new agenda for applied fluvial geomorphology. *Earth Surface Processes and Landforms*, 31(13), 1606–1624.

- O'Briain, R., Corenblit, D., & Gurnell, A. (2023). Interacting effects of climate change and invasions by alien plant species on the morphodynamics of temperate rivers. *Wiley Interdisciplinary Reviews: Water*, 10(5), e1649.
- O'Briain, R., Shephard, S., & Coghlan, B. (2017). Pioneer macrophyte species engineer fine-scale physical heterogeneity in a shallow lowland river. *Ecological Engineering*, 102, 451–458.
- O'Briain, R., Shephard, S., McCollom, A., O'Leary, C., & Coghlan, B. (2022). Plants as agents of hydromorphological recovery in lowland streams. *Geomorphology*, 400, 108090.
- O'Hare, J. M., O'Hare, M. T., Gurnell, A. M., Scarlett, P. M., Liffen, T. O. M., & McDonald, C. (2012). Influence of an ecosystem engineer, the emergent macrophyte *Sparganium erectum*, on seed trapping in lowland rivers and consequences for landform colonisation. *Freshwater Biology*, 57(1), 104–115.
- O'Hare, M. T. (2015). Aquatic vegetation—A primer for hydrodynamic specialists. *Journal of Hydraulic Research*, 53(6), 687–698.
- O'Hare, M. T., Mountford, J. O., Maroto, J., & Gunn, I. D. M. (2016). Plant traits relevant to fluvial geomorphology and hydrological interactions. *River Research and Applications*, 32(2), 179–189.
- Palmer, M., Allan, J. D., Meyer, J., & Bernhardt, E. S. (2007). River restoration in the twenty-first century: Data and experiential knowledge to inform future efforts. *Restoration Ecology*, 15(3), 472–481.
- Palmer, M., & Ruhi, A. (2019). Linkages between flow regime, biota, and ecosystem processes: Implications for river restoration. *Science*, 365(6459), eaaw2087.
- Palmer, M. A., & Allan, J. D. (2006). Restoring rivers. *Issues in Science and Technology*, 22(2), 40–48.
- Parker, G., Shimizu, Y., Wilkerson, G. V., Eke, E. C., Abad, J. D., Lauer, J. W., Paola, C., Dietrich, W. E., & Voller, V. R. (2011). A new framework for modelling the migration of meandering rivers. *Earth Surface Processes and Landforms*, 36(1), 70–86.
- Perucca, E., Camporeale, C., & Ridolfi, L. (2007). Significance of the riparian vegetation dynamics on meandering river morphodynamics. *Water Resources Research*, 43(3), W03430.
- Poff, N. L., Allan, J. D., Bain, M. B., Karr, J. R., Prestegard, K. L., Richter, B. D., Sparks, R. E., & Stromberg, J. C. (1997). The natural flow regime. *Bioscience*, 47(11), 769–784.
- Polvi, L. E., Lind, L., Persson, H., Miranda-Melo, A., Pilotto, F., Su, X., & Nilsson, C. (2020). Facets and scales in river restoration: Nestedness and interdependence of hydrological, geomorphic, ecological, and biogeochemical processes. *Journal of Environmental Management*, 265, 110288.
- Polvi, L. E., & Sarneel, J. M. (2018). Ecosystem engineers in rivers: An introduction to how and where organisms create positive biogeomorphic feedbacks. *Wiley Interdisciplinary Reviews: Water*, 5(2), e1271.

- Polvi, L. E., & Wohl, E. (2013). Biotic drivers of stream planform: Implications for understanding the past and restoring the future. *Bioscience*, 63(6), 439–452.
- Poole, G. C. (2002). Fluvial landscape ecology: Addressing uniqueness within the river discontinuum. *Freshwater Biology*, 47(4), 641–660.
- Poole, G. C. (2010). Stream hydrogeomorphology as a physical science basis for advances in stream ecology. *Journal of the North American Benthological Society*, 29(1), 12–25.
- Rice, S. P. (2021). Why so skeptical? The role of animals in fluvial geomorphology. *Wiley Interdisciplinary Reviews: Water*, 8(6), e1549.
- Rogers, J. B., Stein, E. D., Beck, M. W., & Ambrose, R. F. (2020). The impact of climate change induced alterations of streamflow and stream temperature on the distribution of riparian species. *PLoS One*, 15(11), e0242682.
- Schumm, S. A. (1985). Patterns of alluvial rivers. *Annual Review of Earth and Planetary Sciences*, 13(1), 5–27.
- Speed, R., Tickner, D., Naiman, R., Gang, L., Sayers, P., Yu, W., Yuanyuan, L., Houjian, H., Jianting, C., Lili, Y., & Zhongnan, Z. (2016). *River restoration: A strategic approach to planning and management*. UNESCO Publishing.
- Tabacchi, E., Lambs, L., Guillo, H., Planty-Tabacchi, A.-M., Muller, E., & Décamps, H. (2000). Impacts of riparian vegetation on hydrological processes. *Hydrological Processes*, 14(16–17), 2959–2976.
- Tabacchi, E., González, E., Corenblit, D., Garófano-Gómez, V., Planty-Tabacchi, A. -M., & Steiger, J. (2019). Species composition and plant traits: Characterization of the biogeomorphological succession within contrasting river corridors. *River Research and Applications*, 35(8), 1228–1240.
- Thoms, M. C., & Parsons, M. (2002). Eco-geomorphology: An interdisciplinary approach to river science. *International Association of Hydrological Sciences*, 276, 113–119.
- Townsend, C. R. (1996). Concepts in river ecology: Pattern and process in the catchment hierarchy. *Large Rivers*, 10(1–4), 3–21.
- Tsujiimoto, T. (1999). Fluvial processes in streams with vegetation. *Journal of Hydraulic Research*, 37(6), 789–803.
- Vannote, R. L., Minshall, G. W., Cummins, K. W., Sedell, J. R., & Cushing, C. E. (1980). The river continuum concept. *Canadian Journal of Fisheries and Aquatic Sciences*, 37(1), 130–137.
- Wang, Y., Lin, J., Wang, F., Tian, Q., Zheng, Y., & Chen, N. (2023). Hydrological connectivity affects nitrogen migration and retention in the land– river continuum. *Journal of Environmental Management*, 326, 116816.
- Ward, J. V. (1989). The four-dimensional nature of lotic ecosystems. *Journal of the North American Benthological Society*, 8(1), 2–8.

- Ward, J. V., Tockner, K., Arscott, D. B., & Claret, C. (2002). Riverine landscape diversity. *Freshwater Biology*, 47(4), 517–539.
- Ward, J. V., Tockner, K., Uehlinger, U., & Malard, F. (2001). Understanding natural patterns and processes in river corridors as the basis for effective river restoration. *Regulated Rivers: Research & Management*, 17(4–5), 311–323.
- Ward, J. V., & Wiens, J. A. (2001). Ecotones of riverine ecosystems: Role and typology, spatio-temporal dynamics, and river regulation. *International Journal of Ecohydrology and Hydrobiology*, 1(1), 25–36.
- Wei, X., Liu, W., & Zhou, P. (2013). Quantifying the relative contributions of forest change and climatic variability to hydrology in large watersheds: A critical review of research methods. *Water*, 5(2), 728–746.
- Wharton, G., Mohajeri, S. H., & Righetti, M. (2017). The pernicious problem of streambed colmation: A multi-disciplinary reflection on the mechanisms, causes, impacts, and management challenges. *Wiley Interdisciplinary Reviews: Water*, 4(5), e1231.
- Wiens, J. A. (2002). Riverine landscapes: Taking landscape ecology into the water. *Freshwater Biology*, 47(4), 501–515.
- Wilkes, M. A., Gittins, J. R., Mathers, K. L., Mason, R., Casas-Mulet, R., Vanzo, D., McKenzie, M., Murray-Bligh, J., England, J., Gurnell, A., & Jones, J. I. (2019). Physical and biological controls on fine sediment transport and storage in rivers. *Wiley Interdisciplinary Reviews: Water*, 6(2), e1331.
- Williams, M., Zalasiewicz, J., Davies, N., Mazzini, I., Goiran, J. P., & Kane, S. (2014). Humans as the third evolutionary stage of biosphere engineering of rivers. *Anthropocene*, 7, 57–63.
- Wohl, E., Angermeier, P. L., Bledsoe, B., Kondolf, G. M., MacDonnell, L., Merritt, D. M., Palmer, M. A., Poff, N. L., & Tarboton, D. (2005). River restoration. *Water Resources Research*, 41(10), W10301.
- Wohl, E., Lane, S. N., & Wilcox, A. C. (2015). The science and practice of river restoration. *Water Resources Research*, 51(8), 5974–5997.
- Wright, J. P., Jones, C. G., & Flecker, A. S. (2002). An ecosystem engineer, the beaver, increases species richness at the landscape scale. *Oecologia*, 132(1), 96–101.
- Zen, S., Gurnell, A. M., Zolezzi, G., & Surian, N. (2017). Exploring the role of trees in the evolution of meander bends: The Tagliamento River, Italy. *Water Resources Research*, 53(7), 5943–5962.
- Zhu, L., Chen, D., Hassan, M. A., & Venditti, J. G. (2022). The influence of riparian vegetation on the sinuosity and lateral stability of meandering channels. *Geophysical Research Letters*, 49(2), e2021GL096346.