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Review

Improving river hydromorphological assessment through better integration of riparian vegetation: Scientific evidence and guidelines

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ABSTRACT

River hydromorphology has long been subjected to huge anthropogenic pressures with severe negative impacts on related ecosystems' functioning and water quality. Therefore, improving river hydromorphological conditions represents a priority task in sustainable river management and requires proper assessment tools. It is well known that riparian vegetation plays a crucial role in sustaining river hydromorphological conditions. However, it has been nearly neglected in most hydromorphological assessment protocols, including the European Water Framework Directive (WFD).

This paper reviews and synthesizes the relevance of riparian vegetation for river hydromorphology, focusing on its contribution to streamflow and sediment regime conditions. We also examine how riparian vegetation is considered in the WFD and how it is included in national hydromorphological protocols currently in use.

Our findings point to a temporal mismatch between the date when the WFD came into force and the emergence of scientific and technologic advances in riparian vegetation dynamism and bio-geomorphic modeling. To overcome this misalignment, we present promising approaches for the characterization and assessment of riparian vegetation, which include the identification of vegetation units and indicators at multiple scales to support management and restoration measures. We discuss the complexity of riparian vegetation assessment, particularly with respect to the establishment of river-type-based reference conditions and the monitoring and management targets, and propose some attributes that can serve as novel indicators of the naturalness vs. artificiality of riparian vegetation. We argue that the hydromorphological context of the WFD should be revisited and offer guidance to integrate riparian vegetation in river hydromorphological monitoring and assessment.

1. Introduction

1.1. Hydromorphological status of rivers and assessment needs

Hydromorphological features of rivers, including flow regime and the dynamic evolution of fluvial morphology (Vogel, 2011), represent the most degraded components worldwide, affecting river functioning and leading to biological impairment of river ecosystems (Meybeck, 2003; Poff et al., 2007). Changes in hydrological regimes, loss of connectivity and degradation of critical habitats are described as major causes of freshwater biodiversity loss (Tockner and Stanford, 2002; Dudgeon et al., 2006; Tickner et al., 2020). In the case of European rivers, hydromorphological impairment is very significant, affecting 40% of water bodies (Kristensen et al., 2018); 79% of European rivers

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are impacted by a combination of multiple pressures (Schinegger et al., 2017). This hydromorphological degradation, as a consequence of the pervasive human impacts on fluvial systems, is one of the major causes of poor ecological status of European rivers (Fehér et al., 2012). Improving their hydromorphological conditions, together with the enhancement of water quality, result necessary in European rivers to achieve the ecological demands of the Water Framework Directive (WFD), and the key commitments of the European Biodiversity Strategy by 2030 (at least 25,000 km of free-flowing restored rivers). These types of initiatives also represent priority objectives in many other countries to achieve a sustainable river management and maintenance of fluvial ecosystem services (Horne et al., 2017; Skoulikidis et al., 2017; Liu et al., 2020; Singh and Singh, 2020).

The improvement of river hydromorphology requires a clear understanding of the dynamism and complexity of rivers, in which multi-dimensional geomorphic processes and adjustments as responses to impacts and disturbances are involved at different spatial and temporal scales (Habersack, 2000; Richards et al., 2002; Brierley and Fryirs, 2005; Gurnell et al., 2016a). In this context, reliable indicators (González del Tánago et al., 2016a) and protocols for hydromorphological assessments (e.g., Rinaldi et al., 2013; Klösch and Habersack, 2017) are crucial for effective river management. They can play a key role in identifying current deficits or distance from conditions that would naturally occur without anthropogenic pressures, and are invaluable aids in diagnosing problems and defining needs for river restoration actions (Roni and Beechie, 2013; Ioana-Toroimac et al., 2017; Polvi et al., 2020).

1.2. The EU Water Framework Directive (WFD): Challenges in the hydromorphological context

The EU WFD, which aims to prevent further deterioration and protect and enhance the aquatic environment, represents one of the most important response to river impairment in European countries. Requirements of this EU Directive include the classification of waterbodies, the assessment of their status based on biological, hydromorphological and physico-chemical quality elements, and the implementation of programs of measures to gradually meet the good environmental status for all European waters according to River Basin Management Plans (RBMPs).

Although the WFD has promoted significant advances in river research and integrated management, its ambitious targets have found many problems in their implementation (Voulvoulis et al., 2017), and after nearly two decades of being active, several methodological approaches need further investigation. The outcomes of this Directive are strongly dependent on the monitoring and evaluation of the waterbodies status, which in turn are considered one of the major weaknesses of the WFD. Current assessment methods do not reflect robust linkages between pressures and effects on the ecosystem (Friberg, 2014; Carvalho et al., 2019) and consequently, programs of measures are not properly targeted to the existing pressures and impacts (Giakoumis and Voulvoulis, 2019). The WFD has fostered considerable research on hydromorphology (Belletti et al., 2015), but there is still plenty of room for innovation, particularly to respect to monitoring and assessment (e.g., Klösch and Habersack, 2017; Zaharia et al., 2018) as well as diagnosis of the causes of freshwater ecosystem deterioration (Villeneuve et al., 2018; Baattrup-Pedersen et al., 2019; Carvalho et al., 2019; Lemm et al., 2019). Improving and harmonizing evaluation procedures of morphological conditions is still a pending issue that merits much attention, taking into account that hydromorphological processes are crucial for structural diversity and for the framework upon which biological communities interact (Ward et al., 2002a; Tockner et al., 2010a). Many authors have noted the inefficiency of many programs of measures included in the RBMPs with respect to ameliorating the ecological status of rivers primarily evaluated by the existing biological communities. Poor hydromorphological assessments not providing links between degradation of the physical habitat of species, pressures and developed management actions may be behind these unsuccessful results (Kail and Wolter, 2011; Giakoumis and Voulvoulis, 2019).

Revisiting the hydromorphological context of the WFD, as a pending task of the WFD legislation, may create opportunities for identifying deficits in the current elements of assessment, and assimilating new approaches to better explain the river status responding to the existing hydromorphological pressures or restoration measures. In this sense, our work represents an attempt to scrutinize the hydromorphological antecedents of the WFD, with the ultimate goal of presenting new alternatives for river assessment. We focus on riparian vegetation, as a key element of riparian zones and floodplains that strongly influences river hydromorphology. We aim to highlight its potential value in informing about and monitoring the hydrological and morphological alterations anticipating river changes, as riparian vegetation responds to synergistic effects of multi-scale environmental processes (Janssen et al., 2021).

1.3. Hydromorphological elements of the WFD: need to integrate riparian vegetation

As outlined by the WFD, hydromorphological assessment is mandatory and must inform three hydromorphological quality elements supporting the biological elements of rivers. These are 1) hydrological regime; 2) river continuity; and 3) morphological conditions (EC, 2000). With respect to the hydrological regime, there is a general science-based agreement on the assessment procedure, basically inspired on the hydrological alteration indicators (HAI) proposed by Richter et al. (1996) which focus on the main components of the natural flow regime (Poff et al., 1997). However, in the case of river continuity assessment, the suggested methods for evaluation may be very different depending on the species affected by river fragmentation (e.g. Radinger et al., 2018). This also occurs with morphological conditions, for which a wide variety of different evaluation approaches and protocols have been proposed (Belletti et al., 2015), with very distinct results.

In the WFD, morphological conditions are defined by river width and depth variation, structure and substrate of the river bed, and structure of the riparian zone. While the former ones attempt to characterize channel geometry and substrate variability shaping the morphological conditions of rivers, the structure of the riparian zone remains undefined in the text of the WFD, without even mention the riparian vegetation as a key element of riparian zones. As a consequence of this, riparian vegetation is almost completely disregarded in most of the hydromorphological protocols currently used within the context of the WFD, and thus, its potential role as integrated indicator of multiple hydromorphological pressures has also been neglected. Furthermore, riparian vegetation is only rarely mentioned in proposals for the integrative management and conservation of riparian zones (Boisjolie et al., 2017; González et al., 2017).

Vegetation is the principal component of riparian zones (Malanson, 1993; Naiman et al., 2005; Hughes et al., 2012) and supports many of the associated ecosystem services (Cole et al., 2020; Riss et al., 2020). Through reciprocal interactions with fluvial processes, riparian vegetation plays a crucial role in river hydromorphology and has strong influence on the resulting river channel forms and functioning (Tal et al., 2004; Corenblit et al., 2007; Gurnell et al., 2012; Gurnell, 2014). At the same time, riparian vegetation may act as a core indicator of riparian zone status (Macfarlane et al., 2017), and reflects the synergism of multiple-stressors anticipating climatic change effects (Martínez-Fernández et al., 2018; García de Jalón et al., 2020; Rodríguez-González et al., 2021). The management of riparian vegetation is frequently at the center of conflicts among stakeholders related to river conservation, farming and flood control practices, and represents an essential issue facing research, management, legislation and water policy (de Sosa et al., 2018; Feld et al., 2018; Rowiński et al., 2018; Dufour et al., 2019; Kiss et al., 2019).

Riparian vegetation plays an essential role in influencing channel stability and the quality of the physical habitat for many aquatic

communities (Reid et al., 2010; Sievers et al., 2017; Dugdale et al., 2018). Thus, it should be recognized, together with flow regime and channel morphology, as a main hydromorphological element supporting the biological quality elements.

In this paper we aim to close the gap between the scientific literature, in which the strong influence of riparian vegetation on river hydromorphology is well documented, and common procedures for hydromorphological assessment, in which riparian vegetation is infrequently and imprecisely incorporated. We argue that, within the context of the WFD, riparian vegetation should be included as a primer component in hydromorphological assessments together with hydrological regime and geomorphic processes, facilitating the identification of hydromorphological pressures and the proposal of restoration measures.

The main goals of this paper are to 1) briefly review scientific evidence of the essential role of riparian vegetation in river hydromorphology; 2) inform and recommend the updating of the hydromorphological background of the WFD in order to explicitly include riparian vegetation in hydromorphological assessments; and 3) propose guidelines for a multi-scale riparian vegetation characterization and assessment, linking patterns and processes across different spatial and temporal scales, and facilitating the understanding of the effects of pressures and restoration and conservation measures. Although our analysis and proposals are mainly focused on the European context of the WFD, they also represent a more general contribution aimed at improving the concepts and procedures associated with hydromorphological assessment worldwide.

2. Relevance of riparian vegetation in river functioning and environmental assessment

2.1. Role of riparian vegetation in river hydromorphology

We define "riparian vegetation" as the vegetation whose establishment, growth and survival depend greatly on fluvial processes (Naiman et al., 2005; Dufour et al., 2019). Once established, riparian vegetation interacts with these fluvial processes (mainly flooding and sediment erosion, transport and deposition) and becomes a key component of river dynamics, increasing its influence throughout its growth and development (Tal and Paola, 2010; Hicks et al., 2007; Corenblit et al., 2007, 2011, 2011; Gurnell et al., 2012).

Riparian vegetation may appear as isolated or fragmented patches but frequently forms corridors along both sides of river channels. Within these corridors, individual plants and plant communities are strongly subjected to and interact with river hydromorphology (Camporeale et al., 2013; Van Oorschot et al., 2016; Martínez-Fernández et al., 2018).

The magnitude, frequency and timing of fluvial disturbances are crucial for plant dispersal, establishment and survival, and for community succession (Mahoney and Rood, 1998; Rood et al., 2005; Steiger et al., 2005; Corenblit et al., 2009a, 2009b, 2009b; Greet et al., 2011; Wilcox and Shafroth, 2013; Gurnell and Bertoldi, 2020). Landscape properties (e.g., elevation, topography), along with climatic, hydrological and geological features, determine air temperature and soil moisture availability, which control vegetation growth. Reciprocally, vegetation growth, species succession and rejuvenation processes influence local temperature and soil moisture availability (Johnson and Jones, 2000; Dugdale et al., 2018). Vegetation growth and succession gradually reinforce the stability of soil on channel banks and may modify flow velocity, flooding frequency and river planform (Gran et al., 2015).

The influence of riparian plants as river engineers (Jones et al., 1994) that affect the physical context of river channels has been widely documented (Gurnell, 2014; Corenblit et al., 2015). Riparian vegetation successively creates and modifies river landforms (Tal and Paola, 2010; Gurnell and Petts, 2002; Gurnell, 2014). Canopy and root architecture, along with the spatial distribution of plants, strongly influence flow resistance and the direction of flows. Additionally, vegetation height and density (i.e., "biovolume" of plants) have a great capacity to retain sediment, which can be frequently reinforced by large woody debris (Gurnell et al., 2001, 2006, 2006; Corenblit et al., 2009b; Politti et al., 2018). The hydromorphological role of riparian vegetation by providing large wood has been deeply studied and demonstrated (Piégay and Gurnell, 1997; Gurnell et al., 2005, 2012, 2012; Bertoldi et al., 2013), showing the crucial joint impact of riparian woodland and large wood on river channel form and dynamics (Bertoldi et al., 2015; Wohl et al., 2019).

Due to these reciprocal interactions between riparian vegetation and water flow and fluvial landforms (Fig. 1), riparian vegetation has been progressively considered by river science as a major influencer on geomorphic changes in river channels and floodplains (Corenblit et al., 2007, 2011). Field and laboratory studies have proved that channel morphology and channel changes are strongly linked to the growth and development of riparian vegetation, which control bank erosion and promote single-thread meandering channels (Tal et al., 2004; Braudrick et al., 2009; Tal and Paola, 2010; Bertoldi et al., 2015).

2.2. Riparian vegetation as an indicator of hydromorphological changes

Riparian vegetation is frequently included in environmental river studies as it responds closely to natural disturbances and anthropogenic pressures and may be a good indicator of changes over time, receiving the influences of multi-scale environmental processes (Poff et al., 2011; Palmquist et al., 2018). A large body of literature exists on biogeomorphic adjustments to multiple stressors (see Stella and Bendix, 2019), especially studies that document vegetation responses to flow regulation by dams and reservoirs (Rood et al., 2003; Merritt and Cooper, 2000; Williams and Cooper, 2005; Stromberg et al., 2007; Bejarano et al., 2011, 2018; Takahashi and Nakamura, 2011; González del Tánago et al., 2015, 2016b; Martínez-Fernández et al., 2017a; Kui et al., 2017; Aguiar et al., 2018; Sanchís-Ibor et al., 2019; Yi et al., 2019; Han et al., 2020). More recently, an increasing amount of research in applied river science has focused on predicting riparian vegetation trends under different climate change scenarios, with vegetation considered as a sentinel of future changes in rivers (Politti et al., 2014; Rivaes et al., 2014; Martínez-Fernández et al., 2018; O'Briain, 2019).

Basically, riparian vegetation responds to climate (e.g., precipitation, temperature, Rodríguez-González et al., 2021), moisture availability, fluvial disturbances (Stella et al., 2013a; Gurnell et al., 2016b; Palmquist et al., 2018) and land use (Ferreira et al., 2005; Fernandes et al., 2011; Fierro et al., 2017; Lind et al., 2019; Dufour et al., 2019). Furthermore, riparian vegetation may act as a valuable indicator of channel presence and hydrologic connectivity in arid regions (Manning et al., 2020). Environmental changes (e.g., global warming, renaturalization of catchments) and direct human pressures (e.g., flow regulation, groundwater overexploitation, urbanization, floodplain occupation) modify the hydroclimate and fluvial hydromorphological context, and thus trigger changes in riparian communities via species composition, diversity, functional structure and landscape arrangement (Aguiar et al., 2009: Rivaes et al., 2013; Dufour et al., 2015). Such pressures may also compromise different types of vegetation and different stages of their life cycles (Cooper et al., 2003; González et al., 2018). For example, large-scale increases in the extent of areas vegetated with woody plants may have hydrological implications by decreasing the magnitude of annual runoff, with effects on soil moisture and extreme high and low flows (García-Ruiz and Lana-Renault, 2011; Qiao et al., 2017).

Vegetation encroachment is one of the most common response to river damming, and increases in vegetation growth and coverage are often observed below dams (Cooper et al., 2003; González del Tánago et al., 2015; Aguiar et al., 2016; Räpple et al., 2017; Kui et al., 2017). The reduction in flood magnitude and frequency associated to dams likely promotes channel narrowing, which further increases the area of dense riparian vegetation and decreases the active channel area (Graf, 2006; Dean and Schmidt, 2011; Takahashi and Nakamura, 2011). Increasing in vegetation cover (e.g., *Populus, Salix* forests) has been also reported

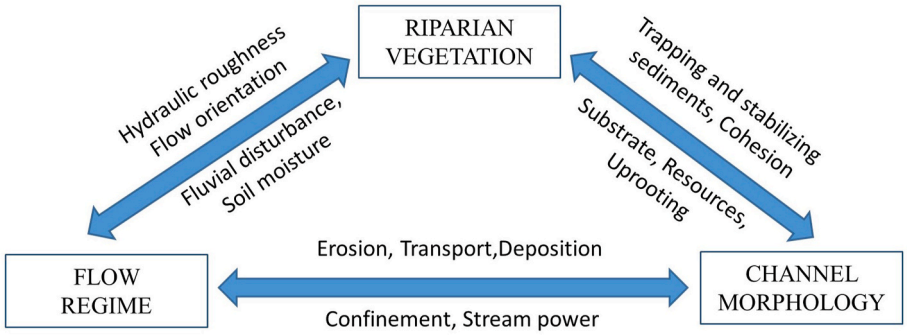

Fig. 1. Mutual interactions between flow regime, channel morphology and riparian vegetation that determine fluvial dynamics (adapted from Corenblit et al., 2007).

upstream of dams, through the emergence of new and dynamic riparian and wetland areas along the backwater fluctuation zones of reservoirs (Volke et al., 2019). However, García de Jalón et al. (2020) hypothesized that vegetation encroachment may be a convergent biogeomorphic response to multiple changes at different spatial scales (e.g., land cover changes and grazing decrease at catchment scale, flow regulation at river segment scale), which could occur in both regulated and non-regulated rivers under different environmental and human-induced disturbances (e.g., climate change inducing hydrologic decline, river damming), all of them promoting decreases in flow variability and sediment supply. Vegetation encroachment has been also associated with river channelization and dredging, and always follows channel narrowing (Stecca et al., 2019) and changes in land use (Liébault and Piégay, 2002; Dufour et al., 2015; González del Tánago et al., 2016b). As an example, Serlet et al. (2018) documented the colonization of previously bare gravel bars by vegetation after channelization along the Isère River (France). In this case, vegetation decreased the initial instability of the bare gravel bars and created a new dynamic equilibrium in the channelized river reach. Subsequent studies have verified the bioconstruction and biostabilization effect of vegetation in transforming small bare alternate gravel bars to fluvial landforms covered by mature forests (Corenblit et al., 2020).

Replacement of riparian species and terrestrialization effects have been observed in response to a generalized decrease in water resources (Santos, 2010; Garófano-Gómez et al., 2013; Stromberg and Merritt, 2016). Additionally, altering the timing and frequency of groundwater pumping and the magnitude of flows in arid-zone rivers may induce changes in riparian vegetation, which can result in the replacement of wetland pioneer trees with more drought-tolerant shrubs (Stromberg et al., 2007). Bejarano et al. (2012) observed simpler and most likely fewer riparian vegetation guilds because of flow regulation. Similarly, Aguiar et al. (2018) reported changes in riparian functional trade-offs after land-cover changes and hydropower flow regulation, which shifted riparian communities from obligate riparian competitors, with hydromorphic leaves and high tolerance to waterlogging, to facultative riparian species, with physical defences, tap roots and high drought tolerance.

Chemical water quality impacts resulting from human pressures can influence riparian vegetation features, such as species composition (Salinas et al., 2000). Macrophytes and bank vegetation overgrowth are frequently observed in response to excess nutrients originating from urban or agricultural land use (Grabowski and Gurnell, 2016; Ochs et al., 2018). In addition, nutrient levels in the substrate can significantly influence the survival and growth of seedlings in riparian systems (Adair and Binkley, 2002). Nutrient inputs from the release of stored water in reservoirs cause vegetation overgrowth below the dams, changing the channel pattern and mobility (Asaeda et al., 2015).

Another significant research focus has been the responses of riparian vegetation to global (i.e., environmental) and more local (i.e., human-induced) hydromorphic changes (Stella et al., 2013b; Surian et al., 2015; González et al., 2018), which represent threats to riparian ecosystems worldwide (e.g., Poff et al., 2011; Schneider et al., 2017). The results of these studies strongly support the use of riparian vegetation as a suitable indicator of channel adjustments (e.g., Van Looy et al., 2008; Gumiero et al., 2015), potential future stream conditions (e.g., Ringold et al., 2009), flow regime alterations (e.g., Stromberg et al., 2007; Pike and Scatena, 2010) and riparian and stream environmental status (Macfarlene et al., 2017; Fernandes et al., 2020).

3. Hydromorphological assessments in the context of the WFD: under-representation of riparian vegetation

3.1. Traditional fluvial geomorphological assessments

Traditionally, the morphological conditions of rivers were assessed by considering channel forms and fluvial processes, neglecting the presence of riparian vegetation (e.g., traditional approaches of Leopold et al., 1964 and Schumm, 1977, the *Stream Reconnaissance Handbook* by Thorne (1998), etc.). The same is shown in classical fluvial geomorphology textbooks, in which riparian vegetation is not used for characterizing and classifying river typologies or for predicting river responses and changes in rivers over time (Knighton, 1984; Rosgen, 1994; Brierley and Fryirs, 2005; Charlton, 2008), or is just eventually mentioned as boundary condition (Thorne et al., 1997). Riparian corridors, i.e., landscape features along rivers which contains and connect elements, were frequently analysed separately from river channel morphology (e.g., Malanson, 1993). Likewise, the use and management of the riparian areas (e.g., USDA, 1998; Winward, 2000; NRC, 2002) were assessed without considering the reciprocal influence of channel morphology and river dynamics. Although the importance of riparian vegetation has been recognized since the beginning of the development of river ecology concepts (Hynes, 1975; Vannote et al., 1980; Junk et al., 1989), the traditional channel morphological approach, based only on physical geomorphic features, prevailed in river assessment protocols and river habitat surveys (Thorne, 1998).

This preponderance of physical features without including riparian vegetation within river assessments is shown in the work of Belletti et al. (2015). In this extensive review of hydromorphological assessment procedures, the smaller number (15) of methods used to assess the status or quality of riparian corridors contrasts with the much larger number of methods worldwide that explored the physical habitat (73) or channel morphology conditions (22), based solely on flow and channel morphological features. Many of these methods were developed before the WFD was approved, and, indeed, some long-standing approaches (e.g., the River Habitat Survey (RHS), Raven et al., 1998) seem to have strongly influenced the hydromorphological context of the WFD. Furthermore, they continue to be used as official protocols to fulfill the WFD assessment requirements, with a very poor or inadequate consideration of riparian vegetation.

There are many reasons that could explain why riparian vegetation is

hardly considered within the hydromorphological elements of the WFD, but one of the most important is probably timing. Although our understanding of the interactions between vegetation and water/sediment flows dates back approximately to the 1980s (Dufour et al., 2019; Viles, 2020), some of the most relevant results, which began to shift the paradigm toward a biogeomorphic approach, were disseminated several years after the approval of the WFD (e.g., Gurnell et al., 2002; Gurnell and Petts, 2002; Corenblit et al., 2007, 2009a, 2009b, 2011).

3.2. Main hydromorphological protocols currently applied at the national level across EU countries

For the implementation of the WFD, each EU country is accorded some flexibility in selecting its own protocols to assess the hydromorphological conditions of rivers. Several countries have maintained their traditional morphological approach based on physical structure of river channel forms, with certain methods (e.g., RHS) exerting a strong influence on the hydromorphological protocols adopted in many other EU countries.

The RHS protocol was developed and tested in the United Kingdom (UK) and has been in use there since 1993. It was later adopted by many other EU countries as their official protocol for WFD-compliant assessments of hydromorphological conditions, with some attempts to be adapted to local contexts (e.g., Portugal, Ferreira et al., 2011; Slovenia, Tavzes and Urbanic, 2009) or incorporated under specific approaches (e.g., Scotland, www. sepa.org.uk). The RHS is based on the traditional channel morphology survey developed by Thorne (1998). It includes observations of channel features (e.g., substrate, flow types, erosion, deposition), bank features (shape and vegetation structure) and land use in the adjacent river corridor (Raven et al., 2002). With this information, the RHS scores habitat quality based on comparisons with benchmark sites the experts have judged as the best river habitats in the UK. The RHS also considers modifications to the channel and bank structure and gives penalty points to the resulting habitat quality based on the physical changes observed. The vegetation structure considered in the RHS is based on the following categories: (1) vegetation height (i.e., bryophytes, short/creeping herbs or grasses, tall herbs or grasses, scrub or shrubs, and saplings and trees), and (2) the variety of existing vegetation types (i.e., bare soil or artificial bank material; uniform: only one vegetation type; simple: mainly 2–3 vegetation types; complex: 4 or more vegetation types; and not visible, when the bank is obscured) (www.riverhabitatsurvey.org/manual/rhs-manuals). As mentioned above, this method is used extensively in the UK and in other countries, but the information collected on riparian vegetation, without any mention of species composition, coverage, age diversity, etc., results very simplistic and inadequate to infer hydromorphological dynamics, processes and interactions.

Other hydromorphological methods widely recognized and applied in EU countries have the same limitations for characterizing and assessing riparian vegetation. For example, the LAWA system used in Germany addresses physical habitat assessments and uses 25 attributes that focus mainly on channel morphology and riverbank modifications. With respect to features of river banks/riparian zone, LAWA method assess bank profile, bank protection and vegetation structure on banks and in the riparian zone. The surveyor is only required to qualify the status of each site, ranging from “unchanged” to “completely changed”, based on the German concept of “leitbild” (i.e., natural state that would establish itself in the absence of human interventions). This riparian dataset exclusively comprises category-based information, with little scope for investigating riparian vegetation features and functions. Similarly, the SEQ-PM (Système d’Evaluation de la Qualité du Milieu Physique) in France, or more recently the SYRAH or CARHYCE systems (Gob et al., 2014), record many physical features of channel morphology and riverbanks, but evaluate only the structure (using qualitative or semi-quantitative classes), the longitudinal continuity and the coverage of riparian vegetation (Raven et al., 2002; Belletti et al., 2015), which again result rather simplistic.

More recently, Rinaldi et al. (2013, 2015) developed the Morphological Quality Index (MQI) to assess stream morphological conditions in Italian rivers. This method considers attributes for assessing geomorphological features, artificiality and channel adjustments, but only a few of these attributes are related to the status of riparian vegetation. Geomorphological features are assessed by 13 indicators that are mainly related to the longitudinal and transversal continuity of water and sediment flows, natural channel forms and bed substratum. Of these 13 indicators, only 2 are directly related to riparian vegetation, and these consider only its spatial dimensions: i) width of connected functional vegetation in relation to channel width and channel pattern and ii) proportion of the maximum available length that is covered by the linear extension of functional vegetation. Similarly, of the 12 indicators developed to assess channel artificiality, which are related to the presence of barriers or structures that alter flows and sediments or channel revetments, only 2 are related to riparian vegetation management: i) existence and relative intensity of large wood removal during the last 20 years and ii) existence and relative intensity of riparian vegetation cuts during the last 20 years. Finally, channel adjustments are assessed using 3 indicators (channel planform, channel width and bed-level changes) that all correspond to physical aspects of the river and completely disregard the role of riparian vegetation potentially driving the reported changes. Compared to previous methods, the MQI represents an advanced, process-based approach for assessing river hydromorphology. Nevertheless, it is strongly based on channel morphology and water and sediment flows; riparian vegetation features are poorly considered and have very little influence on the resulting scores for the assessment of the river hydromorphological status.

In an attempt to gain a clearer understanding of how riparian vegetation is currently monitored and assessed across EU countries, the CONVERGES network (a COST Action focused on riparian vegetation, www.converges.eu) recently disseminated the results of a workshop and the responses of a questionnaire distributed to members of CONVERGES (González del Tánago et al., 2020). Overall, national protocols to characterize and assess riparian vegetation differ among countries, and basically correspond to the same WFD-compliant protocols for assessing hydromorphological conditions. In general, most countries collect qualitative information, mainly related to the type and structure of vegetation, following the qualitative classes established by the RHS. Other attributes of riparian corridors are occasionally assessed, such as longitudinal continuity, vegetation cover, size and shape of vegetation patches and the presence of large wood. Most protocols exclude species composition, and additional information such as age structure, spatial distribution along functional zones, or data on plant functional traits is not required by any country.

The analysis of these worldwide applied hydromorphological protocols, together with the revision of some other methods that have been proposed in other countries (e.g., Benjankar et al., 2013; Klösch and Habersack, 2017; Zaharia et al., 2018) demonstrates that riparian vegetation is not being properly considered or evaluated in national-level efforts to monitor hydromorphological conditions of rivers within the context of the WFD. Information on the composition of riparian vegetation, or on the structure and temporal succession of plant communities, could provide valuable insights on current response to hydrological pressures (i.e., hydrological alteration, channel adjustments) or on the outcomes of programmes of measures (i.e., environmental flows, connectivity enhancement). Instead, these data are not collected or systematically ignored in national hydromorphological status reports. At the national scale, the available data on riparian vegetation mainly refer to height classes or spatial dimensions (e.g., RHS data), and result greatly inadequate in describing current status and tracking the recovery processes of river systems. The poor quality of information on riparian vegetation characteristics and dynamism limits further understanding of river trajectories from the past to the present under natural or human-induced disturbances, and hinder our abilities

to predict responses to restoration measures (Hughes et al., 2005; Dufour and Piégay, 2009).

4. A novel approach for the characterization and assessment of riparian vegetation: a multi-scale framework

4.1. Riparian vegetation dynamics across spatial scales

The hierarchical framework developed in the EU REFORM project follows a multi-scale conceptualization of river systems for the characterization and assessment of river hydromorphology in European rivers (Gurnell et al., 2016a; González del Tánago et al., 2016a) (Fig. 2). A similar approach is also suitable for the characterization and assessment of riparian vegetation at multiple scales. The REFORM approach assumes that within a catchment (as delineated by its water divide), different "landscape units" may be identified, according to relatively similar pattern of topography and land cover. These landscape units are expected to produce similar regional divisions along the river mainstem, similar to those proposed by the traditional longitudinal zonation of river systems (Illies and Botosaneanu, 1963), each with relatively internal homogeneous geomorphic processes (Montgomery, 1999) responding to broad gradients of longitudinal slope and channel style (Ward et al., 2002b). Within each landscape unit, different "river segments" may be identified along the main channel, each with a homogenous internal geological context, valley setting and patterns of flow and sediment regime; this river segmentation likely corresponds to river sections between confluences of significant tributaries (Benda et al., 2004). Within each river segment, different "river reaches" may be identified assuming relatively homogenous internal assemblages of geomorphic units and channel forms. Finally, a biogeographic region can be identified above the scale of the catchment, which would be broadly delineated by climate and geological settings with specific land-cover features, determining the potential pool of riparian species.

The cascade of hydromorphological processes and landforms that ultimately emerge along these spatial scales frame the conditions of riparian vegetation development and succession (Richards et al., 2002; Tockner et al., 2010b; Gurnell et al., 2016a; Palmquist et al., 2018). The result of continuous mechanisms of reciprocal feedbacks enables and controls the recruitment, establishment, growth and mortality processes (Cooper et al., 2003: Corenblit et al., 2009a; Wilcox and Shafroth, 2013) (Fig. 3). Although riparian ecosystems respond and change mainly across the transversal gradient of flood disturbance (Steiger et al., 2005), they also reflect hydromorphological constraints across the longitudinal and vertical gradients of river systems (Amorós and Petts, 1993; Ward et al., 2002a). These gradients occur over a range of spatial and temporal scales, from the large scale, i.e., region or catchment (e.g., climate and biogeographic contexts, topography and hillslope processes), to the more local scale, i.e., reach or geomorphic (e.g., moisture availability and fluvial disturbance constraints) (Wiens, 2002; Beechie et al., 2010; Gurnell et al., 2016b).

Following an up-scaling approach, from the reach to the catchment scale, it is assumed that the recruitment and establishment of pioneer species (e.g., Salicaceae species) on bare alluvial bars (i.e., habitat mosaics, geomorphic units) are facilitated by water availability and by flood disturbance and geomorphic unit re-creation at the local scale (e.g., site specific shear stress, flood frequency and timing) (Johnson, 2000; Karrenberg et al., 2002; González et al., 2018). The occurrence of bare alluvial bars depends on the variability in the flow regime (e.g., high and low flows magnitude and frequency), coarse-sediment availability (i.e., sediment supply, large wood supply) and channel confinement (Martínez-Fernández et al., 2016), which vary greatly among river segments (Richards et al., 2002; Church, 2002; Brierley and Fryirs, 2005; Reid et al., 2013; González del Tánago et al., 2016b). Both flow regime and sediment supply are related to runoff, erosion processes and functional connectivity resulting from topography and hydrological conditions of each landscape unit, which are themselves ultimately influenced by

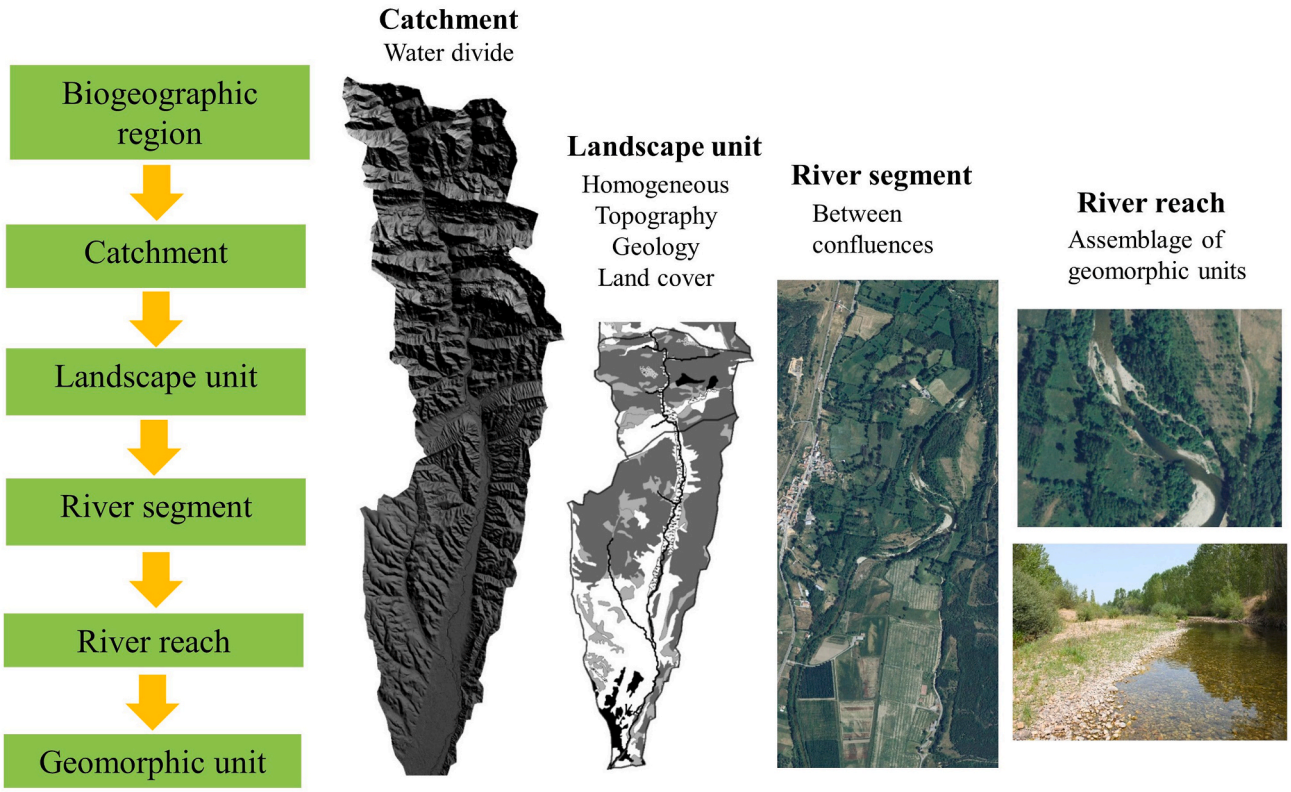

Fig. 2. Multi-scale hierarchical approach for hydromorphological studies, developed within the REFORM Project (Gurnell et al., 2016a) and proposed to characterize and assess riparian vegetation at multiple spatial scales.

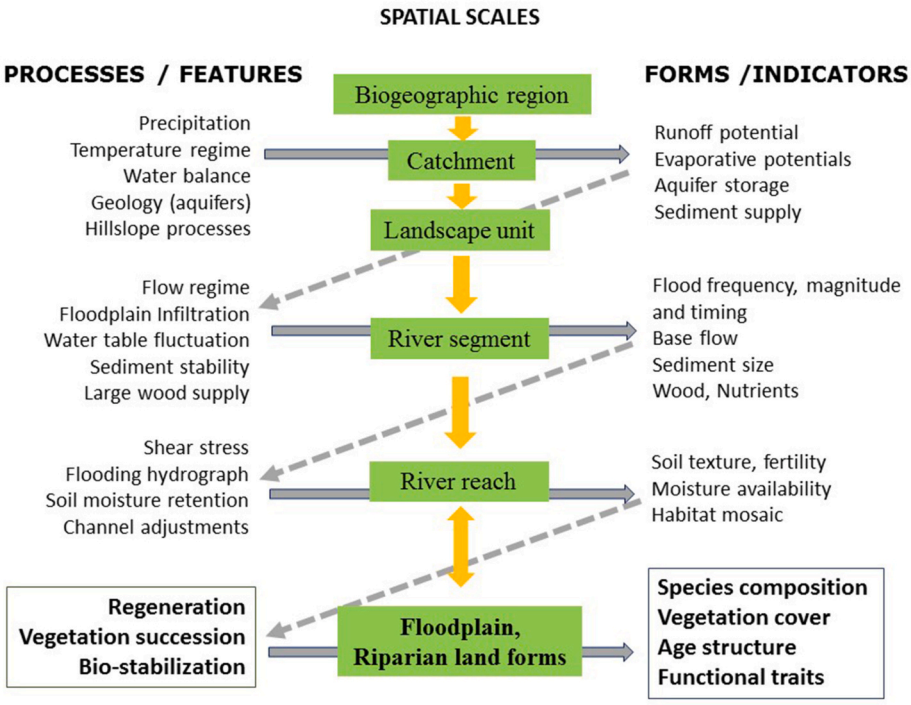

Fig. 3. Hierarchical cascade of hydromorphological processes and forms that interact with seed dispersal, recruitment, growth and mortality of riparian vegetation (i.e., vegetation processes as regeneration, vegetation succession and bio-stabilization) and determine the resulting composition, coverage, population structure, age diversity and functional traits of riparian vegetation at a given time (i.e., vegetation forms shaping the riparian corridors and their evolution overtime) (adapted from González del Tánago et al., 2016a). Thick grey arrows represent the influence of processes on the forms at the same spatial scale. Dotted grey arrows represent the influence of forms on the processes at the next smaller scale.

climate, geology and land-cover settings within the catchment (Fryirs et al., 2007; Fryirs and Brierley, 2013). Similarly, vegetation growth and development in certain river reaches are promoted by local soil-moisture availability associated mainly with riparian soil texture, nutrients and groundwater-surface water interactions (Gilvear and Willby, 2006; Asaeda et al., 2015; Bätz et al., 2016; Gomes Marques et al., 2018). Plant mortality is mainly caused by continuous flooding, desiccation, or burial and uprooting, and it depends on the flood regime and water table fluctuations, and at the local scale on the water depth, flow velocity and sediment transport rate, which are determined by local micro-topography and substrate conditions (Camporeale et al., 2013; Politti et al., 2018). These local substrate, moisture conditions and hydraulic thresholds are determined by sediment supply and fluvial disturbance patterns within the river segment, which are ultimately driven by sediment-cascade connectivity and erosion processes and hydromorphological context at the respective landscape unit and catchment scales (Fryris et al., 2007; Wohl, 2013).

Inversely, following a down-scaling approach from the catchment to the reach scale, the scale-dependent influence of climate, geology, topography, and successively the flow regime, valley settings and local transversal floodplains, determine channel dynamics and the formation and maintenance of geomorphic units (Fryirs and Brierley, 2013). All of them act as hierarchical environmental filters that constrain riparian vegetation settlement, growth, development and succession (Poff, 1997; Hough-Snee et al., 2015a; Palmquist et al., 2018).

4.2. Riparian vegetation units and indicators

By extending the multiscale hierarchical approach to the riparian vegetation, it is possible to define four main vegetation units (individual plant, vegetation patch, plant community, riparian corridor) that are associated with specific spatial and temporal scales (Fig. 4). These vegetation units, together with their respective indicators (Table 1), can be used to characterize and assess the status of riparian vegetation from the local site to the catchment. Vegetation units and indicators at different spatial scales correspond with different temporal scales that are indicative of the turnover ratios of the respective vegetation feature.

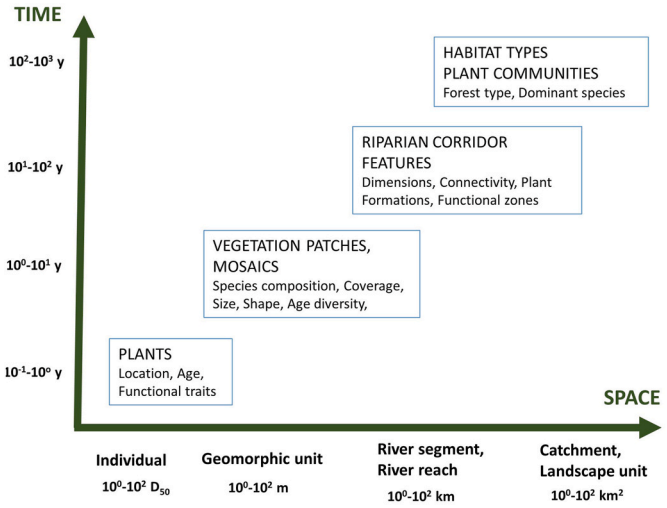

Fig. 4. Vegetation units (capital letters) and indicators used to characterize riparian vegetation at different spatial scales (km^2 of catchment, km or m of river length, D_{50} cm of grain size) with respect to the approximate temporal scales (years) associated with them.

Scale-dependent fluvial and ecological processes support the proposed hierarchical array of vegetation units (Richards et al., 2002). Habitat types and/or plant communities emerge as a result of adaptation to climatic, hydrologic and sedimentologic history; riparian corridors are the result of metapopulation processes within geologic and valley features and floodplain human interactions; and vegetation patches and individual plants result from local succession processes, clonal growth, recruitment and dispersal of propagules and seeds linked to local channel pattern dynamics, hydraulic roughness and sediment transport (Merritt and Wohl, 2002; Corenblit et al., 2009a).

From a temporal perspective, the same vegetation units can provide insights into river adjustments or changes over time caused by either natural or human-induced disturbances (Fryirs et al., 2012). Short term

Table 1
Vegetation units and indicators resulting from hydromorphological processes and the potential influence of disturbances or pressures at multiple spatial scales.

SPATIAL SCALE (Vegetation Units)	HYDROMORPHOLOGICAL PROCESS/ VARIABLES	VEGETATION INDICATORS	DISTURBANCES/ PRESSURES
CATCHMENT (Habitat Types) LANDSCAPE UNIT (Plant communities)	Precipitation, Evapotranspiration Topography/Landforms Land Cover, Land Uses Hillslope runoff, Aquifer storage Erosion processes Sediment supply	Phytosociological classes, Habitat types Dominant species Longitudinal/Transversal zonation of plant formations	Global changes, Warming Land Cover changes Wildfires Road construction Irrigation, Overgrazing
RIVER SEGMENT (Riparian corridors, Vegetation mosaics)	Valley-settings interactions Flow regime, Sediment budget Channel size and planform Channel adjustments Sediment size, Alluvial depth Floodplain sediment erosion/deposition Water table fluctuation	Plant communities and guilds Corridor width, coverage Connectivity, Functional zones based on dominant fluvial processes Patch structure Landscape complexity	River damming Flow regulation Water abstraction Channelization Dredging, Gravel mining Floodplain occupation Groundwater depletion
RIVER REACH (Patches, individuals)	Flood frequency and duration Shear stress Riparian soil texture Soil moisture Burial and scour processes	Species composition, Diversity Size, Location to channel Recruitment areas Plant functional traits Genetic diversity	Embankments, Dredging Channel revetments Weirs, check-dams Floodplain sealing, Debris filling Plantations

responses to local hydromorphological conditions can determine the location of recruitment (Mahoney and Rood, 1998; Cooper et al., 2003), which in several years can determine the spatial arrangement and structure of vegetation patches. In several decades, or even beyond centuries up to a geologic scale, vegetation succession shape riparian corridor features and succesively plant communities and habitat types, as the result of dynamic co-evolution of vegetation and river systems under both natural and human-induced disturbance regimes (Hicks et al., 2007; Corenblit et al., 2009a; Newaz et al., 2019; García de Jalón et al., 2020).

The vegetation units under study may be characterized by different attributes which can be used as indicators of the ecological status of riparian zones (Table 1). First, these attributes represent measures of the spatial structure of riparian vegetation. They provide insights into how river hydromorphology creates vegetation forms and the spatial arrangement of habitats, and give a static perspective of riparian vegetation structure (e.g., area and coverage of vegetation patches). However, they also represent measures of how riparian vegetation is interacting spatially within the river system. They provide insights into how hydromorphology promotes riparian vegetation dynamism and offer a dynamic perspective of riparian vegetation behaviour and succession (e.g., age diversity of vegetation patches) at multiple scales. Biophysical or human-induced disturbances and pressures may alter vegetation indicators directly (e.g., vegetation removal and/or species changes due to overgrazing, floodplain occupation) or indirectly, by altering the hydromorphological processes that drive the establishment and survival of riparian vegetation (e.g., riparian plant desiccation or terrestrialization due to loss of connectivity and decreases in riparian soil moisture from groundwater overexploitation, channel dredging). Thus, vegetation units and indicators may accurately reflect hydromorphological pressures and river status at multiple scales, through both short-term and long-term responses to hydromorphological conditions arising from the nested influence of environmental filters acting within the catchment (Fig. 3).

4.3. Analytical approaches

The wide array of analytical approaches for the characterization and assessment of riparian vegetation units and indicators can be grouped around three main families: 1) taxonomic composition, 2) spatial landscape structure of vegetation mosaics and 3) dominant processes that create and maintain vegetation patterns (Table 2). Each approach requires different methods and expertise and are complementary to each other, with all of them, individually or collectively, are applicable to the clusters identified in Fig. 4.

Table 2
Basic approaches to analyse riparian vegetation units and indicators at different spatial scales.

ANALYSIS APPROACH *(MAIN DATA SOURCE)*	PLANT/PATCHES RIVER REACH ($0.1–10^2$ m)	RIPARIAN CORRIDOR RIVER SEGMENT ($1–10^2$ km)	CORRIDOR/FOREST TYPES LANDSCAPE UNIT/ CATCHMENT ($10–10^2$ km^2)
Taxonomy based *(field work)*	Species composition, Abundance/ Dominance Diversity	Plant formations, Plant communities	Phytosociological classes Habitat types Dominant species
Landscape-mosaic approach *(GIS analysis)*	Size, Shape, Coverage, Edge, Relative location to channel, Spatial distribution	Riparian corridor width, Coverage Connectivity Fragmentation	Corridor types, Spatial assemblage of patches Landscape diversity
Functional approach (process-based) *(field work + GIS analysis)*	Pioneer recruitment areas (size, location) Plant functional traits Inter and intraspecific variability, Genetic diversity	Functional zones based on dominant fluvial processes Plant guilds	Broad Longitudinal/ Transversal zonation of Plant communities, Broad location of Pioneer/Late-seral species

4.3.1. Taxonomic composition

Riparian analysis based on taxonomy requires expertise in identifying families, genera and species of the potential riparian species. Taxonomical knowledge has been relatively disregarded in the last decades in favour of more ecological-statistically-based approaches. Although ecological and statistical perspectives offer valuable interpretation of results, the taxonomical background remains unavoidable for clear distinction of vegetation types and for the precise assessment of vegetation responses to environmental changes or restoration measures.

The indicator value of species according to their tolerance to pressures has been frequently used in traditional approaches for environmental assessments using fish communities (Karr et al., 1986) or macroinvertebrate fauna (Wright et al., 1988; Smith et al., 1999). In agreement with this, species composition should be considered the

obligated basic information to describe and assess the existing riparian vegetation in an area. Only by means of species identification, further qualitative and quantitative attributes can be used to infer riparian vegetation types, formations and associations, dominant species or phytosociological classes at larger spatial scales, or species richness, diversity, and percentage of exotic and/or invasive species at smaller scales. Different approaches to collect vegetation data can be considered (e.g., line transect, belt transect, quadrat) according to specific plot size for phytosociological sampling (Chytrý and Otýpkova, 2003). Although some advances have been made in using remote sensing to identify woody species (e.g., Fernandes et al., 2013; Rodríguez-González et al., 2017), field work is usually required for taxonomic descriptions of plant communities at the local scale (Nagler et al., 2005; Gómez-Sapiens et al., 2020). Spectral separability of riparian species remains challenging due to the overlap of spectral signatures among species, as well as the intra-annual phenological variability. However, at larger scales, existing maps and documents can be used to characterize phytosociological classes in riparian corridors, a useful procedure for linking EU water and other EU policy regulations, as the EU Habitats Directive (92/43/EEC).

4.3.2. *Landscape mosaics*

With the increasing availability of GIS and remote sensing, riparian studies based on landscape analysis have been growing rapidly. Nowadays, landscape analysis is one of the most frequent practice in riparian vegetation research (Dufour et al., 2019).

Spatial metrics obtained by GIS-based analysis, vegetation mapping by visual interpretation of aerial imagery or remote sensing sources, and multispectral vegetation indices are interesting up-dated approaches to analysing riparian vegetation characteristics and trajectories (Nagler et al., 2004, 2005; Van Looy et al., 2008; Fernandes et al., 2011; Dufour et al., 2012; Aguiar et al., 2016; Rodríguez-González et al., 2017; Huylenbroeck et al., 2020). Combinations of repeated air photographs and LIDAR analysis are frequently used to document changes in vegetation structure (Michez et al., 2017; Huylenbroeck et al., 2021), wood recruitment (e.g., Bertoldi et al., 2013) or trajectories of riparian corridors (e.g., Sanchis-Ibor et al., 2019) over time. At the large scale, total coverage and fragmentation are frequently reported as one of the easiest vegetation characteristics to track temporal changes over time via diachronic analysis (González del Tánago et al., 2016b; Sanchis-Ibor et al., 2019; García de Jalón et al., 2020). At reach scale, remotely sensed measurements of multispectral vegetation indices (e.g., NDVI, EVI) have been used to relate changes in vegetation greenness and evapotranspiration to hydrological (e.g., flow diversion, environmental flows) and bioclimatic processes (Nagler et al., 2020). Several authors have used other easily obtainable spatial measures, such as the number of vegetation patches, the size and shape of patches, and distance among patches, to differentiate among distinct vegetation structures likely related to pressures or impacts (Fernandes et al., 2011). These spatial measures previously require the manual or automatic delineation of vegetation patches. As these measures can vary greatly along the river course, they are normally used to represent riparian vegetation characteristics at the river segment or reach scale.

4.3.3. *Functional approach*

Studies that focus on functional aspects of riparian zones require expertise in fluvial bio-geomorphology, as well as the ability to identify riparian species and define guilds using basic knowledge on their hydromorphological requirements, and/or apply functional diversity metrics. This type of studies represents a more holistic comprehension of the interactions between riparian vegetation and channel dynamics (Merrit et al., 2010; Gurnell et al., 2016a; Stromberg and Merritt, 2016), as well as the responses of riparian vegetation to hydrological alterations (Bejarano et al., 2012; Lytle et al., 2017).

4.3.3.1. Functional zones. Functional and process-based indicators of riparian vegetation status can be derived from the typology and dimensions of the functional zones defined by Gurnell et al. (2016b). These authors distinguish five functional zones along river channels, with each typically created and maintained by different dominant fluvial processes. These five zones change along river corridors according to available space (i.e., valley confinement, human floodplain occupation) and river types (i.e., channel planform based on valley width, valley slope, sediment size, etc.). Zone 1 corresponds to the permanently inundated area, with high sediment dynamics, where aquatic plants are currently established. Zone 2 corresponds to the contiguous area which is frequently flooded but also has high sediment dynamics (coarse substratum). It typically contains emergent riparian macrophytes and pioneer woody species that tolerate frequent floods, scour and burial. Zone 3 is frequently flooded and has significant sediment deposition (finer substratum). It contains riparian plants that tolerate frequent flooding and moderate sedimentation. Zone 4 represents areas that are occasionally flooded but have no significant sediment dynamics. It contains riparian plants that have varying flood tolerance depending on the local microtopography and are considered late-seral riparian species. Zone 5 corresponds to the more distal area of riparian corridors in which flooding is absent or extremely rare, and soil moisture is fed mainly by subsurface or groundwater runoff. Plants in this zone tolerate local soil moisture and the alluvial/groundwater regime and connect with terrestrial hillslope species.

The existence and dimensions of these five functional zones, along with the species composition and age structure of each, may closely reflect the effects of current hydromorphology in riparian corridors. For example, changes in the flow regime due to dams and reservoirs are likely to promote the gradual disappearance of Zones 2 and 3 and trigger vegetation encroachment. In such a case, Zone 4 would extend to the channel banks and late-successional plant formations would develop in the proximal riparian zones, replacing the initial pioneer-species that were growing in these previously fluvial disturbance dominated zones (Martínez-Fernández et al., 2017b) (Fig. 5).

Apart from the functional riparian zones, there are other attributes of riparian vegetation that indicate their dynamics and river functioning. Floodplains and riparian zones are generally dynamic environments where erosion and deposition processes periodically remove older vegetation and create new bare locations for recruitment of pioneer species (Hughes, 2003). Thus, age diversity (i.e., frequency distribution of ages of a species in an area of habitat *sensu* Richards et al., 2002), the extent and location of areas with pioneer recruitment, or the percentage of area covered by late-seral species or mature forest compared to that covered by early-seral species or young stands, may be indicators of channel dynamics, heterogeneity of successional stages or temporal trends of riparian vegetation (Garófano-Gómez et al., 2017).

4.3.3.2. Functional traits. Functional traits of riparian species have also been included in riparian vegetation assessments as a complementary approach to the species-based analysis, which may be relatively simple and inexpensive but does not adequately capture relevant underlying ecosystem processes (Brooks et al., 2002). A functional traits approach 1) relates riparian structure to ecological processes; 2) provides a mechanistic understanding of the spatial variation of species within different bioclimatic contexts (related to biogeography and different regional pools of species) and 3) assess species interactions and community assembly at local level. Functional traits may be perceived as ecological-response traits, which describe how a plant responds to abiotic stressors, or as morphological-effect traits, which inform how plant directly influences the flow of water, the transport of sediments and the stabilization of landforms (O'Hare et al., 2016; Diehl et al., 2017).

Common functional response-traits used in riparian forest studies may be grouped in families of traits such as resource acquisition, reproduction, response to disturbance, etc., and include height, SLA

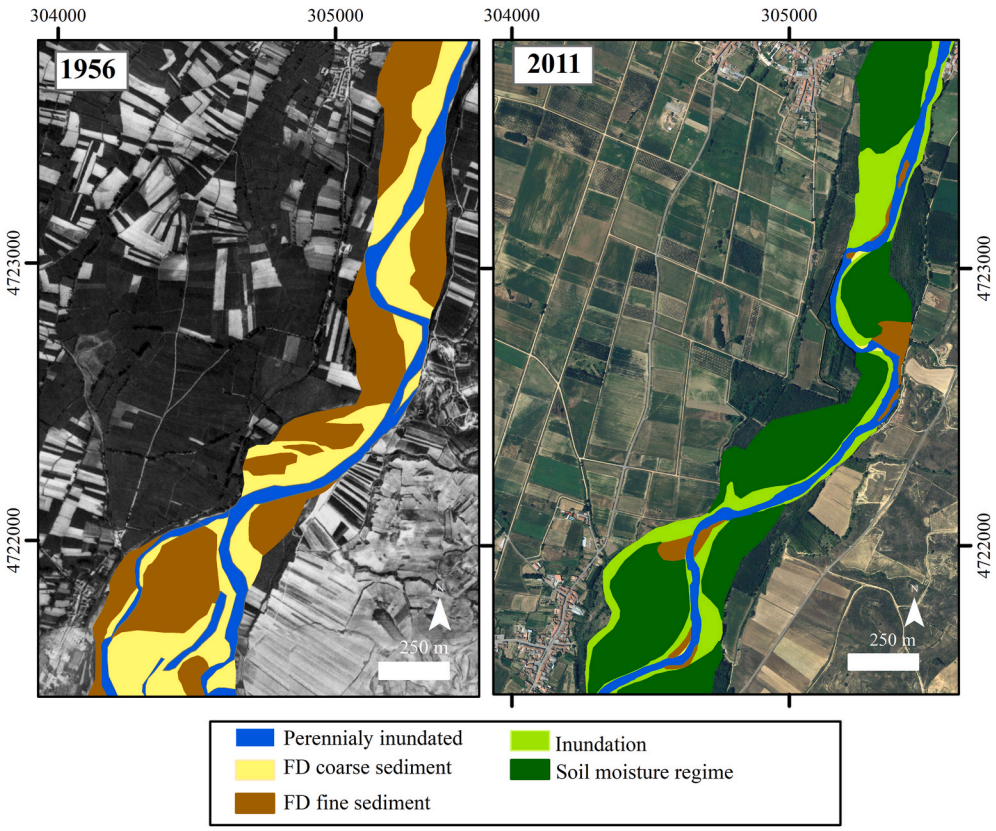

Fig. 5. Example of identification of functional zones in a regulated segment of the Porma River (Spain), based on dominant fluvial processes defined by Gurnell et al. (2016b): Zone1: Perennially inundated, Zone 2: Fluvial Disturbance (FD) dominated (coarse sediment erosion and deposition), Zona 3: Fluvial Disturbance (FD) dominated (finer sediment deposition), Zone 4: Inundation dominated, and Zone 5: Soil moisture regime dominated. Before regulation (1956) FD dominated zones occupied nearly all the active channel width; after several decades of dam operation (2011), FD zones have nearly disappeared, and the previous fluvial space is only occasionally inundated (Zone 4) or under a soil moisture regime from subsurface and groundwater runoff (Zone 5).

(Specific Leaf Area), seed mass, seed size and production, growth rate, dispersal ability and vectors, diaspore characteristics, phenology in relation to flood-pulse timing, tolerance to disturbance, etc. Species traits reflect different aspects of available resources and habitat requirements, and thus may be good indicators of complex patterns of hydromorphological changes (Kyle and Leishman, 2009; Bertoldi and Gurnell, 2020). Seed and germination traits can determine plant distribution patterns (Leyer and Pross, 2009), while niche differentiation traits (e.g., flowering time) and competitive hierarchy traits (e.g., plant height, seed mass) can predict the potential coexistence of native species with invasive species (Fried et al., 2019). Morphological-effect traits are those that influence river morphodynamics, such as frontal area, flexibility, buoyancy, leaf area, root architecture, etc. Plants with similar morphological traits frequently show similar responses to flow variability and disturbance. Strong correlations between morphological and response traits evidence the interest of the functional trait framework, which may capture the response of plant community dynamics and their corresponding interactions with fluvial morphological processes (Diehl et al., 2017).

In recent years, functional diversity indices have been used more frequently to assess environmental and human-induced impacts on functional diversity in riparian forests (Bruno et al., 2016; Lozanovska et al., 2018). Among these, the most frequently used are functional richness, functional evenness and functional divergence (e.g. Arsénio et al., 2020), although their ability to explain or predict riparian community responses to environmental or human-induced functional changes can vary greatly (Lozanovska et al., 2018, 2020).

Riparian vegetation guilds, as groups of individual species of common life history strategies based on species morphological and/or functional traits (Hough-Snee et al., 2015a), are also considered as a very useful functional approach for understanding riparian vegetation responses to hydrologic regime alterations (Merritt et al., 2010; Bejarano et al., 2012). Most studies using guilds or functional diversity indices in riparian settings have focused almost exclusively in response traits. A more robust approach capturing the coupled information on the ecological and hydromorphological meaning of riparian vegetation traits, would facilitate their modelling and generalization across environmental gradients (Diehl et al., 2017).

4.4. Characterization of riparian vegetation to inform diagnosis and potential management

When attributes of riparian vegetation are characterized at different spatial scales and over different periods, it becomes possible to detect changes over time (Fig. 6). Based on the vast available scientific literature, the observed changes could be associated with environmental changes or specific human-induced disturbances occurring at the reach or segment scale (e.g., construction of dams and reservoirs, channelization) or at larger scales (e.g., land-cover changes within a catchment, regional hydrological decrease, e-flows releases from big dams). Detailed information on the magnitude and timing of disturbances at their respective scales, including biological invasions and pests/diseases, will give valuable insights to relate altered fluvial processes with vegetation changes. This could help to enhance the diagnosis of riparian vegetation status and to understand the trajectory from the past, as well as predict the most likely future trends under different management scenarios and hydrological contexts (Fig. 6). Nevertheless, riparian diagnosis is not always straightforward, as the effects of pressures and disturbances may often be delayed on time and vegetation responses could take decades to be detected (Pont et al., 2009; Fryirs et al., 2012; Han and Brierley, 2020; Janssen et al., 2020).

4.5. Assessment of riparian vegetation to inform quality status and effects of programmes of measures

Within the context of the WFD, the status of the quality elements of water bodies must be assessed in order to verify the improvement of the status and the efficiency of the planned programs of restoration

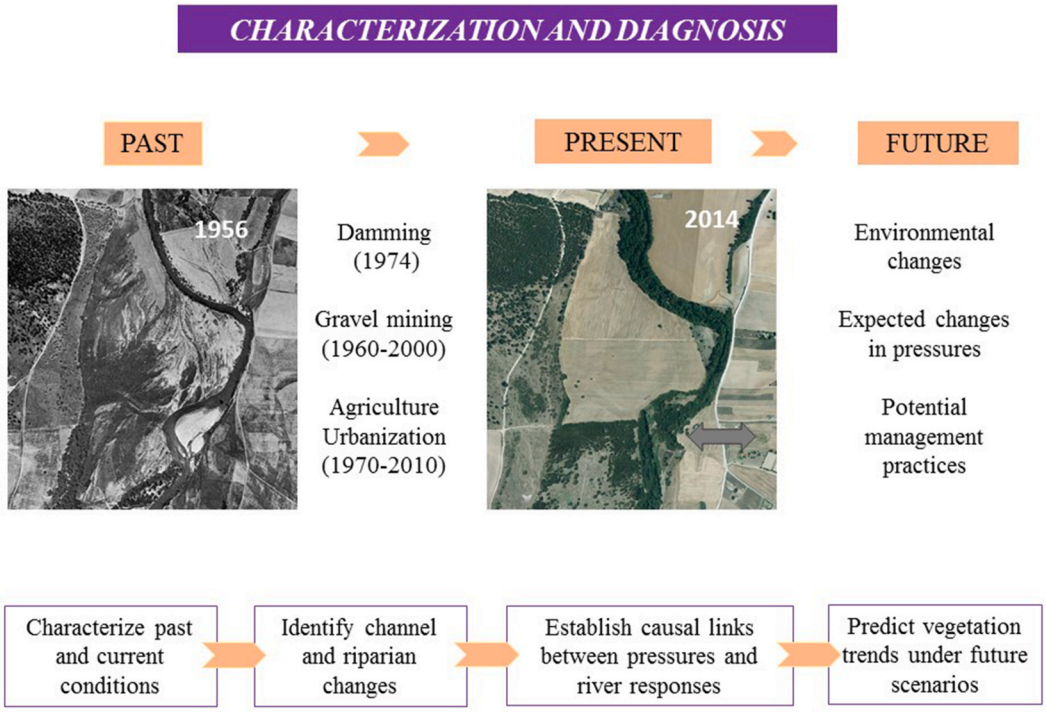

Fig. 6. Basic steps towards characterizing and diagnosing riparian vegetation status based on i) characterization of current conditions and past conditions at multiple scales, ii) identification of changes, and iii) establishment of potential cause-effect links with existing pressures. Reconstruction of past trajectories will facilitate the prediction of future trends under potential scenarios of environmental changes or management practices. (Pictures and pressures from the Jarama River, central Spain).

measures.

Assessing the status of riparian vegetation (i.e., evaluating and ranking its quality) represents a further step from characterization and diagnosis (i.e., detailed description of forms and processes and statement of causes and effects), and requires additional information that is often complex and difficult to obtain. Characterizing riparian vegetation status by describing vegetation units and indicators is relatively simple to achieve and verify, but assessing the quality of this status requires comparison of the current conditions to a previously established reference condition, which can be challenging to define. This reference condition would need to account for the natural vegetation dynamism following relevant floods, consider species succession according to channel evolution at different temporal scales, and evaluate the potential dynamic equilibrium on the long term.

Defining reference conditions represents a critical step for river management programs, as it requires a clear exposition of objectives and targets (which are a mix of what we could have in a given location for a given period and what the society would like to have; Dufour and Piégay, 2009). Once the differences between the current status and reference status are quantified, thresholds may be established that reflect different classes of status quality (e.g., very good, good, fair, poor, very poor). As with the reference conditions, this can be subjective and can involve a great deal of uncertainty (Fig. 7). Furthermore, it could be exposed to change following shifts in management objectives and social preferences (Hughes et al., 2005; Horne et al., 2017; Chen et al., 2020).

As mentioned above, environmental assessments require knowledge of current conditions as well as defined reference conditions that correspond either to sites that are similar but with totally or nearly totally undisturbed conditions, or to the desired or targeted conditions. These theoretical "healthy" or reference conditions, which serve as controls to be compared to current conditions, must always take into account unavoidable human influence on catchment hydrological processes (Dufour and Piégay, 2009) and may combine river historical conditions and the best possible conditions that can be expected at a given site.

The definition of reference conditions for riparian vegetation should be different according to hydromorphological-processes-based river typologies. Rinaldi et al. (2016) developed a river classification system that could be useful for this purpose. It includes morphological features (i.e., valley confinement, planform pattern and bed material size), floodplain typologies based on formation processes (i.e., bankfull unit stream power, floodplain form and material size), flow regime types based on intermittency and prevailing type of flow source (i.e., hydrological regime based on magnitude, frequency, and timing of flows) and groundwater-surface water interactions.

Based on the river typology and the biogeographic context of the catchments, riparian vegetation types and features could be theoretically predicted as "natural" communities (i.e., spontaneous in the absence of direct human interventions) (Kujanová et al., 2018). Biogeographical studies that provide information about spatial distribution patterns of species at the catchment scale (Ricklefs and Jenkins, 2011), along with studies of broad plant functional traits, could be used to identify theoretical "undisturbed" vegetation types, riparian plant formations and associations along the river corridor at the regional scale. Similarly, valley settings, the river planform and sediment and flow regime patterns can help in identifying the theoretical species composition and structure of vegetation patches along river segments, and can also inform about riparian dynamism. Sediment size, channel geometry and flood/drought disturbance regime at the reach scale can be theoretically used to infer local riparian vegetation features based on functional zones, spatial distribution of pioneer species, age structure or location and dimensions of dominant riparian guilds (Bejarano et al., 2012; Gurnell et al., 2016b; Hough-Snee et al., 2015b). Some modelling approaches are currently under development and may assist in predicting the potential vegetation that can be expected (Ochs et al., 2020).

The definition of reference conditions is accompanied by many challenges, both conceptual and methodological. A different approach could be to evaluate the riparian ecosystem with respect to its

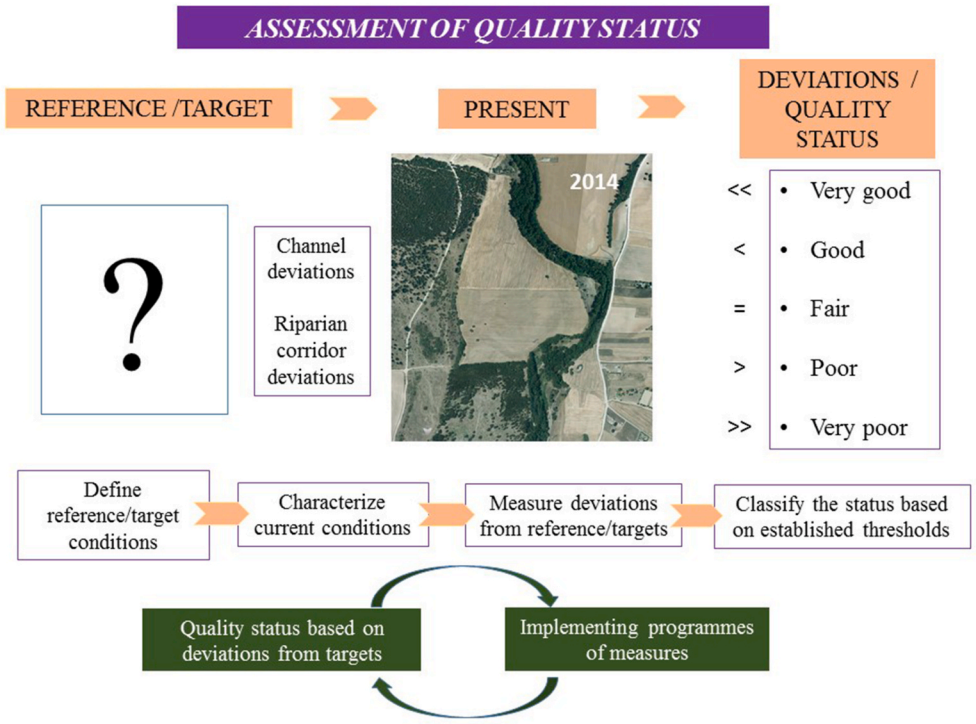

Fig. 7. Basic steps towards assessing the current status of riparian vegetation, based on i) characterization of reference conditions, ii) measurements of deviations from the current status, and iii) classification of quality status according to established ranking scores and thresholds. The procedure will help to select programmes of measures that addresses the deviations from reference conditions, as well as to assess the effectiveness of the implemented measures in improving the resultant ecological status.

naturalness/functionality vs. artificiality. With this perspective, we could distinguish vegetation attributes that may be related more to the "naturalness" of a riparian system (reflecting no or very little alteration by human influence) or "healthy" functionality (reflecting free fluvial processes, e.g., channel mobility, natural regeneration) from attributes that may be related more to "artificiality" (reflecting human pressures that induce changes in riparian vegetation structure).

Potential indicators of both vegetation naturalness/functionality and artificiality (Table 3) should meet the criteria of being quantifiable (e.g., scoring systems with the highest values corresponding to the highest naturalness (i.e., best status) or to the highest artificiality (i.e., worst status); and being independent or little inter-correlated but complementary (i.e., attributes of naturalness scoring different issues from attributes of artificiality). In general, high values of naturalness/functionality should be expected to occur with low values of artificiality, although this does not necessarily have to be the case (e.g., in terms of functionality, proper functioning conditions could theoretically exist under non-native vegetation communities). Under this approach, we could assume that the highest quality status would correspond primarily to the lowest artificiality (Fryris and Brierley, 2009), indicating absence or no-significant direct human influence on riparian vegetation status, which could be used as a surrogate of naturalness, which can be very cumbersome to define.

The second stage of the assessment entails establishing thresholds of deviations from the reference conditions that correspond to the discrete quality classes of vegetation status. This second stage may involve different approaches, such as considering individual criteria of artificiality vs. naturalness in 1) taxonomic features (e.g., presence and abundance of obligate species, percentage of invasive alien species), 2) landscape features (e.g., fragmentation, encroachment) or 3) functional features (e.g., changes in functional diversity, riparian guilds, spontaneous recruitment); or defining multicriteria indices whose combined quantitative range of values can be divided evenly into multiple classes of quality status.

4.6. New perspectives for the integration of riparian vegetation in hydromorphological assessments

As pointed out by Langhans et al. (2013), hydromorphological protocols are strongly biased according to the scientific background of their author(s). At present, hydromorphological assessments within the context of the WFD have been strongly based on traditional river morphology, disregarding the relevance of the biotic component of river dynamics. Recognizing the influence of vegetation on river forms and processes we advocate for the integration of riparian vegetation in hydromorphological monitoring and assessment tasks. This fully agrees with the new paradigms of river management encompassing not only plants but also big and small animals in river assessment and restoration proposals (Johnson et al., 2020).

As an enhancement of WFD procedures, we propose that assessments of hydromorphological status (Q_{hymo}) of river water bodies be based on evaluation of the main hydromorphological elements, flow regime ($Q_{\text{flow regime}}$), channel form and processes ($Q_{\text{channel dynamic}}$) and riparian vegetation ($Q_{\text{riparian vegetation}}$) (see Fig. 1), following the expression:

$$Q_{hymo} = k_1\, Q_{\text{flow regime}} + k_2\, Q_{\text{channel dynamic}} + k_3\, Q_{\text{riparian vegetation}}$$

In which k coefficients represent the weight of each element that could be different in each river reach, according to river typology and other site-specific constraints (e.g., lower values of k_2 and k_3 in confined valleys where small capability of river adjustments may be expected, Brierley et al., 2002). With this model, aligned with the recent work by Castro and Thorne (2019) integrating hydrology, geology and biology, each country would be able to maintain its current system for evaluating flow regime and morphological conditions, and simply incorporate the evaluation of the riparian vegetation, as an independent element that will complement the hydromorphological assessments of rivers offering valuable insights on their dynamism.

By combining data on riparian vegetation with existing information on hydrological regime and channel morphology, this approach gives an integrated perspective of hydromorphological quality of river sites. Further steps would involve the creation of a supplementary and validated list of riparian vegetation attributes with quantitative scores for

Table 3
Potential indicators for use in assessing the status of riparian vegetation and the responses to pressures or restoration measures at the respective spatial scales. The applicability of each indicator may vary depending on bioclimatic/geographic contexts, river type and on other specific features that could determine the status of riparian vegetation at certain spatial scales (i.e., assessment of each indicator is always based on what is expected to be "natural", spontaneous and/or maybe desirable at each river site).

SPATIAL SCALE	RIPARIAN VEGETATION INDICATOR		PRESSURES/ IMPACTS
	NATURALNESS/ FUNCTIONALITY	ARTIFICIALITY	
CATCHMENT LANDSCAPE UNIT	Native[a] riparian plant formations: • Habitat types • Diversity • Coverage	Human-induced plant formations: • Number of alien/invasive species • Coverage of alien/invasive plants	Land-cover changes at larger scales: Agriculture/ Forestry Grazing Urbanization Groundwater overexploitation Mining
RIVER SEGMENT	Riparian corridor features: • Width of the corridor with native riparian communities • Diversity of vegetation patches (landscape complexity) • % of vegetation dominated by the fluvial erosion and deposition processes that correspond to the valley and river type	Alteration of riparian corridors: • % river length of artificially fragmented or disconnected corridor • % river length with artificially reduced width of riparian corridor[b] • % forest plantations (e.g., poplars) or managed vegetation (e.g., periodically cut or pruned) • % riparian zone with only late-seral species[c]	Flow regulation Water abstraction Channelization Dredging Floodplain occupation Gravel Mining Silvicultural/ Agricultural practices Fire Dikes
RIVER REACH	Riparian vegetation mosaics: • % expected species composition and abundance depending on river typology and site •Diversity of age classes • % area of pioneer species recruitment	Alteration of riparian vegetation mosaics: • Coverage of aged pioneer species[d] • Unbalanced proportion of sexes • % of terrestrial species • % of nitrophyllous and ruderal species • Deviation from certain % of dead trees[e] • % artificially planted vegetation • % artificially bare or ploughed soil	Flow regulation Channelization Channel revetments Pavements Bank elevation Fillings Excavations Water pollution Local grazing Reprofiling Vegetation removal

[a] Native for the given biogeographic region and river typology.
[b] To use in partially-confined or unconfined rivers, relating width of existing corridor with channel width.
[c] To use in artificially stabilized or regulated rivers.
[d] To use in artificially disconnected reaches.
[e] To use when high mortality is related to human influence.

the establishment of quality classes according to river typologies and natural or anthropogenic constraints.

5. Conclusions

Riparian vegetation is a key element of river systems that closely interacts with water and sediment flows. A vast body of scientific literature supports riparian vegetation as a major determinant of river hydromorphology and as a valuable indicator of hydromorphological pressures. It is thus critical to include riparian vegetation in river management, and integrate riparian vegetation in tools and procedures to assess and monitor river status.

At EU scale, the WFD has been a major challenge for developing river hydromorphological research since its approval in 2000. Although the outcomes of the WFD have been considerable, some inefficiencies have been identified, many of them associated with inaccurate monitoring and assessment procedures that do not provide functional links between habitat degradation, hydromorphological pressures and management measures. The last several decades of river research have made it clear that biology is unavoidably intertwined with hydrology and channel morphology. We therefore advocate for the WFD to be reviewed and updated with the goal of integrating riparian vegetation as a core hydromorphological quality element supporting biological communities, thus bringing the WFD in line with the scientific consensus on the influence of riparian vegetation in river hydromorphology that has emerged since its approval.

Here, we offer process-based riparian vegetation units and indicators at different spatial and temporal scales for use in river assessment procedures. The proposed hierarchical, multi-scale approach uses taxonomic, landscape and functional vegetation attributes and should facilitate both the identification of causal links between vegetation status and hydromorphological processes, and the accurate prediction of future evolutionary trends under different potential scenarios of management and environmental changes.

The complexity of assessing riparian vegetation status based on reference conditions may be addressed by evaluating attributes of riparian vegetation naturalness or functionality and attributes of riparian vegetation artificiality, according to river typologies and management targets.

This paper presents a thoughtful hierarchical set of indicators at different scales, but their use and combination remain flexible and open, depending on data acquisition facilities and management targets. Additionally, we propose a novel multi-criteria approach that considers riparian vegetation together with flow regime and channel morphology, in order to integrate riparian vegetation features in the hydromorphological assessment protocols currently in use within the context of the WFD.

Future work is needed to validate the proposed vegetation indicators and establish their metrics and relative weights, as well as to identify the attributes that are most relevant and generalizable across different contexts of pressures and environmental gradients. Research on potential riparian conditions at different scales according to river typologies, and morphological and functional riparian vegetation responses to human induced and environmental changes, would be indispensable to scientifically support the proposed attributes. This work represents an innovative approach in this field, but there is still plenty of room for researching and practising, encompassing new emerging paradigms of river science.

Declaration of competing interest

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

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References

Adair, E.C., Binkley, D., 2002. Co-limitation of first year Fremont cottonwood seedlings by nitrogen and water. Wetlands 22 (2), 425–429. https://doi.org/10.1672/0277-5212(2002)022[0425:CLOFYF]2.0.CO;2.

Aguiar, F.C., Ferreira, M.T., Albuquerque, A., Rodríguez-González, P., Segurado, P., 2009. Structural and functional responses of riparian vegetation to human disturbance: performance and spatial scale-dependence. Fundam. Appl. Limnol. 175 (3), 249–267. https://doi.org/10.1127/1863-9135/2009/0175-0249.

Aguiar, F.C., Martins, M.J., Silva, P.C., Fernandes, M.R., 2016. Riverscapes downstream of hydropower dams: effects of altered flows and historical land-use change. Landsc. Urban Plann. 153, 83–98. https://doi.org/10.1016/j.landurbplan.2016.04.009.

Aguiar, F.C., Segurado, P., Martins, M.J., Bejarano, M.D., Nilsson, C., Portela, M.M., Merritt, D., 2018. The abundance and distribution of guilds of riparian woody plants change in response to land use and flow regulation. J. Appl. Ecol. 55, 2227–2240. https://doi.org/10.1111/1365-2664.13110.

Amoros, C., Petts, G.E., 1993. Hydrosystèmes Fluviaux. Masson, Paris.

Arsénio, P., Rodríguez-González, P.M., Bernez, I., Dias, F.S., Bugalho, M.N., Dufour, S., 2020. Riparian vegetation restoration: does social perception reflect ecological value? River Res. Appl. 36 (6), 907–920. https://doi.org/10.1002/rra.3514.

Asaeda, T., Rashid, M.H., Sanjaya, H.L.K., 2015. Flushing sediment from reservoirs triggers forestation in the downstream reaches. Ecohydrology 8 (3), 426–437. https://doi.org/10.1002/eco.1513.

Baattrup-Pedersen, A., Larsen, S.E., Rasmussen, J.J., Riis, T., 2019. The future of European water management: demonstration of a new WFD compliant framework to support sustainable management under multiple stress. Sci. Total Environ. 654, 53–59. https://doi.org/10.1016/j.scitotenv.2018.11.008.

Bätz, N., Colombini, P., Cherubini, P., Lane, S.N., 2016. Groundwater controls on biogeomorphic succession and river channel morphodynamics. J. Geophys. Res.: Earth Surface 121 (10), 1763–1785. https://doi.org/10.1002/2016JF004009.

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. https://doi.org/10.1525/bio.2010.60.3.7.

Bejarano, M.D., González del Tánago, M., García de Jalón, D., Marchamalo, M., Sordo-Ward, Á., Solana-Gutiérrez, J., 2012. Responses of riparian guilds to flow alterations in a Mediterranean stream. J. Veg. Sci. 23 (3), 443–458. https://doi.org/10.1111/j.1654-1103.2011.01360.x.

Bejarano, M.D., Nilsson, C., González del Tánago, M., Marchamalo, M., 2011. Responses of riparian trees and shrubs to flow regulation along a boreal stream in northern Sweden. Freshw. Biol. 56 (5), 853–866. https://doi.org/10.1111/j.1365-2427.2010.02531.x.

Bejarano, M.D., Jansson, R., Nilsson, C., 2018. The effects of hydropeaking on riverine plants: a review. Biol. Rev. 93 (1), 658–673. https://doi.org/10.1111/brv.12362.

Belletti, B., Rinaldi, M., Buijse, A.D., Gurnell, A.M., Mosselman, E., 2015. A review of assessment methods for river hydromorphology. Environ. Earth Sci. 73 (5), 2079–2100. https://doi.org/10.1007/s12665-014-3558-1.

Benda, L., Andras, K., Miller, D., Bigelow, P., 2004. Confluence effects in rivers: interactions of basin scale, network geometry, and disturbance regimes. Water Resour. Res. 40, W05402. https://doi.org/10.1029/2003wr002583.

Benjankar, R., Koenig, F., Tonina, D., 2013. Comparison of hydromorphological assessment methods: application to the Boise river, USA. J. Hidrol. 492, 128–138. https://doi.org/10.1016/j.jhydrol.2013.03.017.

Bertoldi, W., Gurnell, A.M., 2020. Physical engineering of an island-braided river by two riparian tree species: evidence from aerial images and airborne lidar. River Res. Appl. https://doi.org/10.1002/rra.3657.

Bertoldi, W., Gurnell, A.M., Welber, M., 2013. Wood recruitment and retention: the fate of eroded trees on a braided river explored using a combination of field and remotely-sensed data sources. Geomorphology 180–181, 146–155. https://doi.org/10.1016/j.geomorph.2012.10.003.

Bertoldi, W., Welber, M., Gurnell, A.M., Mao, L., Comiti, F., Tal, M., 2015. Physical modelling of the combined effect of vegetation and wood on river morphology. Geomorphology 246, 178–187. https://doi.org/10.1016/j.geomorph.2015.05.038.

Boisjolie, B.A., Santelmann, M.V., Flitcroft, R.L., Duncan, S.L., 2017. Legal ecotones: a comparative analysis of riparian policy protection in the Oregon Coast Range, USA. J. Environ. Manag. 197, 206–220. https://doi.org/10.1016/j.jenvman.2017.03.075.

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. Proc. Natl. Acad. Sci. Unit. States Am. 106 (40), 16936–16941. https://doi.org/10.1073/pnas.0909417106.

Brierley, G., Fryirs, K., Outhet, D., Massey, C., 2002. Application of the river styles framework as a basis for river management in new south Wales, Australia. Appl. Geogr. 22 (1), 91–122. https://doi.org/10.1016/S0143-6228(01)00016-9.

Brierley, G.J., Fryirs, K.A., 2005. Geomorphology and River Management: Applications of the River Styles Framework. Blackwell publishing, Victoria, Australia.

Brooks, S.S., Palmer, M.A., Cardinale, B.J., Swan, C.M., Ribblett, S., 2002. Assessing stream ecosystem rehabilitation: limitations of community structure data. Restor. Ecol. 10 (1), 156–168. https://doi.org/10.1046/j.1526-100X.2002.10117.x.

Bruno, D., Gutiérrez-Cánovas, C., Velasco, J., Sánchez-Fernández, D., 2016. Functional redundancy as a tool for bioassessment: a test using riparian vegetation. Sci. Total Environ. 566–567, 1268–1276. https://doi.org/10.1016/j.scitotenv.2016.05.186.

Camporeale, C., Perucca, E., Ridolfi, L., Gurnell, A.M., 2013. Modeling the interactions between river morphodinamics and riparian vegetation. Rev. Geophys. 51 (3), 379–414. https://doi.org/10.1002/rog.20014.

Carvalho, L., Mackay, E.B., Cardoso, A.C., Baattrup-Pedersen, A., Birk, S., Blackstock, K. L., Borics, G., Borja, A., Feld, C.K., Ferreira, M.T., Globevnik, L., Grizzetti, B., Hendry, S., Hering, D., Kelly, M., Langaas, S., Meissner, K., Panagopoulos, Y., Penning, E., Rouillard, J., Sabater, S., Schmedtje, U., Spears, B.M., Venohr, M., van de Bund, W., Solheim, A.L., 2019. Protecting and restoring Europe's waters: an analysis of the future development needs of the Water Framework Directive. Sci. Total Environ. 658, 1228–1238. https://doi.org/10.1016/j.scitotenv.2018.12.255.

Castro, J.M., Thorne, C.R., 2019. The stream evolution triangle: integrating geology, hydrology, and biology. River Res. Appl. 35 (4), 315–326. https://doi.org/10.1002/rra.3421.

Cole, L.J., Stockan, J., Helliwell, R., 2020. Managing riparian buffer strips to optimise ecosystem services: a review. Agric. Ecosyst. Environ. 296, 106891. https://doi.org/10.1016/j.agee.2020.106891.

Cooper, D.J., Andersen, D.C., Chimner, R.A., 2003. Multiple pathways for woody plant establishment on floodplains at local to regional scales. J. Ecol. 91 (2), 182–196. https://doi.org/10.1046/j.1365-2745.2003.00766.x.

Corenblit, D., Baas, A., Balke, T., Bouma, T., Fromard, F., Garófano-Gómez, V., González, E., Gurnell, A.M., Hortobágyi, B., Julien, F., Kim, D., Lambs, L., Stallins, J. A., Steiger, J., Tabacchi, E., Walcker, R., 2015. Engineer pioneer plants respond to and affect geomorphic constraints similarly along water–terrestrial interfaces world-wide. Global Ecol. Biogeogr. 24 (12), 1363–1376. https://doi.org/10.1111/geb.12373.

Corenblit, D., Baas, A.C.W., 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 Sci. Rev. 106 (3–4), 307–331. https://doi.org/10.1016/j.earscirev.2011.03.002.

Corenblit, D., Steiger, J., Gurnell, A.M., Naiman, R.J., 2009a. Plants intertwine fluvial landform dynamics with ecological succession and natural selection: a niche construction perspective for riparian systems. Global Ecol. Biogeogr. 18 (4), 507–520. https://doi.org/10.1111/j.1466-8238.2009.00461.x.

Corenblit, D., Steiger, J., Gurnell, A.M., Tabacchi, E., Roques, L., 2009b. Control of sediment dynamics by vegetation as a key function driving biogeomorphic succession within fluvial corridors. Earth Surf. Process. Landforms 34 (13), 1790–1810. https://doi.org/10.1002/esp.1876.

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 Sci. Rev. 84 (1–2), 56–86. https://doi.org/10.1016/j.earscirev.2007.05.004.

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 Surf. Process. Landforms 45 (9), 2020–2035. https://doi.org/10.1002/esp.4863.

Charlton, R., 2008. Fundamentals of Fluvial Geomorphology. Routledge, New York.

Chen, A., Wu, M., McClain, M.E., 2020. Classifying dams for environmental flow implementation in China. Sustainability 12 (1), 107. https://doi.org/10.3390/su12010107.

Church, M., 2002. Geomorphic thresholds in riverine landscapes. Freshw. Biol. 47 (4), 541–557. https://doi.org/10.1046/j.1365-2427.2002.00919.x.

Chytrý, M., Otýpková, Z., 2003. Plot sizes used for phytosociological sampling of European vegetation. J. Veg. Sci. 14 (4), 563–570. https://doi.org/10.1111/j.1654-1103.2003.tb02183.x.

de Sosa, L.L., Williams, A.P., Orr, H.G., Jones, D.L., 2018. Riparian research and legislation, are they working towards the same common goals? A UK case study. Environ. Sci. Pol. 82, 126–135. https://doi.org/10.1016/j.envsci.2018.01.023.

Dean, D.J., Schmidt, J.C., 2011. The role of feedback mechanisms in historic channel changes of the lower Rio Grande in the Big Bend region. Geomorphology 126 (3–4), 333–349. https://doi.org/10.1016/j.geomorph.2010.03.009.

Diehl, R.M., Merritt, D.M., Wilcox, A.C., Scott, M.L., 2017. Applying functional traits to ecogeomorphic processes in riparian ecosystems. Bioscience 67 (8), 729–743. https://doi.org/10.1093/biosci/bix080.

Dudgeon, D., Arthington, A.H., Gessner, M.O., Kawabata, Z.-I., Knowler, D.J., Lévêque, C., Naiman, R.J., Prieur-Richard, A.-H., Soto, D., Stiassny, M.L.J., Sullivan, C.A., 2006. Freshwater biodiversity: importance, threats, status and conservation challenges. Biol. Rev. 81 (2), 163–182. https://doi.org/10.1017/s1464793105006950.

Dufour, S., Muller, E., Straatsma, M., Corgne, S., 2012. Image utilisation for the study and management of riparian vegetation: overview and applications. In: Carbonneau, P. E., Piégay, H. (Eds.), Fluvial Remote Sensing for Science and Management. Wiley-Blackwell, Oxford, UK, pp. 215–239. https://doi.org/10.1002/9781119940791.ch10.

Dufour, S., Piégay, H., 2009. From the myth of a lost paradise to targeted river restoration: forget natural references and focus on human benefits. River Res. Appl. 25 (5), 568–581. https://doi.org/10.1002/rra.1239.

Dufour, S., Rinaldi, M., Piégay, H., Michalon, A., 2015. How do river dynamics and human influences affect the landscape pattern of fluvial corridors? Lessons from the Magra River, Central–Northern Italy. Landsc. Urban Plann. 134, 107–118. https://doi.org/10.1016/j.landurbplan.2014.10.007.

Dufour, S., Rodríguez-González, P.M., Laslier, M., 2019. Tracing the scientific trajectory of riparian vegetation studies: main topics, approaches and needs in a globally changing world. Sci. Total Environ. 653, 1168–1185. https://doi.org/10.1016/j.scitotenv.2018.10.383.

Dugdale, S.J., Malcolm, I.A., Kantola, K., Hannah, D.M., 2018. Stream temperature under contrasting riparian forest cover: understanding thermal dynamics and heat exchange processes. Sci. Total Environ. 610–611, 1375–1389. https://doi.org/10.1016/j.scitotenv.2017.08.198.

EC, 2000. Directive 2000/60/EC (water framework directive) of the European commission. Official Journal of the European communities, 22 December 2000.

Fehér, J., Gáspár, J., Veres, K.S., Kiss, A., Kristensen, P., Peterlin, M., Globevnik, L., Kirn, T., Semerádová, S., Künitzer, A., Stein, U., Austnes, K., Spiteri, C., Prins, T., Laukkonen, E., Heiskanen, A.S., 2012. Hydromorphological Alterations and Pressures in European Rivers, Lakes, Transitional and Coastal Waters. Thematic Assessment for EEA Water 2012. Report. European Topic Centre on Inland, Coastal and Marine Waters, Prague, p. 75.

Feld, C.K., Fernandes, M.R., Ferreira, M.T., Hering, D., Ormerod, S.J., Venohr, M., Gutiérrez-Cánovas, C., 2018. Evaluating riparian solutions to multiple stressor problems in river ecosystems — a conceptual study. Water Res. 139, 381–394. https://doi.org/10.1016/j.watres.2018.04.014.

Fernandes, M.R., Aguiar, F.C., Ferreira, M.T., 2011. Assessing riparian vegetation structure and the influence of land use using landscape metrics and geostatistical tools. Landsc. Urban Plann. 99 (2), 166–177. https://doi.org/10.1016/j.landurbplan.2010.11.001.

Fernandes, M.R., Aguiar, F.C., Martins, M.J., Rivaes, R., Ferreira, M.T., 2020. Long-term human-generated alterations of Tagus River: effects of hydrological regulation and land-use changes in distinct river zones. Catena 188, 104466. https://doi.org/10.1016/j.catena.2020.104466.

Fernandes, M.R., Aguiar, F.C., Pereira, J.M., Ferreira, M.T., 2013. Spectral separability of riparian forests from small and medium-sized rivers across a latitudinal gradient using multispectral imagery. Int. J. Rem. Sens. 34 (7), 2375–2401. https://doi.org/10.1080/01431161.2012.744491.

Ferreira, J., Pádua, J., Hughes, S.J., Cortes, R.M., Varandas, S., Holmes, N., Raven, P., 2011. Adapting and adopting River Habitat Survey: problems and solutions for fluvial hydromorphological assessment in Portugal. Limnética 30 (2), 263–272. https://doi.org/10.23818/limn.30.20.

Ferreira, M.T., Aguiar, F.C., Nogueira, C., 2005. Changes in riparian woods over space and time: influence of environment and land use. For. Ecol. Manage. 212 (1–3), 145–159. https://doi.org/10.1016/j.foreco.2005.03.010.

Fierro, P., Bertrán, C., Tapia, J., Hauenstein, E., Peña-Cortés, F., Vergara, C., Cerna, C., Vargas-Chacoff, L., 2017. Effects of local land-use on riparian vegetation, water quality, and the functional organization of macroinvertebrate assemblages. Sci. Total Environ. 609, 724–734. https://doi.org/10.1016/j.scitotenv.2017.07.197.

Friberg, N., 2014. Impacts and indicators of change in lotic ecosystems. Wiley Interdiscip. Rev. Water 1 (6), 513–531. https://doi.org/10.1002/wat2.1040.

Fried, G., Carboni, M., Mahaut, L., Violle, C., 2019. Functional traits modulate plant community responses to alien plant invasion. Perspect. Plant Ecol. Evol. Systemat. 37, 53–63. https://doi.org/10.1016/j.ppees.2019.02.003.

Fryirs, K., Brierley, G.J., 2009. Naturalness and place in river rehabilitation. Ecol. Soc. 14 (1). https://www.jstor.org/stable/26268049.

Fryirs, K., Brierley, G.J., 2013. Geomorphic Analysis of River Systems. An Approach to Reading the Landscape. John Wiley & sons.

Fryirs, K., Brierley, G.J., Erskine, W.D., 2012. Use of ergodic reasoning to reconstruct the historical range of variability and evolutionary trajectory of rivers. Earth Surf. Process. Landforms 37 (7), 763–773. https://doi.org/10.1002/esp.3210.

Fryirs, K.A., Brierley, G.J., Preston, N.J., Kasai, M., 2007. Buffers, barriers and blankets: the (dis)connectivity of catchment-scale sediment cascades. Catena 70 (1), 49–67. https://doi.org/10.1016/j.catena.2006.07.007.

García-Ruiz, J.M., Lana-Renault, N., 2011. Hydrological and erosive consequences of farmland abandonment in Europe, with special reference to the Mediterranean region – a review. Agric. Ecosyst. Environ. 140 (3–4), 317–338. https://doi.org/10.1016/j.agee.2011.01.003.

García de Jalón, D., Martínez-Fernández, V., Fazelpoor, K., González del Tánago, M., 2020. Vegetation encroachment ratios in regulated and non-regulated Mediterranean rivers (Spain): an exploratory overview. J. Hydro-Env. Res. 30, 35–44. https://doi.org/10.1016/j.jher.2019.11.006.

Garófano-Gómez, V., Martínez-Capel, F., Bertoldi, W., Gurnell, A., Estornell, J., Segura-Beltrán, F., 2013. Six decades of changes in the riparian corridor of a Mediterranean river: a synthetic analysis based on historical data sources. Ecohydrology 6 (4), 536–553. https://doi.org/10.1002/eco.1330.

Garófano-Gómez, V., Metz, M., Egger, G., Díaz-Redondo, M., Hortobágyi, B., Geerling, G., Corenblit, D., Steiger, J., 2017. Vegetation succession processes and fluvial dynamics of a mobile temperate riparian ecosystem: the lower river Allier (France). Géomorphologie 23 (3), 187–202. https://doi.org/10.4000/geomorphologie.11805.

Giakoumis, T., Voulvoulis, N., 2019. Water Framework Directive programmes of measures: lessons from the 1st planning cycle of a catchment in England. Sci. Total Environ. 668, 903–916. https://doi.org/10.1016/j.scitotenv.2019.01.405.

Gilvear, D., Willby, N., 2006. Channel dynamics and geomorphic variability as controls on gravel bar vegetation; River Tummel, Scotland. River Res. Appl. 22 (4), 457–474. https://doi.org/10.1002/rra.917.

Gob, F., Bilodeau, C., Thommeret, N., Belliard, J., Albert, M.-B., Tamisier, V., Baudoin, J.-M., Kreutzenberger, K., 2014. Un outil de caractérisation hydromorphologique des cours d'eau pour l'application de la DCE en France (CARHYCE). Géomorphologie 20 (1), 57–72. https://doi.org/10.4000/geomorphologie.10497.

Gomes Marques, I., Campelo, F., Rivaes, R., Albuquerque, A., Ferreira, M.T., Rodríguez-González, P.M., 2018. Tree rings reveal long-term changes in growth resilience in Southern European riparian forests. Dendrochronologia 52, 167–176.

Gómez-Sapiens, M.M., Jarchow, C.J., Flessa, K.W., Shafroth, P.B., Glenn, E.P., Nagler, P. L., 2020. Effect of an environmental flow on vegetation growth and health using ground and remote sensing metrics. Hydrol. Process. 34 (8), 1682–1696. https://doi.org/10.1002/hyp.13689.

González del Tánago, M., Bejarano, M.D., García de Jalón, D., Schmidt, J.C., 2015. Biogeomorphic responses to flow regulation and fine sediment supply in Mediterranean streams (the Guadalete River, southern Spain). J. Hidrol. 528, 751–762. https://doi.org/10.1016/j.jhydrol.2015.06.065.

González del Tánago, M., Gurnell, A.M., Belletti, B., García de Jalón, D., 2016a. Indicators of river system hydromorphological character and dynamics: understanding current conditions and guiding sustainable river management. Aquat. Sci. 78 (1), 35–55. https://doi.org/10.1007/s00027-015-0429-0.

González del Tánago, M., Martínez-Fernández, V., García de Jalón, D., 2016b. Diagnosing problems produced by flow regulation and other disturbances in southern European rivers: the Porma and Curueño rivers (Duero basin, NW Spain). Aquat. Sci. 78 (1), 121–133. https://doi.org/10.1007/s00027-015-0428-1.

González del Tánago, M., Martínez-Fernández, V., García de Jalón, D., Rodríguez-González, P.M., Dufour, S., Garófano-Gómez, V., 2020. Knowledge Conversion for Enhancing Management of European Riparian Ecosystem and Services: Guidance to Implement the Protocol for the Status/pressures Assessment. Report. COST Action CA16208 CONVERGES. Accessible at. https://converges.eu/resources/guidance-to-assess-riparian-vegetation-status-and-pressures. , p. 60.

González, E., Felipe-Lucia, M.R., Bourgeois, B., Boz, B., Nilsson, C., Palmer, G., Sher, A. A., 2017. Integrative conservation of riparian zones. Biol. Conserv. 211, 20–29. https://doi.org/10.1016/j.biocon.2016.10.035.

González, E., Martínez-Fernández, V., Shafroth, P.B., Sher, A.A., Henry, A.L., Garófano-Gómez, V., Corenblit, D., 2018. Regeneration of Salicaceae riparian forests in the Northern Hemisphere: a new framework and management tool. J. Environ. Manag. 218, 374–387. https://doi.org/10.1016/j.jenvman.2018.04.069.

Grabowski, R.C., Gurnell, A.M., 2016. Diagnosing problems of fine sediment delivery and transfer in a lowland catchment. Aquat. Sci. 78 (1), 95–106. https://doi.org/10.1007/s00027-015-0426-3.

Graf, W.L., 2006. Downstream hydrologic and geomorphic effects of large dams on American rivers. Geomorphology 79 (3–4), 336–360. https://doi.org/10.1016/j.geomorph.2006.06.022.

Gran, K.B., Tal, M., Wartman, E.D., 2015. Co-evolution of riparian vegetation and channel dynamics in an aggrading braided river system, Mount Pinatubo, Philippines. Earth Surf. Process. Landforms 40 (8), 1101–1115. https://doi.org/10.1002/esp.3699.

Greet, J.O.E., Webb, A.J., Cousens, R.D., 2011. The importance of seasonal flow timing for riparian vegetation dynamics: a systematic review using causal criteria analysis. Freshw. Biol. 56 (7), 1231–1247. https://doi.org/10.1111/j.1365-2427.2011.02564.x.

Gumiero, B., Rinaldi, M., Belletti, B., Lenzi, D., Puppi, G., 2015. Riparian vegetation as indicator of channel adjustments and environmental conditions: the case of the Panaro River (Northern Italy). Aquat. Sci. 77 (4), 563–582. https://doi.org/10.1007/s00027-015-0403-x.

Gurnell, A., 2014. Plants as river system engineers. Earth Surf. Process. Landforms 39 (1), 4–25. https://doi.org/10.1002/esp.3397.

Gurnell, A.M., Bertoldi, W., 2020. Extending the conceptual model of river island development to incorporate different tree species and environmental conditions. River Res. Appl. 36 (8), 1730–1747. https://doi.org/10.1002/rra.3691.

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 Sci. Rev. 111 (1–2), 129–141. https://doi.org/10.1016/j.earscirev.2011.11.005.

Gurnell, A.M., Corenblit, D., García de Jalón, D., González del Tánago, M., Grabowski, R. C., O'Hare, M.T., Szewczyk, M., 2016b. A conceptual model of vegetation–hydrogeomorphology interactions within river corridors. River Res. Appl. 32 (2), 142–163. https://doi.org/10.1002/rra.2928.

Gurnell, A., Morrissey, I., Boitsidis, A., Bark, T., Clifford, N., Petts, G., Thompson, K., 2006. Initial adjustments within a new river channel: interactions between fluvial processes, colonizing vegetation, and bank profile development. Environ. Manag. 38 (4), 580–596. https://doi.org/10.1007/s00267-005-0190-6.

Gurnell, A.M., Petts, G.E., 2002. Island-dominated landscapes of large floodplain rivers, a European perspective. Freshw. Biol. 47 (4), 581–600. https://doi.org/10.1046/j.1365-2427.2002.00923.x.

Gurnell, A.M., Petts, G.E., Hannah, D.M., Smith, B.P.G., Edwards, P.J., Kollmann, J., Ward, J.V., Tockner, K., 2001. Riparian vegetation and island formation along the gravel-bed Fiume Tagliamento, Italy. Earth Surf. Process. Landforms 26 (1), 31–62. https://doi.org/10.1002/1096-9837(200101)26:1<31::aid-esp155>3.0.co;2-y.

Gurnell, A.M., Piégay, H., Swanson, F.J., Gregory, S.V., 2002. Large wood and fluvial processes. Freshw. Biol. 47 (4), 601–619. https://doi.org/10.1046/j.1365-2427.2002.00916.x.

Gurnell, A.M., Rinaldi, M., Belletti, B., Bizzi, S., Blamauer, B., Braca, G., Buijse, A.D., Bussettini, M., Camenen, B., Comiti, F., Demarchi, L., García de Jalón, D., González del Tánago, M., Grabowski, R.C., Gunn, I.D.M., Habersack, H., Hendriks, D., Henshaw, A.J., Klösch, M., Lastoria, B., Latapie, A., Marcinkowski, P., Martínez-Fernández, V., Mosselman, E., Mountford, J.O., Nardi, L., Okruszko, T., O'Hare, M. T., Palma, M., Percopo, C., Surian, N., van de Bund, W., Weissteiner, C., Ziliani, L., 2016a. A multi-scale hierarchical framework for developing understanding of river behaviour to support river management. Aquat. Sci. 78 (1), 1–16. https://doi.org/10.1007/s00027-015-0424-5.

Gurnell, A., Tockner, K., Edwards, P., Petts, G., 2005. Effects of deposited wood on biocomplexity of river corridors. Front. Ecol. Environ. 3 (7), 377–382. https://doi.org/10.1890/1540-9295(2005)003[0377:eodwob]2.0.co;2.

Habersack, H.M., 2000. The river-scaling concept (RSC): a basis for ecological assessments. Hydrobiologia 422/423, 49–60. https://doi.org/10.1007/978-94-011-4164-2_4.

Han, M., Brierley, G., 2020. Channel geomorphology and riparian vegetation interactions along four anabranching reaches of the Upper Yellow River. Prog. Phys. Geogr. https://doi.org/10.1177/0309133320938768.

Hicks, D.M., Duncan, M.J., Lane, S.N., Tal, M., Westaway, R., 2007. Contemporary morphological change in braided gravel-bed rivers: new developments from field and laboratory studies, with particular reference to the influence of riparian vegetation. Ch. 21. In: Habersack, H., Piégay, H., Rinaldi, M. (Eds.), Developments in Earth Surface Processes. Gravel-Bed Rivers VI: from Process Understanding to River Restoration. Elsevier, pp. 557–584. https://doi.org/10.1016/S0928-2025(07)11143-3.

Horne, A.C., Webb, J.A., O'Donnell, E., Arthington, A.H., McClain, M., Bond, N., Acreman, M., Hart, B., Stewardson, M.J., Richter, B., Poff, N.L., 2017. Research priorities to improve future environmental water outcomes. Front. Environ. Sci. 5, 89. https://doi.org/10.3389/fenvs.2017.00089.

Hough-Snee, N., Laub, B.G., Merritt, D.M., Long, A.L., Nackley, L.L., Roper, B.B., Wheaton, J.M., 2015a. Multi-scale environmental filters and niche partitioning govern the distributions of riparian vegetation guilds. Ecosphere 6 (10), art173. https://doi.org/10.1890/es15-00064.1.

Hough-Snee, N., Roper, B.B., Wheaton, J.M., Lokteff, R.L., 2015b. Riparian vegetation communities of the American Pacific Northwest are tied to multi-scale environmental filters. River Res. Appl. 31 (9), 1151–1165. https://doi.org/10.1002/rra.2815.

Hughes, F.M.R., 2003. The Flooded Forest: Guidance for Policy Makers and River Managers in Europe on the Restoration of Floodplain Forests. FLOBAR2. Department of Geography, University of Cambridge, Cambridge, UK, p. 96.

Hughes, F.M.R., Colston, A., Mountford, J.O., 2005. Restoring riparian ecosystems: the challenge of accommodating variability and designing restoration trajectories. Ecol. Soc. 10 (1). http://www.ecologyandsociety.org/vol10/iss1/art12/.

Hughes, F.M.R., González del Tánago, M., Mountford, J.O., 2012. Restoring floodplain forests in Europe. In: Stanturf, J., Madsen, P., Lamb, D. (Eds.), A Goal-Oriented Approach to Forest Landscape Restoration. Springer Netherlands, Dordrecht, pp. 393–422. https://doi.org/10.1007/978-94-007-5338-9_15.

Huylenbroeck, L., Laslier, M., Dufour, S., Georges, B., Lejeune, P., Michez, A., 2020. Using remote sensing to characterize riparian vegetation: a review of available tools and perspectives for managers. J. Environ. Manag. 267, 110652. https://doi.org/10.1016/j.jenvman.2020.110652.

Huylenbroeck, L., Latte, N., Lejeune, P., Georges, B., Claessens, H., Michez, A., 2021. What factors shape spatial distribution of biomass in riparian forests? Insights from a LiDAR survey over a large area. Forests 12, 371. https://doi.org/10.3390/f12030371.

Hynes, H.B.N., 1975. The stream and its valley. Internationale Vereinigung für Theoretische und Angewandte Limnologie: Verh Proc. Trav. SIL 19 (1), 1–15. https://doi.org/10.1080/03680770.1974.11896033.

Illies, J., Botosaneanu, L., 1963. Problèmes et méthodes de la classification et de la zonation écologique des eaux courantes, considerées surtout du point de vue faunistique. Internationale Vereinigung für Theoretische und Angewandte Limnologie: Mitteilungen 12 (1), 1–57. https://doi.org/10.1080/05384680.1963.11903811.

Ioana-Toroimac, G., Zaharia, L., Minea, G., Moroşanu, G.A., 2017. Using a multi-criteria analysis to identify rivers with hydromorphological restoration priority: braided rivers in the south-eastern Subcarpathians (Romania). Sci. Total Environ. 599–600, 700–709. https://doi.org/10.1016/j.scitotenv.2017.04.209.

Janssen, P., Piégay, H., Evette, A., 2020. Fine-grained sediment deposition alters the response of plant CSR strategies on the gravel bars of a highly regulated river. Appl. Veg. Sci. 23 (3), 452–463. https://doi.org/10.1111/avsc.12494.

Janssen, P., Stella, J.C., Räpple, B., Gruel, C.R., Seignemartin, G., Pont, B., Dufour, S., Piégay, H., 2021. Long-term river management legacies strongly alter riparian forest attributes and constrain restoration strategies along a large, multi-use river. J. Environ. Manag. 279, 111630. https://doi.org/10.1016/j.jenvman.2020.111630.

Johnson, S.L., Jones, J.A., 2000. Stream temperature responses to forest harvest and debris flows in western Cascades, Oregon. Can. J. Fish. Aquat. Sci. 57 (S2), 30–39. https://doi.org/10.1139/f00-109.

Johnson, W.C., 2000. Tree recruitment and survival in rivers: influence of hydrological processes. Hydrol. Process. 14, 3051–3074. https://doi.org/10.1002/1099-1085(200011/12)14:16/17<3051::AID-HYP134>3.0.CO;2-1.

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 Res. Appl. 36, 3–12. https://doi.org/10.1002/rra.3529.

Jones, C.G., Lawton, J.H., Shachak, M., 1994. Organisms as ecosystem engineers. Oikos 69 (3), 373–386. https://doi.org/10.2307/3545850.

Junk, W.J., Bayley, P.B., Sparks, R.E., 1989. The flood pulse concept in river-floodplain systems. Can. J. Fish. Aquat. Sci. 106 (1), 110–127.

Kail, J., Wolter, C., 2011. Analysis and evaluation of large-scale river restoration planning in Germany to better link river research and management. River Res. Appl. 27 (8), 985–999. https://doi.org/10.1002/rra.1382.

Karr, J.R., Fausch, K.D., Angermeier, P.L., Yant, P.R., Schlosser, I.J., 1986. Assessing Biological Integrity in Running Waters: A Method and its Rationale. Special Publication 5. Illinois Natural History Survey, Champaign, Illinois, USA, p. 28.

Karrenberg, S., Edwards, P.J., Kollmann, J., 2002. The life history of Salicaceae living in the active zone of floodplains. Freshw. Biol. 47 (4), 733–748. https://doi.org/10.1046/j.1365-2427.2002.00894.x.

Kiss, T., Nagy, J., Fehérváry, I., Vaszkó, C., 2019. (Mis) management of floodplain vegetation: the effect of invasive species on vegetation roughness and flood levels. Sci. Total Environ. 686, 931–945. https://doi.org/10.1016/j.scitotenv.2019.06.006.

Klösch, M., Habersack, H., 2017. The hydromorphological evaluation tool (HYMET). Geomorphology 291, 143–158. https://doi.org/10.1016/j.geomorph.2016.06.005.

Knighton, D., 1984. Fluvial Forms and Processes. Edward Arnold. Inc., New York.

Kristensen, P., Whalley, C., Klančnik, K., 2018. European Waters: Assessment of Status and Pressures 2018. European Environment Agency.

Kui, L., Stella, J.C., Shafroth, P.B., House, P.K., Wilcox, A.C., 2017. The long-term legacy of geomorphic and riparian vegetation feedbacks on the dammed Bill Williams River, Arizona, USA. Ecohydrology 10 (4), e1839. https://doi.org/10.1002/eco.1839.

Kujanová, K., Matoušková, M., Hošek, Z., 2018. The relationship between river types and land cover in riparian zones. Limnologica 71, 29–43. https://doi.org/10.1016/j.limno.2018.05.002.

Kyle, G., Leishman, M.R., 2009. Plant functional trait variation in relation to riparian geomorphology: the importance of disturbance. Austral Ecol. 34 (7), 793–804. https://doi.org/10.1111/j.1442-9993.2009.01988.x.

Langhans, S.D., Lienert, J., Schuwirth, N., Reichert, P., 2013. How to make river assessments comparable: a demonstration for hydromorphology. Ecol. Indicat. 32, 264–275. https://doi.org/10.1016/j.ecolind.2013.03.027.

Lemm, J.U., Feld, C.K., Birk, S., 2019. Diagnosing the causes of river deterioration using stressor-specific metrics. Sci. Total Environ. 651, 1105–1113. https://doi.org/10.1016/j.scitotenv.2018.09.157.

Leopold, L.B., Wolman, M.G., Miller, J.P., 1964. Fluvial Processes in Geomorphology. W. H. Freeman and Company, San Francisco, USA.

Leyer, I., Pross, S., 2009. Do seed and germination traits determine plant distribution patterns in riparian landscapes? Basic Appl. Ecol. 10 (2), 113–121. https://doi.org/10.1016/j.baae.2008.01.002.

Liébault, F., Piégay, H., 2002. Causes of 20th century channel narrowing in mountain and piedmont rivers of southeastern France. Earth Surf. Process. Landforms 27 (4), 425–444. https://doi.org/10.1002/esp.328.

Lind, L., Hasselquist, E.M., Laudon, H., 2019. Towards ecologically functional riparian zones: a meta-analysis to develop guidelines for protecting ecosystem functions and biodiversity in agricultural landscapes. J. Environ. Manag. 249, 109391. https://doi.org/10.1016/j.jenvman.2019.109391.

Liu, Y., Zhu, J., Li, E.Y., Meng, Z., Song, Y., 2020. Environmental regulation, green technological innovation, and eco-efficiency: the case of Yangtze river economic belt in China. Technol. Forecast. Soc. Change 155, 119993. https://doi.org/10.1016/j.techfore.2020.119993.

Lozanovska, I., Bejarano, M.D., Martins, M.J., Nilsson, C., Ferreira, M.T., Aguiar, F.C., 2020. Functional diversity of riparian woody vegetation is less affected by river regulation in the mediterranean than boreal region. Front. Plant Sci. 11, 857. https://doi.org/10.3389/fpls.2020.00857.

Lozanovska, I., Ferreira, M.T., Aguiar, F.C., 2018. Functional diversity assessment in riparian forests – multiple approaches and trends: a review. Ecol. Indicat. 95, 781–793. https://doi.org/10.1016/j.ecolind.2018.08.039.

Lytle, D.A., Merritt, D.M., Tonkin, J.D., Olden, J.D., Reynolds, L.V., 2017. Linking river flow regimes to riparian plant guilds: a community-wide modeling approach. Ecol. Appl. 27 (4), 1338–1350. https://doi.org/10.1002/eap.1528.

Macfarlane, W.W., Gilbert, J.T., Jensen, M.L., Gilbert, J.D., Hough-Snee, N., McHugh, P. A., Wheaton, J.M., Bennett, S.N., 2017. Riparian vegetation as an indicator of riparian condition: detecting departures from historic condition across the North American West. J. Environ. Manag. 202, 447–460. https://doi.org/10.1016/j.jenvman.2016.10.054.

Mahoney, J.M., Rood, S.B., 1998. Streamflow requirements for cottonwood seedling recruitment – an integrative model. Wetlands 18 (4), 634–645. https://doi.org/10.1007/BF03161678.

Malanson, G.P., 1993. Riparian Landscapes. Cambridge University Press, Cambridge, UK.

Manning, A., Julian, J.P., Doyle, M.W., 2020. Riparian vegetation as an indicator of stream channel presence and connectivity in arid environments. J. Arid Environ. 178, 104167. https://doi.org/10.1016/j.jaridenv.2020.104167.

Martínez-Fernández, V., González del Tánago, M., García de Jalón, D., 2017b. Using a conceptual model to assess the status and temporal changes of riparian corridors. Geophys. Res. Abstr. 19. EGU2017-12386, EGU General Assembly 2017.
Martínez-Fernández, V., González del Tánago, M., García de Jalón, D., 2016. The use of stream power as an indicator of geomorphological processes. In: Durán Valsero, J.J., Montes Santiago, M., Robador Moreno, A., Salazar Rincón, A. (Eds.), Comprendiendo el relieve: del pasado al futuro. Instituto Geológico y Minero de España, Madrid, pp. 357–364.
Martínez-Fernández, V., González del Tánago, M., Maroto, J., García de Jalón, D., 2017a. Fluvial corridor changes over time in regulated and non-regulated rivers (upper Esla River, NW Spain). River Res. Appl. 33 (2), 214–223. https://doi.org/10.1002/rra.3032.
Martínez-Fernández, V., Van Oorschot, M., De Smit, J., González del Tánago, M., Buijse, A.D., 2018. Modelling feedbacks between geomorphological and riparian vegetation responses under climate change in a Mediterranean context. Earth Surf. Process. Landforms 43 (9), 1825–1835. https://doi.org/10.1002/esp.4356.
Merritt, D.M., Cooper, D.J., 2000. Riparian vegetation and channel change response to river regulation: a comparative study of regulated and unregulated streams in the Green River Basin, USA. Regul. Rivers Res. Manag. 16 (6), 543–564. https://doi.org/10.1002/1099-1646(200011/12)16:6<543::AID-RRR590>3.0.CO;2-N.
Merritt, D.M., Scott, M.L., Poff, N.L., Auble, G.T., Lytle, D.A., 2010. Theory, methods and tools for determining environmental flows for riparian vegetation: riparian vegetation-flow response guilds. Freshw. Biol. 55 (1), 206–225. https://doi.org/10.1111/j.1365-2427.2009.02206.x.
Merritt, D.M., Wohl, E.E., 2002. Processes governing hydrochory along rivers: hydraulics, hydrology, and dispersal phenology. Ecol. Appl. 12 (4), 1071–1087. https://doi.org/10.1890/1051-0761(2002)012[1071:pgharh]2.0.co;2.
Meybeck, M., 2003. Global analysis of river systems: from Earth system controls to Anthropocene syndromes. Philos. Trans. R. Soc. B 358 (1440), 1935–1955. https://doi.org/10.1098/rstb.2003.1379.
Michez, A., Piégay, H., Lejeune, P., Claessens, H., 2017. Multi-temporal monitoring of a regional riparian buffer network (>12,000 km) with LiDAR and photogrammetric point clouds. J. Environ. Manag. 202, 424–436. https://doi.org/10.1016/j.jenvman.2017.02.034.
Montgomery, D.R., 1999. Process domains and the river continuum. J. Am. Water Resour. Assoc. 35 (2), 397–410. https://doi.org/10.1111/j.1752-1688.1999.tb03598.x.
Nagler, P.L., Barreto-Muñoz, A., Chavoshi Borujeni, S., Jarchow, C.J., Gómez-Sapiens, M. M., Nouri, H., Herrmann, S.M., Didan, K., 2020. Ecohydrological responses to surface flow across borders: two decades of changes in vegetation greenness and water use in the riparian corridor of the Colorado River delta. Hydrol. Process. 34 (25), 4851–4883. https://doi.org/10.1002/hyp.13911.
Nagler, P., Glenn, E.P., Hursh, K., Curtis, C., Huete, A., 2005. Vegetation mapping for change detection on an arid-zone river. Environ. Monit. Assess. 109 (1), 255–274. https://doi.org/10.1007/s10661-005-6285-y.
Nagler, P.L., Glenn, E.P., Thompson, T.L., Huete, A., 2004. Leaf area index and normalized difference vegetation index as predictors of canopy characteristics and light interception by riparian species on the Lower Colorado River. Agric. For. Meteorol. 125 (1–2), 1–17. https://doi.org/10.1016/j.agrformet.2004.03.008.
Naiman, R.J., Décamps, H., McClain, M.E., 2005. Riparia – Ecology, Conservation and Management of Streamside Communities. Elsevier Academic Press, Oxford, UK.
Newaz, M.S., Mallik, A.U., Mackereth, R.W., 2019. Riparian vegetation recovery in a 23 year chronosequence of clear-cuts along boreal headwater streams. For. Ecol. Manage. 443, 69–83. https://doi.org/10.1016/j.foreco.2019.04.010.
NRC, 2002. Riparian Areas: Functions and Strategies for Management. National Academies Press, Washington, DC.
O'Briain, R., 2019. Climate change and European rivers: an eco-hydromorphological perspective. Ecohydrology 12 (5), e2099. https://doi.org/10.1002/eco.2099.
Ochs, K., Egger, G., Weber, A., Ferreira, T., Householder, J.E., Schneider, M., 2020. The potential natural vegetation of large river floodplains – from dynamic to static equilibrium. J. Hydro-Env. Res. 30, 71–81. https://doi.org/10.1016/j.jher.2020.01.005.
Ochs, K., Rivaes, R.P., Ferreira, T., Egger, G., 2018. Flow management to control excessive growth of macrophytes – an assessment based on habitat suitability modelling. Front. Plant Sci. 9, 356. https://doi.org/10.3389/fpls.2018.00356.
O'Hare, M.T., Mountford, J.O., Maroto, J., Gunn, I.D.M., 2016. Plant traits relevant to fluvial geomorphology and hydrological interactions. River Res. Appl. 24, 941–959.
Palmquist, E.C., Ralston, B.E., Merritt, D.M., Shafroth, P.B., 2018. Landscape-scale processes influence riparian plant composition along a regulated river. J. Arid Environ. 148, 54–64. https://doi.org/10.1016/j.jaridenv.2017.10.001.
Piégay, H., Gurnell, A.M., 1997. Large woody debris and river geomorphological pattern: examples from S.E. France and S. England. Geomorphology 19 (1–2), 99–116. https://doi.org/10.1016/S0169-555X(96)00045-1.
Pike, A.S., Scatena, F.N., 2010. Riparian indicators of flow frequency in a tropical montane stream network. J. Hidrol. 382 (1), 72–87. https://doi.org/10.1016/j.jhydrol.2009.12.019.
Poff, B., Koestner, K.A., Neary, D.G., Henderson, V., 2011. Threats to riparian ecosystems in Western North America: an analysis of existing literature. J. Am. Water Resour. Assoc. 47 (6), 1241–1254. https://doi.org/10.1111/j.1752-1688.2011.00571.x.
Poff, N.L., 1997. Landscape filters and species traits: towards mechanistic understanding and prediction in stream ecology. J. North Am. Benthol. Soc. 16 (2), 391–409. https://doi.org/10.2307/1468026.
Poff, N.L., Allan, J.D., Bain, M.B., Karr, J.R., Prestegaard, K.L., Richter, B.D., Sparks, R.E., Stromberg, J.C., 1997. The natural flow regime: a paradigm for river conservation and management. Bioscience 47 (11), 769–784. https://doi.org/10.2307/1313099.
Poff, N.L., Olden, J.D., Merritt, D.M., Pepin, D.M., 2007. Homogenization of regional river dynamics by dams and global biodiversity implications. Proc. Natl. Acad. Sci. U.S.A. 104 (14), 5732–5737. https://doi.org/10.1073/pnas.0609812104.
Politti, E., Bertoldi, W., Gurnell, A., Henshaw, A., 2018. Feedbacks between the riparian Salicaceae and hydrogeomorphic processes: a quantitative review. Earth Sci. Rev. 176, 147–165. https://doi.org/10.1016/j.earscirev.2017.07.018.
Politti, E., Egger, G., Angermann, K., Rivaes, R., Blamauer, B., Klösch, M., Tritthart, M., Habersack, H., 2014. Evaluating climate change impacts on Alpine floodplain vegetation. Hydrobiologia 737 (1), 225–243. https://doi.org/10.1007/s10750-013-1801-5.
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. J. Environ. Manag. 265, 110288. https://doi.org/10.1016/j.jenvman.2020.110288.
Pont, D., Piégay, H., Farinetti, A., Allain, S., Landon, N., Liébault, F., Dumont, B., Richard-Mazet, A., 2009. Conceptual framework and interdisciplinary approach for the sustainable management of gravel-bed rivers: the case of the Drôme River basin (S. E. France). Aquat. Sci. 71, 356–370. https://doi.org/10.1007/s00027-009-9201-7.
Qiao, L., Zou, C.B., Stebler, E., Will, R.E., 2017. Woody plant encroachment reduces annual runoff and shifts runoff mechanisms in the tallgrass prairie, USA. Water Resour. Res. 53 (6), 4838–4849. https://doi.org/10.1002/2016wr019951.
Radinger, J., Hölker, F., Horký, P., Slavík, O., Wolter, C., 2018. Improved river continuity facilitates fishes' abilities to track future environmental changes. J. Environ. Manag. 208, 169–179. https://doi.org/10.1016/j.jenvman.2017.12.011.
Räpple, B., Piégay, H., Stella, J.C., Mercier, D., 2017. What drives riparian vegetation encroachment in braided river channels at patch to reach scales? Insights from annual airborne surveys (Drôme River, SE France, 2005–2011). Ecohydrology 10 (8), e1886. https://doi.org/10.1002/eco.1886.
Raven, P.J., Holmes, N.T.H., Charrier, P., Dawson, F.H., Naura, M., Boon, P.J., 2002. Towards a harmonized approach for hydromorphological assessment of rivers in Europe: a qualitative comparison of three survey methods. Aquat. Conserv. Mar. Freshw. Ecosyst. 12 (4), 405–424. https://doi.org/10.1002/aqc.536.
Raven, P.J., Holmes, N.T.H., Dawson, F.H., Everard, M., 1998. Quality assessment using river habitat survey data. Aquat. Conserv. Mar. Freshw. Ecosyst. 8 (4), 477–499. https://doi.org/10.1002/(sici)1099-0755(199807/08)8:4<477::aid-aqc299>3.0.co;2-k.
Reid, D.J., Quinn, J.M., Wright-Stow, A.E., 2010. Responses of stream macroinvertebrate communities to progressive forest harvesting: influences of harvest intensity, stream size and riparian buffers. For. Ecol. Manage. 260 (10), 1804–1815. https://doi.org/10.1016/j.foreco.2010.08.025.
Reid, H.E., Brierley, G.J., McFarlane, K., Coleman, S.E., Trowsdale, S., 2013. The role of landscape setting in minimizing hydrogeomorphic impacts of flow regulation. Int. J. Sediment Res. 28 (2), 149–161. https://doi.org/10.1016/S1001-6279(13)60027-X.
Richards, K., Brasington, J., Hughes, F., 2002. Geomorphic dynamics of floodplains: ecological implications and a potential modelling strategy. Freshw. Biol. 47, 559–579. https://doi.org/10.1046/j.1365-2427.2002.00920.x.
Richter, B.D., Baumgartner, J.V., Powell, J., Braun, D., 1996. A method for assessing hydrologic alteration within ecosystems. Conserv. Biol. 10 (4), 1163–1174. https://doi.org/10.1046/j.1523-1739.1996.10041163.x.
Ricklefs, R.E., Jenkins, D.G., 2011. Biogeography and ecology: towards the integration of two disciplines. Philos. Trans. R. Soc. B 366, 2438–2448. https://doi.org/10.1098/rstb.2011.0066.
Riis, T., Kelly-Quinn, M., Aguiar, F.C., Paraskevi, M., Bruno, D., Bejarano, M.D., Clerici, N., Fernandes, M.R., Franco, J.C., Pettit, N., Portela, A.P., Tammeorg, O., Tammeorg, P., Rodríguez-González, P.M., Dufour, S., 2020. Global overview of ecosystem services provided by riparian vegetation. Bioscience 70 (6), 501–514. https://doi.org/10.1093/biosci/biaa041.
Rinaldi, M., Gurnell, A.M., González del Tánago, M., Bussettini, M., Hendriks, D., 2016. Classification of river morphology and hydrology to support management and restoration. Aquat. Sci. 78 (1), 17–33. https://doi.org/10.1007/s00027-015-0438-z.
Rinaldi, M., Surian, N., Comiti, F., Bussettini, M., 2013. A method for the assessment and analysis of the hydromorphological condition of Italian streams: the Morphological Quality Index (MQI). Geomorphology 180–181, 96–108. https://doi.org/10.1016/j.geomorph.2012.09.009.
Rinaldi, M., Surian, N., Comiti, F., Bussettini, M., 2015. A methodological framework for hydromorphological assessment, analysis and monitoring (IDRAIM) aimed at promoting integrated river management. Geomorphology 251, 122–136. https://doi.org/10.1016/j.geomorph.2015.05.010.
Ringold, P.L., Van Sickle, J., Bollman, M., Welty, J., Barker, J., 2009. Riparian forest indicators of potential future stream condition. Ecol. Indicat. 9 (3), 462–475. https://doi.org/10.1016/j.ecolind.2008.06.009.
Rivaes, R., Rodríguez-González, P.M., Albuquerque, A., Pinheiro, A.N., Egger, G., Ferreira, M.T., 2013. Riparian vegetation responses to altered flow regimes driven by climate change in Mediterranean rivers. Ecohydrology 6 (3), 413–424. https://doi.org/10.1002/eco.1287.
Rivaes, R.P., Rodríguez-González, P.M., Ferreira, M.T., Pinheiro, A.N., Politti, E., Egger, G., García-Arias, A., Francés, F., 2014. Modelling the evolution of riparian woodlands facing climate change in three European rivers with contrasting flow regimes. PloS One 9 (10), e110200. https://doi.org/10.1371/journal.pone.0110200.
Rodríguez-González, P.M., Albuquerque, A., Martínez-Almarza, M., Díaz-Delgado, R., 2017. Long-term monitoring for conservation management: lessons from a case study integrating remote sensing and field approaches in floodplain forests. J. Environ. Manag. 202, 392–402. https://doi.org/10.1016/j.jenvman.2017.01.067.
Rodríguez-González, P.M., Colangelo, M., Sánchez-Miranda, Á., Sánchez-Salguero, R., Campelo, F., Rita, A., Gomes Marques, I., Albuquerque, A., Ripullone, F.,

Camarero, J.J., 2021. Climate, drought and hydrology drive narrow-leaved ash growth dynamics in southern European riparian forests. For. Ecol. Manage. 490, 119128. https://doi.org/10.1016/j.foreco.2021.119128.
Roni, P., Beechie, T., 2013. Introduction to restoration: key steps for designing effective programs and projects. In: Roni, P., Beechie, T. (Eds.), Stream and Watershed Restoration: A Guide to Restoring Riverine Processes and Habitats. John Wiley & Sons, Ltd.
Rood, S.B., Braatne, J.H., Hughes, F.M., 2003. Ecophysiology of riparian cottonwoods: stream flow dependency, water relations and restoration. Tree Physiol. 23 (16), 1113–1124. https://doi.org/10.1093/treephys/23.16.1113.
Rood, S.B., Samuelson, G.M., Braatne, J.H., Gourley, C.R., Hughes, F.M.R., Mahoney, J. M., 2005. Managing river flows to restore floodplain forests. Front. Ecol. Environ. 3 (4), 193–201. https://doi.org/10.1890/1540-9295(2005)003[0193:MRFTRF]2.0.CO;2.
Rosgen, D.L., 1994. A classification of natural rivers. Catena 22 (3), 169–199. https://doi.org/10.1016/0341-8162(94)90001-9.
Rowiński, P.M., Västilä, K., Aberle, J., Järvelä, J., Kalinowska, M.B., 2018. How vegetation can aid in coping with river management challenges: a brief review. Ecohydrol. Hydrobiol. 18 (4), 345–354. https://doi.org/10.1016/j.ecohyd.2018.07.003.
Salinas, M.J., Blanca, G., Romero, A.T., 2000. Riparian vegetation and water chemistry in a basin under semiarid Mediterranean climate, Andarax River, Spain. Environ. Manag. 26 (5), 539–552. https://doi.org/10.1007/s002670010111.
Sanchis-Ibor, C., Segura-Beltrán, F., Navarro-Gómez, A., 2019. Channel forms and vegetation adjustment to damming in a Mediterranean gravel-bed river (Serpis River, Spain). River Res. Appl. 35, 37–47. https://doi.org/10.1002/rra.3381.
Santos, M.J., 2010. Encroachment of upland Mediterranean plant species in riparian ecosystems of southern Portugal. Biodivers. Conserv. 19 (9), 2667–2684. https://doi.org/10.1007/s10531-010-9866-1.
Schneider, C., Flörke, M., De Stefano, L., Petersen-Perlman, J.D., 2017. Hydrological threats to riparian wetlands of international importance – a global quantitative and qualitative analysis. Hydrol. Earth Syst. Sci. 21, 2799–2815. https://doi.org/10.5194/hess-21-2799-2017.
Schumm, S.A., 1977. The Fluvial System. John Wiley and Sons, New York, USA.
Serlet, A.J., Gurnell, A.M., Zolezzi, G., Wharton, G., Belleudy, P., Jourdain, C., 2018. Biomorphodynamics of alternate bars in a channelized, regulated river: an integrated historical and modelling analysis. Earth Surf. Process. Landforms 43 (9), 1739–1756. https://doi.org/10.1002/esp.4349.
Sievers, M., Hale, R., Morrongiello, J.R., 2017. Do trout respond to riparian change? A meta-analysis with implications for restoration and management. Freshw. Biol. 62 (3), 445–457. https://doi.org/10.1111/fwb.12888.
Singh, R., Singh, G.S., 2020. Integrated management of the Ganga River: an ecohydrological approach. Ecohydrol. Hydrobiol. 20 (2), 153–174. https://doi.org/10.1016/j.ecohyd.2019.10.007.
Skoulikidis, N.T., Sabater, S., Datry, T., Morais, M.M., Buffagni, A., Dörflinger, G., Zogaris, S., del Mar Sánchez-Montoya, M., Bonada, N., Kalogianni, E., Rosado, J., Vardakas, L., De Girolamo, A.M., Tockner, K., 2017. Non-perennial Mediterranean rivers in Europe: status, pressures, and challenges for research and management. Sci. Total Environ. 577, 1–18. https://doi.org/10.1016/j.scitotenv.2016.10.147.
Smith, M.J., Kay, W.R., Edward, D.H.D., Papas, P.J., Richardson, K.S.J., Simpson, J.C., Pinder, A.M., Cale, D.J., Horwitz, P.H.J., Davis, J.A., Yung, F.H., Norris, R.H., Halse, S.A., 1999. AusRivAS: using macroinvertebrates to assess ecological condition of rivers in Western Australia. Freshw. Biol. 41 (2), 269–282. https://doi.org/10.1046/j.1365-2427.1999.00430.x.
Stecca, G., Zolezzi, G., Hicks, D.M., Surian, N., 2019. Reduced braiding of rivers in human-modified landscapes: converging trajectories and diversity of causes. Earth Sci. Rev. 188, 291–311. https://doi.org/10.1016/j.earscirev.2018.10.016.
Steiger, J., Tabacchi, E., Dufour, S., Corenblit, D., Peiry, J.L., 2005. Hydrogeomorphic processes affecting riparian habitat within alluvial channel–floodplain river systems: a review for the temperate zone. River Res. Appl. 21 (7), 719–737. https://doi.org/10.1002/rra.879.
Stella, J.C., Bendix, J., 2019. Multiple stressors in riparian ecosystems, 2018. In: Sabater, S., Elosegi, A., Ludwig, R. (Eds.), Multiple Stressors in River Ecosystems: Status, Impacts and Prospects for the Future. Elsevier, pp. 81–110. https://doi.org/10.1016/B978-0-12-811713-2.00005-4. Chapter 5.
Stella, J.C., Riddle, J., Piégay, H., Gagnage, M., Trémélo, M.-L., 2013a. Climate and local geomorphic interactions drive patterns of riparian forest decline along a Mediterranean Basin river. Geomorphology 202, 101–114. https://doi.org/10.1016/j.geomorph.2013.01.013.
Stella, J.C., Rodríguez-González, P.M., Dufour, S., Bendix, J., 2013b. Riparian vegetation research in Mediterranean-climate regions: common patterns, ecological processes, and considerations for management. Hydrobiologia 719 (1), 291–315. https://doi.org/10.1007/s10750-012-1304-9.
Stromberg, J.C., Beauchamp, V.B., Dixon, M.D., Lite, S.J., Paradzick, C., 2007. Importance of low-flow and high-flow characteristics to restoration of riparian vegetation along rivers in arid south-western United States. Freshw. Biol. 52 (4), 651–679. https://doi.org/10.1111/j.1365-2427.2006.01713.x.
Stromberg, J.C., Merritt, D.M., 2016. Riparian plant guilds of ephemeral, intermittent and perennial rivers. Freshw. Biol. 61 (8), 1259–1275. https://doi.org/10.1111/fwb.12686.
Surian, N., Barban, M., Ziliani, L., Monegato, G., Bertoldi, W., Comiti, F., 2015. Vegetation turnover in a braided river: frequency and effectiveness of floods of different magnitude. Earth Surf. Process. Landforms 40 (4), 542–558. https://doi.org/10.1002/esp.3660.
Takahashi, M., Nakamura, F., 2011. Impacts of dam-regulated flows on channel morphology and riparian vegetation: a longitudinal analysis of Satsunai River, Japan. Lands. Ecol. Eng. 7 (1), 65–77. https://doi.org/10.1007/s11355-010-0114-3.
Tal, M., Gran, K., Murray, A.B., Paola, C., Hicks, D.M., 2004. Riparian vegetation as a primary control on channel characteristics in multi-thread rivers. In: Bennett, S.J., Simon, A. (Eds.), Riparian Vegetation and Fluvial Geomorphology: Hydraulic, Hydrologic, and Geotechnical Interaction. Water Science and Application, vol. 8. American Geophysical Union, Washington, DC, pp. 43–58.
Tal, M., Paola, C., 2010. Effects of vegetation on channel morphodynamics: results and insights from laboratory experiments. Earth Surf. Process. Landforms 35 (9), 1014–1028. https://doi.org/10.1002/esp.1908.
Tavzes, B., Urbanic, G., 2009. New indices for assessment of hydromorphological alteration of rivers and their evaluation with benthic invertebrate communities; Alpine case study. Rev. Hydrobiol. 2 (2), 131–169.
Thorne, C., Hey, R., Newson, M., 1997. Applied Fluvial Geomorphology for River Engineering and Management. John Wiley and Sons Ltd.
Thorne, C.R., 1998. Stream Reconnaissance Handbook: Geomorphological Investigation and Analysis of River Channels. John Wiley & Sons Ltd, Chichester, UK.
Tickner, D., Opperman, J.J., Abell, R., Acreman, M., Arthington, A.H., Bunn, S.E., Cooke, S.J., Dalton, J., Darwall, W., Edwards, G., Harrison, I., Hughes, K., Jones, T., Leclère, D., Lynch, A.J., Leonard, P., McClain, M.E., Muruven, D., Olden, J.D., Ormerod, S.J., Robinson, J., Tharme, R.E., Thieme, M., Tockner, K., Wright, M., Young, L., 2020. Bending the curve of global freshwater biodiversity loss: an emergency recovery plan. Bioscience 70 (4), 330–342. https://doi.org/10.1093/biosci/biaa002.
Tockner, K., Lorang, M.S., Stanford, J.A., 2010a. River floodplains are model ecosystems to test general hydrogeomorphic and ecological concepts. River Res. Appl. 26 (1), 76–86. https://doi.org/10.1002/rra.1328.
Tockner, K., Pusch, M., Borchardt, D., Lorang, M.S., 2010b. Multiple stressors in coupled river–floodplain ecosystems. Freshw. Biol. 55, 135–151. https://doi.org/10.1111/j.1365-2427.2009.02371.x.
Tockner, K., Stanford, J.A., 2002. Riverine flood plains: present state and future trends. Environ. Conserv. 29 (3), 308–330. https://doi.org/10.1017/S037689290200022X.
USDA (U.S Department of Agriculture), 1998. A User Guide to Assessing Proper Functioning Condition and the Supporting Science for Lotic Areas. Riparian Area Management, TR 1737-15. Bureau of Land Management, Denver, Colorado, US.
Van Looy, K., Meire, P., Wasson, J.-G., 2008. Including riparian vegetation in the definition of morphologic reference conditions for large rivers: a case study for Europe's Western plains. Environ. Manag. 41 (5), 625–639. https://doi.org/10.1007/s00267-008-9083-9.
Van Oorschot, M., Kleinhans, M., Geerling, G., Middelkoop, H., 2016. Distinct patterns of interaction between vegetation and morphodynamics. Earth Surf. Process. Landforms 41 (6), 791–808. https://doi.org/10.1002/esp.3864.
Vannote, R.L., Minshall, G.W., Cummins, K.W., Sedell, J.R., Cushing, C.E., 1980. The river continuum concept. Can. J. Fish. Aquat. Sci. 37 (1), 130–137. https://doi.org/10.1139/f80-017.
Viles, H., 2020. Biogeomorphology: past, present and future. Geomorphology 366, 106809. https://doi.org/10.1016/j.geomorph.2019.06.022.
Villeneuve, B., Piffady, J., Valette, L., Souchon, Y., Usseglio-Polatera, P., 2018. Direct and indirect effects of multiple stressors on stream invertebrates across watershed, reach and site scales: a structural equation modelling better informing on hydromorphological impacts. Sci. Total Environ. 612, 660–671. https://doi.org/10.1016/j.scitotenv.2017.08.197.
Vogel, R.M., 2011. Hydromorphology. J. Water Resour. Plann. Manage. 137 (2), 147–149. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000122.
Volke, M.A., Johnson, W.C., Dixon, M.D., Scott, M.L., 2019. Emerging reservoir delta-backwaters: biophysical dynamics and riparian biodiversity. Ecol. Monogr., e01363 https://doi.org/10.1002/ecm.1363, 00(00).
Voulvoulis, N., Arpon, K.D., Giakoumis, T., 2017. The EU Water Framework Directive: from great expectations to problems with implementation. Sci. Total Environ. 575, 358–366. https://doi.org/10.1016/j.scitotenv.2016.09.228.
Ward, J.V., Robinson, C.T., Tockner, K., 2002a. Applicability of ecological theory to riverine ecosystems. Internationale Vereinigung für Theoretische und Angewandte Limnologie: Verh Proc. Trav. SIL 28 (1), 443–450. https://doi.org/10.1080/03680770.2001.11902621.
Ward, J.V., Tockner, K., Arscott, D.B., Claret, C., 2002b. Riverine landscape diversity. Freshw. Biol. 47 (4), 517–539. https://doi.org/10.1046/j.1365-2427.2002.00893.x.
Wiens, J.A., 2002. Riverine landscapes: taking landscape ecology into the water. Freshw. Biol. 47 (4), 501–515. https://doi.org/10.1046/j.1365-2427.2002.00887.x.
Wilcox, A.C., Shafroth, P.B., 2013. Coupled hydrogeomorphic and woody-seedling responses to controlled flood releases in a dryland river. Water Resour. Res. 49 (5), 2843–2860. https://doi.org/10.1002/wrcr.20256.
Williams, C.A., Cooper, D.J., 2005. Mechanisms of riparian cottonwood decline along regulated rivers. Ecosystems 8 (4), 382–395. https://doi.org/10.1007/s10021-003-0072-9.
Winward, A.H., 2000. Monitoring the Vegetation Resources in Riparian Areas. Gen. Tech. Rep. RMRS-GTR-47. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Ogden, UT.
Wohl, E., 2013. Mountain Rivers Revisited. American Geophysical Union, Washington, DC. https://doi.org/10.1029/WM019.
Wohl, E., Kramer, N., Ruiz-Villanueva, V., Scott, D.N., Comiti, F., Gurnell, A.M., Piégay, H., Lininger, K.B., Jaeger, K.L., Walters, D.M., Fausch, K.D., 2019. The natural wood regime in rivers. Bioscience 69 (4), 259–273. https://doi.org/10.1093/biosci/biz013.
Wright, J.F., Armitage, P.D., Furse, M.T., Moss, D., 1988. A new approach to the biological surveillance of river quality using macroinvertebrates. Internationale

Vereinigung für theoretische und angewandte Limnologie: Verh Proc. Trav. SIL 23 (3), 1548–1552. https://doi.org/10.1080/03680770.1987.11898060.

Yi, Y.-j., Zhou, Y., Song, J., Zhang, S., Cai, Y., Yang, W., Yang, Z., 2019. The effects of cascade dam construction and operation on riparian vegetation. Adv. Water Resour. 131, 103206. https://doi.org/10.1016/j.advwatres.2018.09.015.

Zaharia, L., Ioana-Toroimac, G., Moroşanu, G.-A., Gălie, A.-C., Moldoveanu, M., Ćanjevac, I., Belleudy, P., Plantak, M., Buzjak, N., Bočić, N., Legout, C., Bigot, S., Ciobotaru, N., 2018. Review of national methodologies for rivers' hydromorphological assessment: a comparative approach in France, Romania, and Croatia. J. Environ. Manag. 217, 735–746. https://doi.org/10.1016/j.jenvman.2018.04.017.