Chapter

The European REFORM Project for Hydromorphological Quality in River Basin Management

Erik Mosselman, Massimo Rinaldi and Diego García de Jalón

Abstract

The Water Framework Directive commits European Union member states to achieve good ecological and chemical status of all water bodies. As hydromorphology is a key factor for ecological status, a consortium of 26 partners from 15 countries studied the role of hydromorphological pressures and measures in the REFORM project. Its main objective was to answer the question: How to make river restoration successful? The project developed guidance for this by structuring the information along the different stages of restoration projects and river basin management plans, posing a logical sequence of questions: How does my river work? What's wrong? How to improve? Things can be wrong for ecological status as a result of morphological alterations. These alterations form pressures that can be countered or mitigated by measures that improve sedimentological and morphological features. We present two specific results of REFORM that focus on river morphology. First, we provide an overview of methods to assess morphological quality and diagnose alteration. Second, we present systematic cause–effect relationships for restoration measures.

Keywords: hydromorphology, river morphology, ecological status, river restoration, water framework directive, river basin management

1. Introduction

The Water Framework Directive commits European Union member states to achieve good ecological and chemical status of all water bodies. Its adoption and publication in 2000, however, caused widespread concern among river engineers and fluvial geomorphologists about the way the directive addresses hydromorphology in rivers. The directive defines hydromorphological quality in terms of visibility of static anthropogenic features, without considering hydromorphological functioning relevant for ecology, and without considering the physical processes of water flow, sediment transport, erosion, and sedimentation. Neither did the directive address temporal variability [1, 2], nor spatial variability in the light of habitat diversity and connectivity [3, 4]. The European Union was receptive to the criticisms and accordingly called for a project to resolve this within its 7th Framework Programme. It granted the project to a consortium of 26 partners from 15 countries under the name “REFORM”, an acronym standing for “Restoring rivers FOR effective catchment Management”. The partners executed the project from November 2011 to October 2015.

REFORM’s main objective was to answer the question: How to make river restoration successful? This requires that river restoration practitioners understand the complex systems of hydromorphology and ecology. Processes operate at different scales, different disciplines play a role, and different species depend on hydromorphology in different ways. It is not easy to find a way in this complexity when developing an integrated design. The project developed guidance by structuring the information along the different stages of restoration projects and river basin management plans, following the cycle of the iterative PDCA management method: Plan – Do – Check – Act. This fits in a logical sequence of questions guiding river basin management planning: How does my river work? What’s wrong? How to improve? (**Figure 1**). The guidance was made accessible through an online wiki: wiki.reformrivers.eu.

Things can be wrong for ecological status as a result of morphological alterations. Examples are alteration of instream habitat, alteration of riparian vegetation, channelization, cross-section alteration, embankments (levees and dikes), impoundment (dams), loss of vertical connectivity, mining of sand and gravel, sedimentation, and sediment input. In Water Framework Directive terminology these alterations are called “pressures”. They can be countered or mitigated by measures that improve sedimentological and morphological features such as sediment flow quantity, longitudinal connectivity, lateral connectivity, riverbed depth variation, width variation, in-channel bed structure, substrate, riparian zone, and floodplains. REFORM compiled information on both pressures and measures. Furthermore, it sought to enhance awareness of the importance of sediment and morphology by summarizing insights and results into one-liners with down-to-earth messages, so-called tiles of wisdom (**Figure 2**). The online wiki presents and explains all these pressures, measures, and tiles of wisdom.

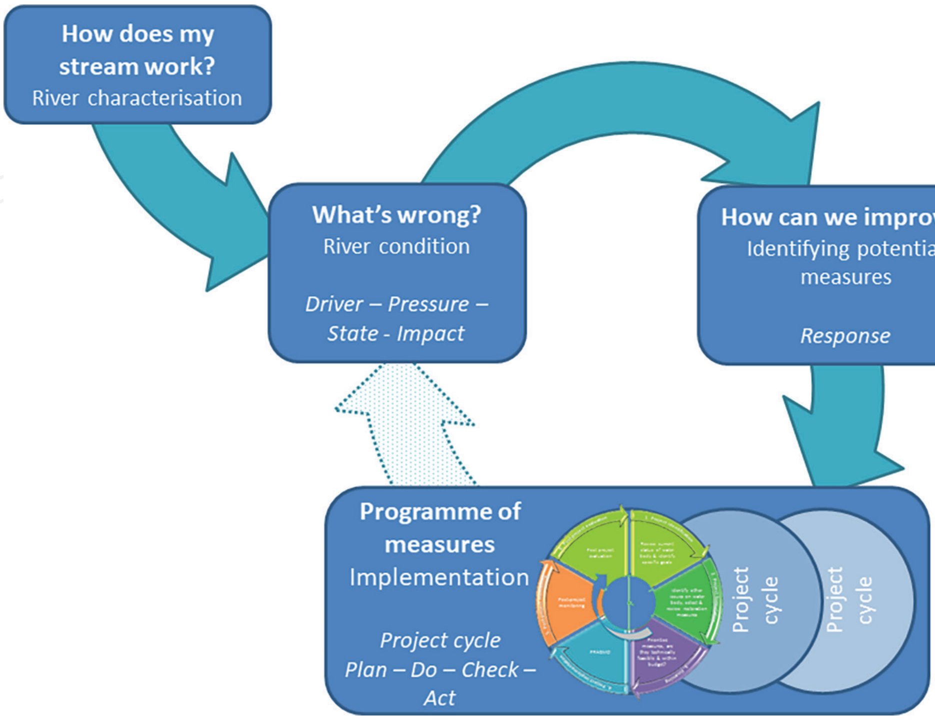


Figure 1.
Cycles of overall river basin management plans and individual river restoration projects.

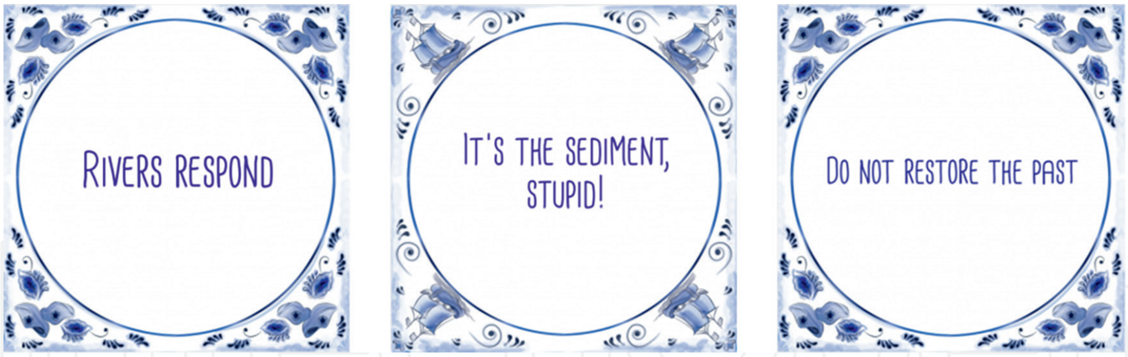


Figure 2.
Tiles of wisdom.

In this chapter, we present two specific results of REFORM that focus on river morphology. First, we present methods to assess hydromorphological quality and diagnose alteration. Second, we present systematic cause–effect relationships for diagnosis and for restoration measures.

2. Hydromorphological quality and alteration

Evaluation of hydromorphological quality and alteration requires a careful assessment that considers physical processes and resulting fluvial forms and physical habitats at appropriate spatial and temporal scales. This type of stream assessment has significantly expanded, with numerous methods in different EU member states that vary widely in terms of their aims, scales, and approaches [5, 6]. REFORM grouped these methods into four broad categories, based on the focus and objectives of each method: (1) physical habitat assessment; (2) riparian habitat assessment; (3) morphological assessment; and (4) assessment of hydrological regime alteration [6]. Their suitability for diagnosing alteration, however, was found to be limited because the methods insufficiently considered the physical processes of natural fluvial systems that maintain or recreate fluvial forms and thereby physical habitats. This contrasted with recent scientific developments that base the interpretation of current conditions on attempts to understand river functioning and evolution, see for instance [7–11].

REFORM therefore developed methods for a process-based hydromorphological assessment that considers how the character and dynamics of river reaches are affected by small-scale and large-scale natural and human-induced changes, in the past and in the present. Gurnell et al. [12] developed a multi-scale framework like previous hierarchical frameworks [7, 10, 13] but tuned to the European context. The framework is open-ended, allowing European member states to incorporate their own datasets, methods, and modeling tools. It distinguishes spatial units at region, catchment, landscape unit, segment, reach, geomorphic unit, hydraulic unit, and river element scales. Rinaldi et al. [14] refined the framework with four stages of assessment (**Table 1**), in accordance with the structure of existing frameworks [7, 15].

Each stage contains a series of procedural steps for consistent assessment of river conditions. The key spatial scale is the reach, defined as river sections along which present valley setting, channel slope, imposed flow, and sediment load are sufficiently uniform [7]. Channel morphology is a fundamental feature for delineating reaches. A first simple level of classification regards the number of river channel threads and

Stage	Definition	Description	Main outputs
I	Catchment-wide delineation and spatial characterization of the fluvial system	delineates, characterizes, and analyzes the catchment and the river system in their current conditions	(i) spatial units; (ii) character of spatial units, including hydrology, sediment sources and delivery, and assemblages of geomorphic units; (iii) main physical pressures and impacts at catchment scale; (iv) spatial patterns of morphological parameters and their control on channel morphology
II	Assessment of temporal changes and current conditions	reconstructs the history and evolutionary trajectories of morphological changes that have resulted in the current river conditions	(i) natural and human factors in historical times; (ii) evolutionary trajectories of channel changes; (iv) catchment-scale maps of pressures and critical reaches; (v) hydrological, morphological, and riparian vegetation state; (vi) geomorphic units; (vii) identified problems and most critical reaches; (viii) reports on monitored parameters or indicators along with their temporal changes
III	Assessment of scenario-based future trends	identifies possible future scenarios of hydromorphological modification	(i) catchment-scale maps of sensitivity and morphological potential; (ii) past channel evolution, current conditions, and possible future trends
IV	Management	identifies possible hydromorphological restoration or management actions	(i) one or more scenarios of management actions or restoration interventions; (ii) potential effects of proposed interventions on physical processes and hydromorphological conditions

Table 1.
Stages and main outputs of the REFORM overall framework, abbreviated from [14].

the channel planform pattern in the context of the valley setting (confinement). This basic river typology (BRT: [16]) defines seven river types using readily available information, mainly remotely sensed imagery. The initial delineation of the river reaches is followed by collecting additional information on reach properties and indicators. Then the river type may be defined during a field survey, according to an extended river typology (ERT) that comprises 22 river types [16].

The temporal context (Stage II) is linked to the concept of evolutionary trajectory [17, 18], expressing that river systems are dynamic and follow a complex trajectory of changes in response to driving variables at various spatial and temporal scales. The specific characteristics of a river result from its historical evolution, including climatic variations, human interventions, and unique sequences of large flood events. Assessment of current conditions and possible future scenarios and adjustments thus requires proper interpretation of temporal adjustments in morphology.

The framework allows selecting representative reaches or sites for monitoring river conditions and for upscaling or downscaling of information. It helps in classifying and understanding current conditions, in assessing the potential for morphological changes, and in supporting prioritization of actions and selection of sustainable management strategies.

The hydromorphological framework contains a set of more specific assessment procedures [14]. One of them is the extended European version of the Morphological

Quality Index (MQI), originally developed in Italy [10] and revised and tested within REFORM [19]. The MQI can be called 'process-based' because:

1. It takes processes into account that go beyond mere channel forms, as it includes indicators linked to the functioning of basic processes such as sediment continuity, wood flux continuity, bank erosion, and lateral channel mobility;

2. It explicitly accounts for the temporal component through indicators for adjustments of channel form through time;

3. Reference conditions are defined in terms of dynamic processes and functions that are expected for each physical context. This differs significantly from most current hydromorphological methods which define reference conditions in terms of channel configuration or channel characteristics.

The spatial scale of MQI application, in accordance with the multi-scale hierarchical framework, is the reach (i.e., a sufficiently uniform section of river, commonly a few kilometers in length). This is generally seen as the most appropriate and meaningful scale for assessing hydromorphology [7, 12]. The MQI includes twenty-eight indicators [10, 15, 19], falling within the following three classes:

1. Geomorphological functionality: indicators to evaluate whether artificial elements or channel adjustments prevent or alter the processes and related forms that are responsible for the correct functioning of the river;

2. Artificiality: indicators to assess the presence and frequency of occurrence of artificial elements, pressures, interventions, and management activities, irrespective of their effects on channel forms and processes;

3. Channel adjustment: indicators to assess morphological changes over about the last 100 years that can indicate systematic instability related to human factors.

Operators with sufficient background and training in fluvial geomorphology collect data by integrating remote sensing, GIS analysis, and field survey. The evaluation is based on a scoring system. The total score is equal to the sum of the scores for all components and aspects. The Morphological Quality Index is then defined as $MQI = 1 - S_{tot} / S_{\max}$, where S_{tot} is the calculated total score, and $S_{\max}$ is the maximum score that could be reached. The index thus increases with quality of the reach and decreases with the level of alteration, varying from 0 (minimum quality) to 1 (maximum quality), allowing investigation of the full range of morphological conditions.

The MQI assessment can be integrated with specific indices of hydrological alteration, such as IARI [20] and IAHRIS [21]. These indices align with the indicators of hydrological alteration (IHA) proposed by [22]. Furthermore, a Morphological Quality Index for monitoring (MQIm) was specifically designed to account for small changes and short time scales. This index is therefore suitable for monitoring and environmental impact assessment of interventions [19].

Rinaldi et al. [10] tested the original version and then applied it to many river reaches in Italy. Within REFORM, Belletti et al., [23] extended the method and tested it on several European streams of types that were underrepresented or entirely unrepresented in the Italian context. The indicators and scores were the same as in the original MQI to ensure data comparability, but with some modification or integration of aspects not covered fully previously. Further extensive application of the MQI at catchment scale was recently carried out on the Guadalquivir River in Southern Spain [24].

3. Cause-effect diagrams for diagnosis and restoration measures

Proper selection and design of restoration measures to improve fluvial ecosystem services require identifying which pressures affect the river and which are the limiting factors causing degradation. The intensity of the limiting hydromorphological processes can be assessed by quantitative measurement of the variables affected by these processes. REFORM proposes conceptual diagrams that relate different types of hydromorphological pressures to fluvial system functioning, accounting for hydromorphological processes and variables that result from both degradation and restoration. The aim is to identify the main hydromorphological effects of different pressure types across spatial and temporal scales, especially those that have a significant impact on aquatic biology.

Often, human pressures affecting rivers do not come alone. Multiple pressures affect rivers simultaneously, stressing many components of the hydrological cycle which have different time-scale responses within fluvial ecosystems. However, for practical reasons the effects of hydromorphological pressures and their most direct impacts on ecosystems were analyzed separately. The results were synthetized in diagrams that show the direct effects on processes and state variables, but also which process changes these effects induce with respect to hydromorphological variables. Corresponding quantitative variables are to be measured in order to monitor river changes and evaluate pressure effects.

The pressures have been grouped into hydrological regime alterations, river fragmentation, morphological alterations, and other elements and processes affected. The hydrological regime may be altered by water abstractions or by flow regulation through temporary storage in reservoirs. Rivers are fragmented by discontinuity in the river's longitudinal, lateral, or vertical dimensions. Such spatial discontinuities disrupt hydrological connectivity [25] and interrupt transfers of water, mineral sediment, organic matter, and organisms, thus affecting the biotic and physical components of the river [26]. Morphological alterations include impoundment, reservoirs with large dams, channelization, alteration of riparian vegetation and instream habitats, embankments, bank reinforcement, extraction of sand and gravel, and floodplain soil sealing and compaction. Other elements and processes include physicochemical pressures such as thermal changes, eutrophication, and overloads of organic material.

Hydromorphological pressures alter structure and composition of fluvial systems through changes in the natural hydromorphological processes, which can be characterized by changes in hydromorphological variables. Hydromorphological processes transform physical components of the fluvial system. These transformations change the morphology and the structure of the river, but they also create different environments that promote changes in the biological communities. Understanding the relationships between physical components and subsequent biological responses is therefore essential for process-based analysis of impacts. Hydrodynamic processes are characterized by variables and parameters. Their effects can be evaluated through selected state variables (**Table 2**). Usually, a modified variable triggers processes

Processes	Variables
• Water flow dynamics • Sediment dynamics a. entrainment b. transport c. deposition d. armoring • Riverbank dynamics a. erosion and failure b. stabilization c. accretion • Vegetation dynamics a. encroachment b. uprooting c. recruitment • Large-wood dynamics a. entrainment b. transport c. deposition • Aquifer dynamics a. recharge b. discharge • Other processes: primary production, heat exchanges, REDOX	1. Hydrological regime variables: • Flow regime (magnitude, variability, floods, and droughts) • Sediment regime • Connection to groundwater 2. Longitudinal river continuity variables 3. Morphological condition variables: • Channel dimensions • Planform • Thalweg • Riverbed structure and grain sizes • Riverbank • Water • Structure of the riparian zone • Structure of the floodplain 4. Physicochemical variables: • Nutrient concentration • Water temperature • Dissolved oxygen

Table 2.
Hydromorphological processes considered and their associated variables for evaluating their effects.

which in turn transform the values of that or other variables. REFORM grouped the hydromorphological variables into flow, flood, flow variability, drought, sediment flow, hydraulic, groundwater connection, longitudinal connectivity, channel dimensions, thalweg, planform, bed substrate, bank, hydraulic energy, riparian, floodplain, and physicochemical variables. Physicochemical variables were included because some impacts of hydromorphological pressures (e.g., large dams) cannot be understood without them.

Anthropogenic impacts of hydromorphological pressures reduce biodiversity by interfering with fluvial succession trajectories, habitat diversification, migratory pathways, and other processes [27]. For each pressure REFORM developed a theoretical diagram of the effects on the system of fluvial hydromorphological interactions [28]. This system is described by the processes involved, the altered variables, and the possible impacts on the biological elements responsible for changes of ecological status.

As an example from the complete set of diagrams [28], **Figure 3** shows the diagram for water abstraction. The red arrows indicate direct effects of pressures on hydromorphological variables, without processes. Water can be abstracted from a river channel by direct surface abstraction or indirect groundwater abstraction.

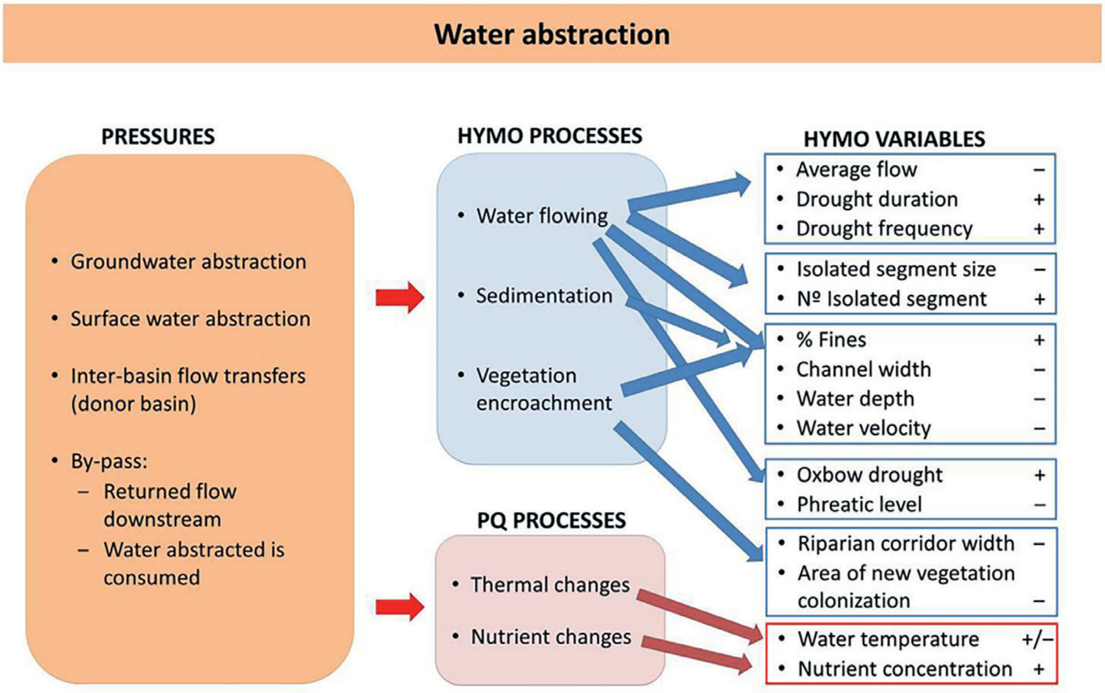


Figure 3.
Conceptual framework representing water abstraction effects on hydromorphological processes and variables that are responsible for their ecological impacts. HYMO stands for hydromorphological and PQ for physicochemical.

Over-abstraction of groundwater can lower the groundwater levels within aquifers or severely reduce the flow in rivers. Surface seepage from aquifers supports groundwater-fed ecosystems such as wetlands and springs. If phreatic levels decline, riparian vegetation rapidly shows signs of water stress and in extreme cases widespread death. Water abstraction alters water flow processes by reducing average flows, reducing flow velocities, increasing duration and frequency of droughts, and lowering phreatic levels. It enhances sedimentation, leading to more fines on the substrate and less water depth and channel width. It reduces the riparian corridor because it forces vegetation to retract at its outer edge, whereas it inhibits invasion of gravel bars due to drought conditions. Finally, water abstraction also alters physicochemical processes by making water temperature more dependent on the air temperature and by increasing eutrophication due to higher concentrations of nutrients in the water.

Changes in the normal functioning of natural and free-flowing rivers occur by natural disturbances, such as floods, droughts, or geological events (**Figure 4**). These disturbances alter the hydromorphological processes that produce changes in habitats and consequently in the biota. However, the resilience capacity of the ecosystem will produce a reversal tendency. Thus, the system follows an oscillatory trajectory that represents the natural variability of the ecosystem and forms an important aspect of its natural biodiversity. The ecosystem services provided by this natural river functioning may be used as a reference.

The non-natural disturbances due to anthropic pressures, however, degrade the status of the fluvial ecosystem and affect its ecosystem services. Some anthropic pressures are hydromorphological as they alter the hydromorphological processes that regulate river functioning. Hydromorphological pressures can change the habitats of biological communities into environments they are not adapted to.

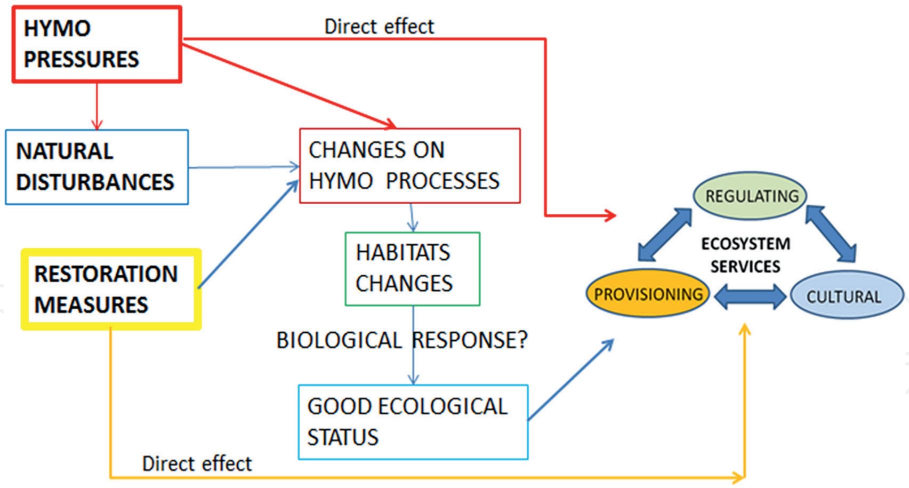


Figure 4.
Mechanisms by which natural disturbances, hydromorphological pressures, and restoration measures may affect fluvial ecosystem services. Direct effects are simple to predict, whereas much more science still needs to be developed for precise predictions of overall interactions affecting hydromorphological processes, habitat changes, and biological response.

This reduces biodiversity or promotes invasive and alien species. Some ecosystem services may also be directly affected by hydromorphological pressures (**Figure 4**). Restoration or mitigation measures are designed to improve habitats, through structural measures or through the recovery of lost hydromorphological processes. Sometimes restoration measures target the recovery of certain ecosystem services. River management thus faces the challenge of understanding how a naturally varying river works, simultaneously subjected to different pressures and programmes of measures.

Main types of restoration measures can be classified according to the hydromorphological elements of the Water Framework Directive [29]:

Water flow quantity improvement:

- Reduce surface water abstraction, with or without return. Improve water retention in upstream catchment. Reduce groundwater extraction. Improve or create water storage. Increase minimum flows. Divert or transfer water. Recycle used water. Reduce water consumption.

Sediment flow quantity improvement:

- Add sediment. Reduce sediment input. Prevent sediment accumulation in reservoirs. Reduce erosion. Improve sediment transport continuity. Manage dams for sediment flow. Trap sediments.

Flow dynamics (water and sediment) improvement:

- Ensure minimum flows. Establish environmental flows. Reduce hydropeaking. Increase frequency and duration of flooding in riparian zones or floodplains. Reduce anthropogenic flow peaks (urban runoff). Favor morphogenic flows. Shorten the length of impounded reaches. Connect flood reduction with ecological restoration. Manage aquatic vegetation.

Longitudinal connectivity or continuity improvement:

- Remove barrier (e.g., weir, dam). Install fish pass or bypass for upstream migration. Facilitate downstream migration. Modify culverts, siphons, and piped streams (e.g., daylighting). Manage sluice and weir operation for fish migration. Apply fish-friendly turbines and pumping stations.

Riverbed depth and width variation improvement:

- Re-meander or widen water courses. Make water courses less deep. Allow or increase lateral channel migration. Make water courses narrower. Create low-flow channels in oversized channels.

In-channel structure and substrate improvement:

- Initiate natural channel dynamics to promote natural regeneration. Remove sediments (e.g., eutrophic, polluted, fine). Modify aquatic vegetation maintenance. Introduce large wood. Add sediments (gravel, sand). Remove bank protection. Re-create gravel bars and riffles. Remove or modify in-channel hydraulic structures. Reduce the impact of dredging.

Riparian zone improvement:

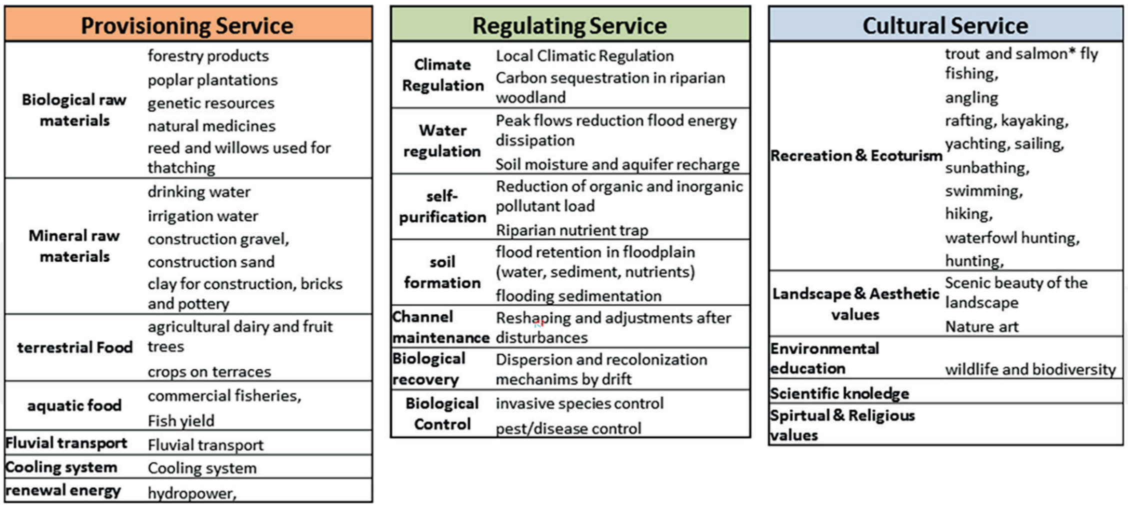
- Adjust land use (e.g., buffer strips) to develop riparian vegetation or to reduce nutrient input, sediment input, or bank erosion. Revegetate riparian zones. Remove non-native substratum. Develop riparian forest.

Floodplains/off-channel/lateral connectivity habitats improvement:

- Make riverbanks or floodplains lower to enlarge inundation. Set back embankments, levees, or dikes. Improve or reconnect backwaters (oxbow lakes) and wetlands. Remove hard engineering structures that impede lateral connectivity. Restore or create wetlands. Retain floodwater (e.g., through local sluice management).

Figure 5 presents the main fluvial ecosystem services that are affected by hydromorphological pressures. Ecosystem services are the benefits that human populations obtain from ecosystems. They can be altered when pressures and water management affect fluvial systems [30]. Three main types have been considered: provisioning, regulating, and cultural ecosystem services. Provisioning services refer to products obtained from ecosystems. Regulating services refer to the benefits obtained from regulating ecosystem processes. Cultural services refer to the nonmaterial benefits that people obtain from ecosystems through spiritual enrichment, cognitive development, reflection, recreation, and esthetic experiences.

Figure 6 shows the effects of water abstraction and corresponding restoration measures on ecosystem services. It shows that water abstraction reduces provisioning services. Reduction of sediment transport affects the provision of mineral raw materials, declined fish habitats affect the provision of aquatic food, and reduced flows affect cooling systems and energy renewal. On the other hand, water abstraction enhances the provisioning service of terrestrial food production as it is mainly done for irrigation and as the remaining low flow rates in the river allow cultivation



Provisioning Service	
Biological raw materials	forestry products poplar plantations genetic resources natural medicines reed and willows used for thatching
Mineral raw materials	drinking water irrigation water construction gravel, construction sand clay for construction, bricks and pottery
terrestrial Food	agricultural dairy and fruit trees crops on terraces
aquatic food	commercial fisheries, Fish yield
Fluvial transport	Fluvial transport
Cooling system	Cooling system
renewal energy	hydropower,

Regulating Service	
Climate Regulation	Local Climatic Regulation Carbon sequestration in riparian woodland
Water regulation	Peak flows reduction flood energy dissipation Soil moisture and aquifer recharge
self-purification	Reduction of organic and inorganic pollutant load Riparian nutrient trap
soil formation	flood retention in floodplain (water, sediment, nutrients) flooding sedimentation
Channel maintenance	Reshaping and adjustments after disturbances
Biological recovery	Dispersion and recolonization mechanims by drift
Biological Control	invasive species control pest/disease control

Cultural Service	
Recreation & Ecoturism	trout and salmon* fly fishing, angling rafting, kayaking, yachting, sailing, sunbathing, swimming, hiking, waterfowl hunting, hunting,
Landscape & Aesthetic values	Scenic beauty of the landscape Nature art
Environmental education	wildlife and biodiversity
Scientific knoledge	
Spirtual & Religious values	

Figure 5.
List of main fluvial ecosystem services that are affected by hydromorphological pressures, classified according to provisioning, regulating, and cultural services.

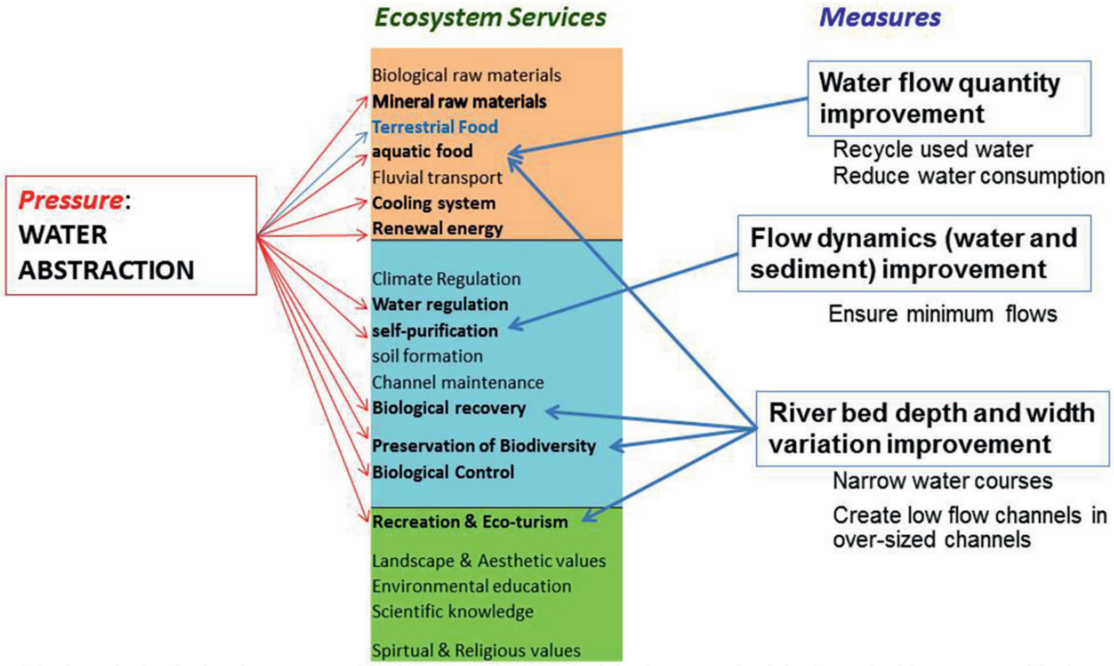


Figure 6.
Scheme of interactions among water abstraction and restoration measures and their effects on ecosystem services. Red arrows indicate inhibit services and blue ones improve them.

of the riverbanks. The figure shows that regulating services are reduced too: water regulation, self-purification, biological recovery, preservation of biodiversity, and biological control. Finally, among the cultural services, flow reduction affects mainly recreation and ecotourism.

Figure 6 shows three possible restoration measures for mitigating the effects of water abstraction:

1. Water flow quantity improvement, by recycling used water and reducing water consumption;

2. Flow dynamics improvement, by ensuring environmental flows;

3. Channel depth and width improvement (although the structural measure of concentrating reduced water flows in narrow water courses and low-flow channels is not sustainable from a geomorphological point of view).

None of these measures mitigates the degraded services of mineral raw materials, cooling, energy renewal, and water regulation. Restoration of these services would have to be the focus of further research and innovation.

4. Conclusion

This chapter has presented methods to assess hydromorphological quality and diagnose alteration in rivers, as well as systematic cause–effect relationships for diagnosis and for river restoration measures. They constitute guidance and tools for addressing hydromorphology in the implementation of the Water Framework Directive.

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