From meta-system theory to the sustainable management of rivers in the Anthropocene

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Running head: A meta-system approach for river management

Abstract

Ecological processes occurring at the regional scale, such as the dispersal of organisms, and spatial flows of material and energy are fundamental for maintaining biodiversity and ecosystem functioning in river networks, yet they remain largely overlooked in most river management practices and underlying policies. We propose a meta-system approach where regional processes acting at different levels of ecological organization – populations, communities and ecosystems – can be integrated into conventional conservation, restoration and biomonitoring of rivers. We recommend a series of measurements and indicators that could be assimilated into the implementation of relevant biodiversity and environmental policies. We highlight the need for alternative management strategies that can guide practitioners towards applying recent advances in ecology to preserve and restore river ecosystems and the ecosystem services they provide in the context of increasing alteration of river network connectivity worldwide.

In a nutshell:

- Rivers are hotspots of biodiversity and provide essential ecosystem functions and services but are heavily threatened globally
- Our understanding on how rivers are organized across spatial scales has progressed considerably over the past decades, proving that regional-scale

processes are vital for preserving population, community and ecosystem dynamics
- However, most existing river conservation, restoration and biomonitoring practices focus on local-scale approaches and measures
- We suggest additional metrics and assessment approaches that better incorporate regional processes to guide the management of river networks in the Anthropocene

River ecosystems sustain disproportionate levels of biodiversity at landscape, regional and continental scales (Reid *et al.* 2019). They contribute substantially to global biogeochemical cycles through release of carbon dioxide to the atmosphere and transport of carbon and nutrients from continents to oceans (Raymond *et al.* 2013). Rivers also provide key ecosystem services, including provision of drinking water, food production, and climate and water regulation, which are critical to sustaining human well-being (Reid *et al.* 2019). However, in the current Anthropocene era (Panel 1), rivers worldwide are largely impaired by human activities, being among the most threatened ecosystems on Earth (Dudgeon *et al.* 2019). This global trend necessitates better management and environmental legislation to guarantee the biodiversity and functional integrity of river ecosystems.

Most river management practices – independently of the spatial scale at which they are implemented – are based on local assessments, as a legacy of the niche paradigm that has prevailed in ecology for decades (Panel 1; Heino 2013). In contrast, scientific understanding of how biodiversity, ecosystem functions and services are organized across river networks has progressed substantially with the emerging meta-system theory (Gounand *et al.* 2018). This framework acknowledges that both local (ie niche selection and biotic interactions at a river reach) and regional (ie dispersal of organisms and spatial flows of material and energy across the river network) mechanisms interact to shape the spatial and temporal organization of populations and communities, and drive ecosystem processes and services. The meta-system framework is particularly relevant for river networks due to their dendritic topology (Panel 1) and the predominantly unidirectional flow of water, which constrain the exchange of matter and organisms at larger spatial scales (Tonkin *et al.* 2018). Current river management practices and underlying policies often fail to incorporate important regional processes. Therefore, our ability to conserve and restore river biodiversity and ecosystem functions efficiently is critically hindered (Erős *et al.* 2018).

Management practices focused on the local scale alone will become increasingly unlikely to achieve desired ecological outcomes. Globally, humans modify catchments through land use changes, flow regulation by dams, water diversion and extraction of surface and ground water, pollution and the introduction of invasive species (Dudgeon 2019). Fragmentation by dams is the major driver of connectivity loss (Grill *et al.* 2019) and is exacerbated by climate change, which increases the intensity and frequency of droughts and subsequent drying of river networks (Döll and Schmied 2012). Where human densities are high, the flow regimes of streams and rivers have been so greatly altered that 'novel' ecosystems exist (Datry *et al.* 2018). Despite having local impacts, most of the threats of the Anthropocene act at the regional or global scale (Dudgeon 2019). Overall, the increasing pressure of multiple threats calls for a better integration of scale-dependent approaches to guide water management and conservation policies in a changing world.

Here, we aim at translating the meta-system theory into management and policy recommendations for rivers. First, we present the meta-system framework and its relevance for these ecosystems, particularly with respect to decreased connectivity resulting from human-induced fragmentation. Second, we show why this framework can inform river management to effectively achieve environmental and conservation targets. Third, we identify specific policy implications, and provide guidance on how a meta-system approach could be implemented.

The meta-system theory and its relevance in river networks

The meta-system theory states that local- and regional-scale processes interact to influence the dynamics of environmental conditions and biota in a given landscape (Gounand *et al.* 2018 Figure 1). Regional-scale processes determine fluxes of individuals, species or material and energy among local populations, communities and ecosystems, respectively, whereas local-scale dynamics represent interactions with abiotic conditions and other species (Hanski 1998; Leibold *et al.* 2004; Gounand *et al.* 2018). Sets of local populations, communities and ecosystems linked by regional fluxes form, respectively, metapopulations, metacommunities and meta-ecosystems (Panel 1,

Figure 1). In river networks, dispersal of organisms can be constrained by the dendritic topology, flow regime, physical barriers and the dispersal capability of the organisms, leading to spatial variation of populations and communities (Brown *et al.* 2011). Matter and energy vary spatially, as sources of terrestrial inputs are differentiated across sub-catchments (Creed *et al.* 2015) and upstream-to-downstream physical linkage dominates transport with en-route biogeochemical modulation. Such spatial dynamics in the flows of matter and organisms at the regional sub-catchment scale can determine riverine ecosystem functioning at the local reach scale. The meta-system theory upgrades the perspectives of metapopulation and metacommunity ecology in river ecosystems focused on spatial flows of organisms by incorporating those of resources, material and energy (Gounand *et al.* 2018). It offers a framework to better understand the spatial coupling of biodiversity dynamics and ecosystem functioning, eventually contributing to ecosystem services (Gounand *et al.* 2018), and it reinforces previous research on ecological processes across spatial scales in river networks (Fausch *et al.* 2002; Brown *et al.* 2011; McCluney *et al.* 2014). By explicitly distinguishing the different levels of ecological organization, it also provides a powerful framework for the implementation of current biodiversity and environmental policies.

The relevance of the meta-system framework for improving river management can be illustrated through fragmented river networks. Fragmentation, by weirs, dams or drying, not only alters the local environment and biota (eg Datry *et al.* 2014), but also disrupts the flux of water, resources and organisms (Gounand *et al.* 2018; Grill *et al.* 2019). The effects of fragmentation cascade across organizational levels, from populations to ecosystems, and eventually to socio-ecological systems, negatively affecting the provision of ecosystem services (Figure 2). Fragmentation can isolate local populations and reduce gene flow within a metapopulation, jeopardizing their long-term persistence due to genetic drift and inbreeding (Fitzpatrick and Reid 2019). Ultimately, this can lead to decreased species ranges and eventually to local or regional extinctions (Hanski 1998). Responses to fragmentation of metapopulations cascade to altered metacommunity dynamics. Reduced dispersal among isolated local communities can lead to shifts in community composition, biodiversity patterns and biological interactions at local and regional scales (Jaeger *et al.* 2014), leading to changes in ecosystem functions (Gounand *et al.* 2018). Fragmentation can also have direct effects on fluxes of material (Figure 2). For example, drying resulting from water overabstraction, dam construction, or climate change can alter the storage and transport of coarse organic matter and nutrients in the network, as they are retained at sites without flow before subsequent massive releases at flow resumption (Datry *et al.* 2018). Fragmentation may ultimately impact ecosystem service provision at the river basin scale by altering service-providing, service-connecting and service-benefiting areas (Datry et al. 2017; Panel 1; Figure 2). Thus, understanding regional processes occurring at each level of organization (ie metapopulation, metacommunity and meta-ecosystem) can be crucial in guiding effective river conservation, monitoring and restoration.

The meta-system theory for integrating regional-scale processes in river conservation, restoration and monitoring

The meta-system theory can help managers to better predict how populations respond to anthropogenic stressors at the regional scale and to design conservation plans accordingly (Schiesari *et al.* 2019). When a population follows source-sink dynamics, the regional persistence of the species mainly depends on key ‘source’ populations that contribute via dispersal to ‘sink’ populations (Hanski 1998). Identifying where these key populations and their main dispersal routes are located is crucial to ensure adequate species conservation. Studies on salmonid fishes show that fragmentation by large reservoir dams, hatchery introductions and deterioration of habitat quality can substantially alter metapopulation structure, and that optimal management strategies should be based on maintaining habitat quality and connectivity of key ‘source’ populations (Fullerton *et al.* 2016). In very fragmented metapopulations, local populations decline, and the risk of extinction is higher than in large and connected metapopulations (Fitzpatrick and Reid 2019). For example, historically connected metapopulations of the endangered Iberian cyprinid fish *Iberochondrostoma almacai* now suffer from fragmentation as a result of river drying and are subjected to strong genetic drift (Sousa *et al.* 2010). Protecting local habitats alone would not be effective, and conservation strategies should target increasing gene flow (Sousa *et al.* 2010). On the contrary, historically isolated populations require careful management practices to maintain isolation-driven evolutionary processes at the landscape scale (Rahel and McLaughlin 2018). Information about population sizes, dispersal capability and physical distance among populations is necessary to distinguish different metapopulation structures in landscapes, which require different management strategies and priorities (Fullerton *et al.* 2016).

Regional-scale thinking is also critical for understanding the spread of invasive species (Strecker and Brittain 2017). In river networks, however, their management is still poorly developed and can be controversial (Chen and Olden 2017). For example, artificial barriers alter natural metapopulation dynamics but also can limit the spread of invasive fish (Rahel and McLaughlin 2018). In contrast, altering naturally intermittent flow regimes of river networks by artificially producing perennial flows can promote new invasions of alien species (Ruhí *et al.* 2019). Identifying the respective role of local and regional processes in the dynamics of invasive species in relation to native ones is fundamental to avoid undesired conservation and management effects (Rahel and McLaughlin 2018).

Considering metapopulation structure can improve the prediction of species range shifts in response to climate change, as dispersal capability can determine whether species will be able to reach new suitable regions and habitats (Markovic *et al.* 2014). However, most assessments based on species distribution modeling only consider the potential effects of climate change on local conditions (ie niche-based modeling). If the target is developing more resilient large-scale conservation strategies, the evaluation of species' vulnerability and extinction risk needs to incorporate dispersal-related processes and indeed the effects of projected river network fragmentation on biota (Markovic *et al.* 2017).

At the community level, information on the metacommunity structure can be powerful in guiding effective restoration and biomonitoring practices. Currently, most restoration projects may fail in achieving biodiversity and/or ecological quality targets because they are typically limited to the local scale (Tonkin *et al.* 2014). For example, the reduced regional pool of colonizers could hamper achieving expected restoration targets in highly-degraded catchments, where unimpacted sites (ie natural recolonization sources) are very isolated due to fragmentation (Tonkin *et al.* 2014; Swan and Brown 2017). Similarly, biomonitoring methods to evaluate river health or ecological status may fail at detecting anthropogenic impacts, mainly as a result of dispersal limitation (Heino 2013). Most biomonitoring methods assume that local communities entirely respond to local environmental conditions and that all species can eventually reach all sites (Cid *et al.* 2020). However, fragmentation can prevent species from reaching their optimal habitats and isolated sites may present lower richness and bioassessment scores despite having good habitat quality (Heino 2013). In naturally intermittent river networks, drying can generate high habitat heterogeneity in terms of wet and dry habitats and might promote species richness, but it can also increase fragmentation and prevent some species from colonizing a site, thereby reducing local species richness (Datry *et al.* 2014). Applications of the basic tenets of metacommunity ecology in biomonitoring and restoration practices can inform on the relative influence of local and regional processes on local community composition (Cid *et al.* 2020).

Metacommunity ecology uses a range of scale-sensitive biodiversity measures that are dismissed in local biodiversity assessments based on alpha diversity (Panel 1). For example, beta diversity (Panel 1) and its components can be useful to identify and preserve those sites contributing the most to maintaining regional diversity (Panel 1; Ruhí *et al.* 2017). Thus, expanding the metrics used in routine assessments can provide essential information to evaluate the structure and functioning of metacommunities and improve their conservation (Simons *et al.* 2019).

Species in a metacommunity interact at the local and regional scales (Hagen *et al.* 2012), and biotic interactions can be altered by changes in hydrologic connectivity across the river network. For example, fragmentation by dams can isolate freshwater mussel metapopulations from their host fish, on which they depend for completing their life cycle and disperse across the network (Ferreira-Rodríguez *et al.* 2019). Fragmentation by drying can simplify food webs following top predator loss, having direct effects on ecosystem processes (Hagen *et al.* 2012). Identifying key biotic interactions across the meta-system will help achieve biodiversity targets closely linked with ecosystem functioning (Hagen *et al.* 2012).

By modifying the flow of water, sediments and organisms, fragmentation affects the fluxes of matter (ie minerals, carbon and nutrients) across river networks. For example, current dam removal efforts benefit sediment transportation, counteract coastal erosion, and also restore upstream movement of migratory fish, thereby allowing transport of marine nutrients to isolated headwaters (Bellmore *et al.* 2019). Fragmentation can also lead to sub-optimal ecosystem processes both locally and regionally if resources accumulate but organisms processing those are lacking and vice-versa (Gounand *et al.* 2018). This might occur when natural drying of stream channels in intermittent rivers stops the transport of organic matter from upstream and thus limits ecosystem functioning downstream (Datry *et al.* 2018). Identifying when and where various kinds of matter (and energy) are processed and transported is essential for the maintenance of ecosystem functioning and services (Datry *et al.* 2017).

Policy implications and management opportunities

Biodiversity and environmental conservation are governed through several interlinked goals and agreements at the international and national levels. Global objectives, such as those stated in the Aichi Biodiversity Targets and the Sustainable Development Goals aiming for a more sustainable world, are reflected in international and national strategies and policies (Figure 3, Table 1). These policies are articulated and enforced through guidance documents, which include common implementation methodologies describing how to obtain indicator metrics for tracking the achievement of environmental and conservation targets (Table 1). Here, we present different options to integrate regional-scale processes into the current local-scale management of river networks, focusing on biodiversity conservation, biomonitoring and restoration. We propose a series of alternative metrics and indicators (Table 1) that could complement such methodologies and sharpen strategies to guide efforts in reversing current trends of freshwater biodiversity loss and ecosystem degradation due to river fragmentation.

Metapopulation and metacommunity perspectives for biodiversity conservation

Conservation policies such as the European Union Habitats Directive or the US Endangered Species Act, collect information on the conservation status of species from population estimates, most of them only accounting for species population size and habitat quality (Table 1). Under a meta-system approach, methods and indicators able to assess metapopulation structure should be incorporated. This includes molecular tools and methods for obtaining genetic diversity metrics to infer connectivity within a delimited spatial area (eg catchment or sub-catchment) and/or direct measures of dispersal (Table 1) using mark and recapture or genetic methods (Fullerton *et al.* 2016). However, empirical data on metapopulations are not always available for managers, and monitoring efforts and open data sharing should be promoted. Such information could be integrated in individual-based models and thereby contribute to identify critical thresholds (Dudley 2018).

Responses for mitigating the effects of altered river network connectivity on biodiversity can be varied (Fuller *et al.* 2016). In general, when freshwater metapopulations are suffering from lack of gene flow, conservation actions should promote connectivity. This can be done by removing artificial barriers, installing fish passages, or implementing environmental flows (Poff *et al.* 2010). Despite important efforts to shift environmental flow management from local to regional scale (eg Stewardson and Guarino 2018), most dam management practices still focus on restoring flow regimes at the immediate downstream river segments. Instead, coordinated dam management across the river network provides an opportunity to increase connectivity and maintain meta-system dynamics (McCluney et al 2014; Chen and Olden 2017). In a meta-system context, environmental flow management should target the conservation and restoration of variation in regional ecological features (eg by using the metrics listed in Table 1). If increasing connectivity is not feasible through restoration, or if populations are too isolated to allow dispersal of individuals after improving connectivity, conservation measures could be directed to protect local habitats and conducting assisted colonization (Lawler and Olden 2011).

Protected areas are major assets for current conservation policies. However, they rarely capture the complex spatial structure of river networks, making conservation of riverine biodiversity challenging (Carrizo *et al.* 2017; Acreman *et al.* 2020). Under a meta-system approach, protected areas within a catchment should be designed to ensure the conservation of key sites across the network that allow metapopulations and metacommunities to persist. This could be achieved using prioritization methods in conservation planning that include the analysis of connectivity and spatial congruence of multiple species (Albert *et al.* 2017). For example, in river networks experiencing fragmentation through drying, the selection of pivotal refugia acting as sources for dispersal are key to ensure the protection of network-wide biodiversity (Hermoso *et al.* 2013). Sites to be protected and/or restored across the network can be selected using information on populations' genetic diversity and on communities' beta diversity components (Table 1; Ruhí *et al.* 2017; Paz-Vinas *et al.* 2018).

Metacommunity-based biomonitoring and restoration for river basin management

Most legislation protecting surface waters relies on local reach-scale evaluations of ecological status (Heino 2013). For example, despite the management unit of the

European Union Water Framework Directive and the US Clean Water Act is the river basin, they prescribe evaluation of different river reaches individually, based on the structural and/or functional properties of ecological assemblages. However, neither of the two policies explicitly encourages biological assessments at multiple spatial scales.

River biomonitoring methods are based on comparing the biotic community of a focal site with a reference value obtained from a group of unimpacted or least impacted sites (Cid *et al.* 2020). Using these unimpacted sites, the expected biological community at a site is predicted based on local environmental conditions (Heino 2013; Cid *et al.* 2020). To consider regional processes in metacommunity dynamics, water managers could integrate proxies for dispersal based on spatial connectivity (eg fragmentation caused by dams, drying, and topographical barriers) and dispersal-related species traits into biomonitoring methods (Cid *et al.* 2020).

To better consider current and predicted levels of fragmentation, monitoring sites within a river network may have to be redesigned. For example, while large dams are usually considered when selecting monitoring sites, fragmentation by small barriers and potential drying events have traditionally been overlooked (Erős *et al.* 2018). Assessing fragmentation within a river network and its potential interactive or additive effect(s) with other anthropogenic stressors will contribute to better predictions of ecological integrity using bioindicators.

Under a meta-system approach, restoration practices should include information on the regional species pool and the capability of species to reach restored habitats. Key sites acting as sources of colonizers should be identified, and their connectivity with restored river reaches should be evaluated (Heino *et al.* 2017). This is especially relevant when fragmentation is due to drying, as source sites within the regional species pool are typically located in dry season refugia (Datry *et al.* 2014). To assess whether improvements in local diversity have positive effects on regional biodiversity, managers could incorporate indices such as taxonomic and functional beta, zeta and gamma diversity (Panel 1, Table 1) (Simons *et al.* 2019).

Towards a more holistic ecosystem-based management in rivers

At the ecosystem level, the need for spatially explicit examinations of biogeochemical, hydromorphological and ecological patterns and processes has been recognized for science and management (Gounand *et al.* 2018; Mc Cluney *et al.* 2014). There are already some prioritization tools available to integrate spatial dynamics into conservation planning (e.g. Hermoso *et al.* 2013; 2018), and most policies and related guidance documents promote adaptive management incorporating cross-ecosystem processes and scale-dependency. However, the implementation of these tools and principles is still rare (Acreman *et al.* 2020). Research and capacity-building on how to overcome these barriers for more effective integration of the state-of-the-art ecological theory to environmental management is needed. Monitoring programs should include measures of ecosystem processes across the river network, such as decomposition of leaf litter and ecosystem metabolism (Young *et al.* 2008), or measures of food web structure (Otto *et al.* 2018), which could help to identify hotspots of functioning (McClain *et al.* 2003). These measures could be integrated systematically in conservation planning. As different biodiversity facets, ecosystem processes and services may vary in their degree of spatial congruence across the river network, prioritization methods that integrate these variables simultaneously could be used to maximize their protection in a holistic way (Hermoso *et al.* 2018; Erős and Bányai 2020).

Conclusions

The meta-system theory is a powerful framework to understand the dynamics of populations, communities and ecosystems, and guide the conservation, biomonitoring and restoration of increasingly fragmented river networks. Yet, the applications of this approach are just emerging, and many methodological and empirical developments are urgently needed to integrate it into environmental legislation and policies. Guidance based on meta-system theory could strengthen the quality of legislation, build understanding of causes and effects across spatial scales, and make significant steps towards sustainable, adaptive management of rivers in the Anthropocene. The relevance of this framework will be even greater in the near future. This is because climate change and increased water needs for human activities are exacerbating the occurrence and magnitude of extreme events, such as floods and droughts, thereby rapidly altering river connectivity and producing unprecedented river network fragmentation.

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Figure captions:

Figure 1: Schematic representation of metapopulations, metacommunities and meta-ecosystems in a drying river network. Local populations, communities and ecosystems (green rectangles) are connected by gene flow, dispersal of individuals, and flow of resources across the landscape, respectively (arrows). Photo credit: N. Bonada.

Figure 2: Conceptual diagram of the cascading effects of the alteration of river network connectivity across the different levels of the meta-system (ie metapopulation, metacommunity and meta-ecosystem) and socioecological system (ie ecosystem services). Note that for ecosystem services, blue and red arrows represent the flow between service-providing and service-benefiting areas (Panel 1).

Figure 3: The current loss of river network connectivity worldwide will be exacerbated by climate change and affect the associated socio-ecological system. Legislation and regulations at all levels should adapt to these changes: international policies include the Aichi Biodiversity Targets or Sustainable Development Goals; related regional policies (here, examples from Europe) reflect these global agreements, which form the basis to national level regulations for water, nature conservation, or spatial planning.

Pannel 1 Glossary of terms

Alpha diversity: The diversity within a specific ecosystem or area (the local species richness) usually expressed as the number of species present (Whittaker 1972).

Anthropocene: A new human-dominated geological epoch, beginning between 1610 and 1964 according to different lines of evidence (Lewis and Maslin 2015).

Beta diversity: A quantification of the number of different communities in a region measured as extent of change (Whittaker 1972).

Dendritic structure (in river networks): Rivers and streams follow a geometric pattern of arborescent bifurcation originating from one node and extending out in one direction, forming a hierarchical network of nodes and branches (Heino 2013).

Dispersal: Movement of individuals from one locality to another (Leibold *et al.* 2004).

Niche: Range of resource availability and physical conditions that a given species can tolerate to survive at a locality (Leibold *et al.* 2004).

Metapopulation: A set of local populations of a single species that are linked by dispersal (Hanski 1998).

Metacommunity: A set of local communities that are linked by dispersal of multiple potentially interacting species (Leibold *et al.* 2004).

Meta-ecosystem: A set of ecosystems connected by spatial flows of energy, material and organisms across ecosystem boundaries (Gounand *et al.* 2018).

Regional diversity (gamma diversity): The total diversity within the entire landscape, ie regional species pool (Whittaker 1972).

Service-providing areas: The spatial units that are the sources of ecosystem services in a given landscape (Syrbe and Walz 2012).

Service-connecting areas: The spatial units where the benefits from ecosystem services are required in a given landscape (Syrbe and Walz 2012).

Service-benefiting areas: The spatial units that are connecting providing and benefiting areas in a given landscape (Syrbe and Walz 2012).

Zeta diversity: The number of species shared by multiple communities (Simons *et al.* 2019)

Table 1 Current metrics and indicators used in core environmental and biodiversity policies. Also shown are additional ones that could be implemented in a meta-system approach.

Management action and organizational level of application	**Policies**	**Current metrics/indicators**	**Additional metrics/indicators**
Conservation/ restoration, (meta) population	European Biodiversity Strategy and Habitats Directive US Endangered Species Act Australia Environment Protection and Biodiversity Conservation Act	Species range* (km) Species occupancy area* (km^2) Species population size* (grid, individuals) Species age structure Species habitat area and quality	Genetic diversity Gene flow Inbreeding Hybridization Species effective dispersal Number and location of metapopulation key habitats (eg refugia, dispersal routes) Area and quality of metapopulation key habitats Connectivity between key habitats (eg dendritic connectivity index)
Biomonitoring/restoration, (meta) community	European Water Framework Directive US Clean Water Act Australia Water Act	Local (alpha) taxonomic richness and diversity of different taxonomic groups (ie macroinvertebrates, fish, diatoms, macrophytes, riparian plants)** Species environmental tolerance** Number and richness of alien species** Riparian vegetation cover** Morphology of the riverbed and riverbanks**	Gamma species diversity Beta and zeta species diversity Species dispersal capability (eg using organisms' traits as a proxy for dispersal) Species effective dispersal Metacommunity key habitats area and quality (ie refugia, dispersal routes) Connectivity between key habitats (eg dendritic connectivity index)

Management action and organizational level of application	**Policies**	**Current metrics/indicators**	**Additional metrics/indicators**
Ecosystem-based management/restoration, (meta) ecosystem and ecosystem services	European Biodiversity Strategy ***	Nutrient load and retention Sediment transport and retention Carbon storage, processing and transport Fish production (catch by fishermen) Wood produced by riparian forest Nº bathing areas and quality Fishing reserves Most of the indicators listed above within other categories (eg riparian vegetation cover)	Leaf litter decomposition Ecosystem metabolism Food web structure Riparian stocks (eg using remote sensing) Number and location of hotspots of functioning (eg organic matter and nutrient processing) Number and location of service-providing, service-connecting and service-benefiting areas

*These metrics are reported at the national level and, usually, for protected areas. The conservation status is assessed using reference values.

**These measurements are the basis for the development of biological and hydromorphological quality metrics under the main water policies such as the Water Framework Directive. They are developed at the national level.

*** One of the main targets is the mapping and assessment of ecosystem services, which uses indicators from several sources.