HyMoCARES project

WPT1. Ecosystem Services (ES) assessment framework

D.T1.2.1 "Report on functional dependencies of ES on river hydromorphology"

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Authors: Mauro Carolli, Martin Pusch, Gabriela Costea, Isabelle Chouquet, Mario Klösch, Mélanie Bertrand, Bruno Boz, Roman Dunst, Giuseppe Fragola, Romain Gaucher, Andrea Goltara, Luka Javornik, Frédéric Liébault, Nicola Marangoni, Peter Molnar, Sebastian Pessenlehner, Daniele Rossi, Davor Rozman, Sašo Šantl, Klemen Savli, Ursula Stephan, Helmut Habersack, Stefano Tettamanti, Sebastiano Piccolroaz, Paolo Negri, Felix Reebs, Andrea Betterle, Andrea Salvetti, Sandro Peduzzi

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1 Introduction

This report reviews the functional dependencies of ecosystem services (ES) on river hydromorphology, mainly based on existing published literature and on the outcomes of previous EU and national projects, which was supplemented by expert opinion from the project consortium.

The relationships between the environment and ecosystem services have been conceptualized in the cascade model proposed by Haines-Young and Potschin (2010) (see also HyMoCARES deliverable D.T1.1.1), which represents the leading current conceptual framework linking environmental processes with ecosystem functions, which in turn determine ES. Following that approach, it is expected that modifications (alteration or restoration) of hydromorphological processes in river corridors always are associated with positive or negative effects on the availability of typical ES provided by rivers and floodplains. Hence, the identification of relevant processes and functions determining ES availability is fundamental in order to understand the functional dependencies of ES on river hydromorphology.

On that purpose, the cause-effect links side need to be established between the various processes and functions in river corridors to i) river hydromorphology on one side and ii) to ES availability on the other side to properly identify the most relevant drivers for change in ES provision.

As the hydromorphology of rivers has been extensively modified by humans, we review in the second part of the report the most common management actions that could be implemented in Alpine rivers to restore their natural conditions, identified their influence on processes and functions, and, consequently, on the availability of ES. Following the same work flow described above, we first present the set of relevant management actions, and then illustrate the links between management actions, processes, functions and ES.

This structure represents the basis of the HyMoCARES conceptual framework, through which the effects of management actions on ES can be monitored, assessed, or predicted applying the tools identified and elaborated in WPT2.

2 Processes and functions

In this chapter we define processes and functions, and the links to the ES identified in D.T T1.1.1. As management actions can modify processes and functions which form the basis for ES, this report on functional dependencies of ES on river hydromorphology also includes a paragraph establishing proper definitions of respective terminology.

2.1 Boundary conditions

The processes, functions and ES of river corridors are restricted and shaped by boundary conditions which are provided by the combination of the orography, geology, climate (including precipitation regime), and land use of the river catchment. Typically, Alpine river corridors are often confined by steep valley slopes, which influence the river and floodplain morphology (e.g., Fryirs et al., 2016). Other boundary conditions are the regional snowfall and rainfall regime and the presence of snow fields and glaciers, which profoundly influence the flow regime of river systems. Regional orography and geology especially influences the erosion rate in the catchment, and thus the rate and type of sediment supply to the river, which profoundly shapes river channels and floodplain structure. Accordingly, hydromorphological analyses need to follow a multi-scale approach (Habersack, 2000; Gurnell et al., 2016; Klösch and Habersack, 2017).

In several Alpine rivers, the effects of human interventions have largely altered the features of river corridors which were originally determined by natural physical components. Typically, sediment supply is reduced given various types of structures acting as sediment barriers, and river channels were artificially straightened, narrowed and fixed, which increases flow velocity, and may thus transform an originally braided river channel into a type resembling a naturally constrained river channel with a supply-limited regime (*sensu* Montgomery and Buffington, 1997).

2.2 Definition of processes

Following the definition of ecosystem services (ES), several definitions of ecosystem processes and functions have been proposed in the literature. In general, though, the term "process" in this context indicates the basic biological and physical transformations that shape an ecosystem. Natural processes can be considered as the result of complex interactions between the biotic and the abiotic attributes of an ecosystem (de Groot et al., 2002). According to the Millennium Ecosystem Assessment report, an ecosystem process is "an intrinsic ecosystem characteristic whereby an ecosystem maintains its integrity (MEA 2005)". Ecosystem processes are for example photosynthesis, microbial respiration, nutrient cycling (Virginia and Wall, 2000). Ecosystem processes "combine abiotic activities and the result of the life-processes of organisms' communities, and their interactions with the abiotic environment" (TEEB 2010).

The EU REFORM project, which has focused specifically on river hydromorphology, suggested a more targeted definition of processes as "the events that result in a transformation in a physical component of the fluvial system" (Garcia de Jalon et al., 2013).

As hence the definition of a process appears quite similar throughout various publications and projects, the HyMoCARES consortium decided to integrate the definition provided by TEEB with the REFORM definition, resulting in the definition of process as "***the abiotic and biotic dynamics that shape the physical component of the fluvial system***".

REFORM has identified six families of hydromorphological processes which also interact among them, and which represent the basis for ecosystem functions, and thus influence directly or indirectly the ES provided by rivers (Garcia de Jalon et al., 2013). We started from the definition provided in REFORM and modified the families of hydromorphological processes as follows:

1. Water flow dynamics
2. Sediment dynamics
3. Morphodynamics
4. Vegetation dynamics
5. Large wood dynamics
6. Aquifer dynamics

Tab. 1 Overview on the hydromorphological processes analysed in the HyMoCARES project, modified from the list elaborated by the EU REFORM project (Garcia de Jalon et al., 2013).

Processes	Sub-processes
Water flow dynamics	Seasonal dynamics
	Short-term dynamics
	Flow velocity
	Flow depth
Sediment dynamics	Fluvial sediment transport (bedload and suspended load)
	Sediment supply (endogenous and exogenous)
Morphodynamics	Lateral shifting of river channels
	Scour and fill processes
	Bedform development
	Bar formation
Vegetation dynamics	Vegetation recruitment
	Vegetation encroachment
	Vegetation disturbance
Large woody debris dynamics	Large wood entrainment
	Large wood transport
	Large wood deposition
Aquifer dynamics	Aquifer recharge
	Aquifer discharge

2.2.1 Detailed processes description

Water flow dynamics

Water flow dynamics is the result of rainfall events, snow and ice melting, catchment orography, soil and vegetation cover which together determine the rate with which water is conveyed from the catchment to the stream system. It can be characterized by several parameters such as average flow, fluctuations, and frequency of high and low flow events (Richter and Baumgartner, 1996). Basic features of the flow regime are the typical and predictable seasonal variations of flow, and the frequency of unpredictable flow peaks within various seasons. Complex interactions between water discharge and boundary conditions (relief and land-use of the valley floor) determines the spatial distribution of flow velocity and water depth, which in turn controls the sediment transport capacity of river channels and the river morphology.

The typical temporal pattern of water discharge fluctuations of a river represents one of the fundamental drivers of hydromorphological processes. The river discharge remains in the river channel up to bankfull discharge, and inundation of the floodplain occurs when the bankfull capacity is exceeded. Although extreme flood events can have significant morphological effects on rivers and their corridors, it is generally recognized that the bankfull geometry of stream channels is adjusted to flow events of moderate intensity (with return periods generally less than 2 years), and that the most effective discharge in terms of sediment transport is the bankfull discharge (Knighton, 1998).

Sediment dynamics

Sediment dynamics refer to the physical processes of sediment production, transport, and deposition in river catchments. In alpine basins, sediment production is strongly controlled by the geomorphic activity of hillslopes (e.g. land sliding, gullying, debris flows), which is a function of the geology, relief, climate and land-use. It is generally proposed to differentiate the exogenous sediment supply (coming from sediment sources outside the active channel, like hillslopes, floodplains, and terraces) from the endogenous sediment supply (coming from in-channel alluvial storage, like gravel bars).

Once sediment is delivered to the stream network, they are transported downstream by the flowing water during floods, as suspended load (for silts and clays), and as bedload (for sands, gravels, cobbles, and boulders). It is recognized that bedload transport strongly interacts with river channels, resulting in the creation and destruction of macroforms, as well as in the lateral shifting of river channels. Mutual interactions between grains during transport, as well as interactions between grains and the transporting fluid are at the origin of complex physical processes of grain segregation and grain-size sorting, which determine specific sedimentological features of stream channels (e.g. coarse surface layer or bed armoring, clogging or colmation, formation of gravel bars). The magnitude of bedload transport during flow events is a function of the transport capacity of the flow (depending on the slope and the discharge or depth of flow), and the sediment supply.

The downstream transfer of bedload along the river network is known to be an intermittent and slow process, with a resulting strong imprint on channel morphology. The suspended load is generally rapidly flushed from the catchment, except during flow discharges above the bankfull capacity, which generate overbank deposition of fines in the floodplain. In some circumstances, fine sediments may accumulate in active channels and induce clogging (or colmation), a process which is known to reduce the porosity of gravels by the deposition of inorganic or organic fine sediments in the interstitial spaces of coarse sediment. Colmation rate is increased e.g. by higher inputs of fine sediment to a river system, or by artificial frequent changes of the water level. Colmation can be reversed by mobilization of sediments during high discharge, which results in the resuspension of fine sediments, and thus in the decolmation of coarse sediments.

Morphodynamics

In morphodynamics we include all the processes that ultimately shape the river morphology.

Lateral shifting of river channels is associated with bank erosion and/or bank accretion. The major processes of bank erosion are bank failures following geotechnical instability (induced by gravitation) as well as fluvial erosion (induced by the shear stresses of the flow), which erodes coarser or finer sediment particles or aggregates from the river bank surface or removes failed material which accumulated along the bank toe. Both, bank failure and fluvial erosion, deliver bed- and/or suspended to the sediment load into river. Bank erosion is often accompanied by aggradation, causing the bank accretion at the opposite bank or the emergence or enlargement of channel bars.

Scour and fill processes result from deposition and erosion of sediment, causing changes in the elevation of the riverbed or floodplain. The tendency of sediment to deposit or erode is determined by changes in the hydraulic load (due to increased or decreased bed shear stresses and turbulence), which is exerted to the riverbed, as well as by the quantity and quality (grain size) of the supplied sediment.

The development of bedforms (ripples, dunes, antidunes) occurs depending on the grain size and the hydraulic load. Diagrams were provided by e.g. Simons and Richardson (1966) or Allen (1983), which predict the existence of bedforms depending on the grain size and the unit stream power or bed shear stresses, respectively. Bedforms are small compared to larger morphologic features such as bars, but may add form roughness to the riverbed (hence increasing water levels) and additionally influence the sediment transport characteristics.

Bar formation is characteristic for braided rivers as well as for the alternating bar-type and transitional rivers between the state of braiding and meandering (wandering rivers). In the state of dynamic equilibrium, the aggradation needed for bar formation increases the hydraulic load onto the surrounding riverbed and banks, hence often accompanied or followed by erosion. Excessive bank erosion was observed to occur after the inception of mid-channel bars (Knighton, 1972), affecting also banks which are not exposed to erosive shear stresses during flood events given a time-lag between aggradation and erosion (Klösch et al., 2015).

Vegetation dynamics

Vegetation interacts with water and sediments, and both affects and is affected by morphodynamic processes of rivers (Gurnell 2014; Hickin 1984).

Vegetation recruitment consists in the plant colonization of available non vegetated habitat created by in-channel or floodplain processes. Recruitment speed depends on the autoecology of the various species (dispersal ability, growth), and especially on the presence of dispersal units (seeds, shoots) in newly deposited sediments. Vegetation recruitment interacts with the sediment regime by trapping fluvial sediments and stabilize river forms, but may also initiate sediment erosion in neighboring areas.

Vegetation encroachment means the extension of a vegetated patch to invade other areas. It depends on well-known hydromorphological conditions (e.g., flow reduction). It has well-studied consequences on riverine processes and ecology (Miller et al., 2013; Bejarano et al. 2011, Hickin 1984).

Vegetation disturbance is e.g. the eradication of vegetation mainly by two mechanisms: direct uproot if the drag forces imposed by flow are larger than the plant resistance; or uproot as a result of the local erosion of riverbed sediments around the plant (Edmaier et al., 2011)

Large wood (LW) dynamics

'Large wood' refers to large pieces of trees (> 1m in length, > 0.1 m in diameter, Garcia de Jalon et al., 2013), or whole trees entrained into the water (driftwood), which may exert profound impacts on river morphodynamics (Gurnell, 2014).

LW deposition may result from receding flow, or by the physical retention of LW by obstacles in the flow channel. Thereby, accumulations of LW may be formed which significantly interact with flow and sediment transport. LW consists mainly by dead material, but some tree species (as willows) may regrow from a drifted stem, and then stabilize bank and morphological structures. In this way, LW deposition may trigger processes as bank or bed erosion and the formation of pools. LW thus represents a key component of fluvial landscapes, and provides unique habitats supporting aquatic and terrestrial biodiversity. LW entrainment is the input of LW after removal from the river bank or floodplain. LW transport is the downstream movement of LW by drift, especially during high flow events.

Aquifer dynamics

Rivers flowing in an alluvial plain consisting of permeable substrate, which thus comprises an aquifer, interact with the groundwater of the floodplain sediments. The interaction depends on hydraulic parameters and sediment properties.

Aquifer recharge or infiltration is the flow of water from the river or its floodplain into the aquifer. The water can flow from the river bed, banks and riparian areas through the hyporheic zone to the groundwater, or can infiltrate vertically during floods.

Aquifer discharge or exfiltration is the flow from groundwater to a surface water or to the land surface. The water can flow directly into the river bed or emerge in springs.

2.3 Definition of functions

In the ecological literature, the term "ecosystem function" has been subject to various interpretation: it is sometimes used to indicate the functioning of the ecosystem, sometimes it is related to the human benefits due to ecosystem processes and properties, sometimes processes and functions are not separated (Boyd & Banzhaf 2006).

De Groot et al. (2002) defined ecosystem functions as “the capacity of natural processes and components to provide goods and services that satisfy human needs, directly or indirectly”. Similarly, TEEB defines ecosystem functions are “a subset of the interactions between ecosystem structure and processes that underpin the capacity of an ecosystem to provide goods and services “(TEEB, 2010).

The HyMoCARES consortium decided to basically follow the TEEB definition of functions, which is consistent with the definition of ES and processes that is used in HyMoCARES D.T1.1.1 and in the previous paragraph of this document. In HyMoCARES, the definition provided by TEEB is further specified, defining functions as “***the result of the interactions among boundary conditions and biotic and abiotic processes that influences positively or negatively the capacity of an ecosystem to provide goods and services***”. Following the former list of processes, we selected a number of functions (see below) which are initiated by these processes and that we considered relevant for river ES.

Thereby, we are aware of the fact that some of the processes presented in the previous paragraph can be considered as functions from a river ecosystem services perspective, as they could have a direct effect on river ES. Similarly, the functions listed below may be influenced by other functions, too, including possible feedback effects.

2.3.1 Functions

The HyMoCARES list of the functions of river corridors and their relationships with the previously defined processes are summarized in Tab. 2.

Biochemical cycling of chemical compounds

The rate of biochemical cycling of chemical compounds (e.g. organic substances, plant nutrients) depends on the presence of a functional riparian strip (Vought et al., 1994), and on the presence and concentrations of these compounds (incl. dissolved oxygen), on temperature, and on the area of substrate surfaces colonized by biofilms which are overflown by river water. The biofilm-covered surfaces (e.g. stone, gravel or sand particle surfaces) may be present at the river bed or in the hyporheic zone (Pusch et al., 1998; Fischer et al., 2005). The physic-chemical quality of river water is the quality of water assessed by measuring the concentration of substances entering streams due to human activities, including priority substances, included in the Water Framework Directive Annex X (Annex II of Directive on Environmental Quality Standards (EQSD; 2008/105/EC). The physic-chemical quality of river water thus represents the result of the respective biogeochemical background (boundary) conditions of the catchment modified by the inputs of various dissolved compounds due to human activities. Inputs are subject to biochemical transformations and degradation by the riparian areas (also called biochemical retention or self-purification) and, inside the river channel, are processed mainly by the benthic and hyporheic biofilms. Thereby, the areal extent of active biofilms represents a result of several processes, as flow dynamics, morphodynamics, sediment dynamics, vegetation dynamics.

Biotic communities (Biocenosis)

Biotic communities are the populations of various species of flora, fauna and microbiota (thus ranging from algae to fish, to terrestrial fauna) living in the same habitat, interacting and establishing functional links and dependencies. The site-specific composition of biotic communities is the result of biogeographical boundary conditions, of the tolerance and/or needs of each species towards the hydromorphological processes previously defined, and of species-specific competitive strength in the interactions (resource competition, consumption, predation, parasitism) among the biological components. The biotic community is the result of the interaction among several processes as water flow dynamics, sediment dynamics, morphodynamics, vegetation dynamics.

Hydraulics

This function represents the spatial and temporal distribution of local hydraulic variables resulting from the interaction between the flow rate dynamics (i.e. the "hydrological regime" function) and the local morphology Hydraulic variables can be for example flow depth, velocity, shear stress.) Hydraulics is the result of the interaction between river morphology and instream flow regime.

Instream flow regime

Instream flow regime represents the integrative result of water flow dynamics and boundary conditions during a hydrological year.

Lateral connectivity

This function represents the degree of interaction between the river and the floodplain, especially during high flood events (Ward 1989) in terms of hydromorphological processes (e.g., erosion and deposition) and exchanges of water, energy and biomass. Lateral connectivity is the result of morphodynamics, sediment continuity, and water flow dynamics.

Physical habitat

The physical habitat is the ensemble of the physical components of the river habitat. These components are for example water depth, flow velocity, water temperature, substrate type and size distribution, oxygen concentration, chemical parameters, degree of shading, or the presence of backwaters (Allan, 2007). In addition to stream channel features, riparian components as vegetation, river banks, floodplain represent additional fundamental characteristics of the river physical habitat. The physical habitat reflects the interactions among water flow and sediment dynamics, morphodynamics, vegetation dynamics, LW dynamics.

Presence and composition of riparian vegetation plant community

In this function we considered both riparian and floodplain vegetation. The plant community is the functional result of the interaction among vegetation dynamics, spread of plant dispersal units (e.g. seeds), water flow dynamics (water availability, flow variations, new colonization areas) and sediment dynamics (substrate).

River morphology

River morphology represents the typical shape of river channels and of their floodplains, which is a result of continuing morphological dynamics in space and time. River morphology results from the interaction of several processes, as water flow dynamics (e.g., bed shear stress), sediment dynamics (e.g., erosion, sediment transport, deposition), morphodynamics (e.g. bank erosion, bank accretion), and vegetation dynamics (e.g., encroachment), LW dynamics (e.g., supply). Thereby, river morphology is a function which influences several other functions.

Sediment continuity

Sediment continuity represents the cascading fluxes of sediment (and woody debris) and associated temporary storages of alluvium along the stream network, supporting physical habitats of river channels and floodplains. It can be seen as the source-to-sink longitudinal connectivity of sediment in river catchments. Sediment continuity is controlled by interactions between the flow regime, sediment transport processes, and channel morphology. It is the primary determinant of river morphology, especially in Alpine environments where channel forms are known to be highly sensitive to fluctuations in sediment supply. Sediment continuity is the main driver of the morphological activity of river channels (e.g. bank erosion, lateral shifting, dynamics of gravel bars), which in turn plays a crucial role in terms of habitat diversity in river corridors. It is influenced by water flow dynamics (water depth, flow velocity) sediment dynamics, river morphology, vegetation.

Vertical connectivity

It is the degree of hydraulic connection between surface and shallow groundwater (Ward 1989). It is a function resulting from several processes, as aquifer discharge and recharge, sediment sorting and type, armoring and colmation of the river bed.

Tab. 2. Functions adopted by HyMoCARES.

Process	Function
Water flow dynamics	Instream flow regime
Water flow dynamics; sediment dynamics; LW dynamics	Sediment continuity
Water flow dynamics; sediment dynamics; morphodynamics	Hydraulics
Vegetation dynamics; water flow dynamics, sediment dynamics, morphodynamics	Presence and composition of riparian vegetation
Water flow dynamics; sediment dynamics; morphodynamics; Vegetation dynamics; Large wood dynamics	River morphology
Aquifer dynamics; sediment dynamics	Vertical connectivity
Morphodynamics; water flow dynamics	Lateral connectivity
Water flow dynamics; sediment dynamics; morphodynamics; Vegetation dynamics; Large wood dynamics	Physical habitat
Water flow dynamics; sediment dynamics; Vegetation dynamics	Biochemical cycling of chemical compounds
Water flow dynamics; morphodynamics; sediment dynamics; vegetation dynamics; aquifer dynamics	Biotic communities (Biocenosis)

All these functions influence each other in different ways and at different degrees, building a complex network of interactions, linkages and feedback effects. The network is shown in Fig. 1. We used this network as a starting point to highlight the interactions among functions for each management actions.

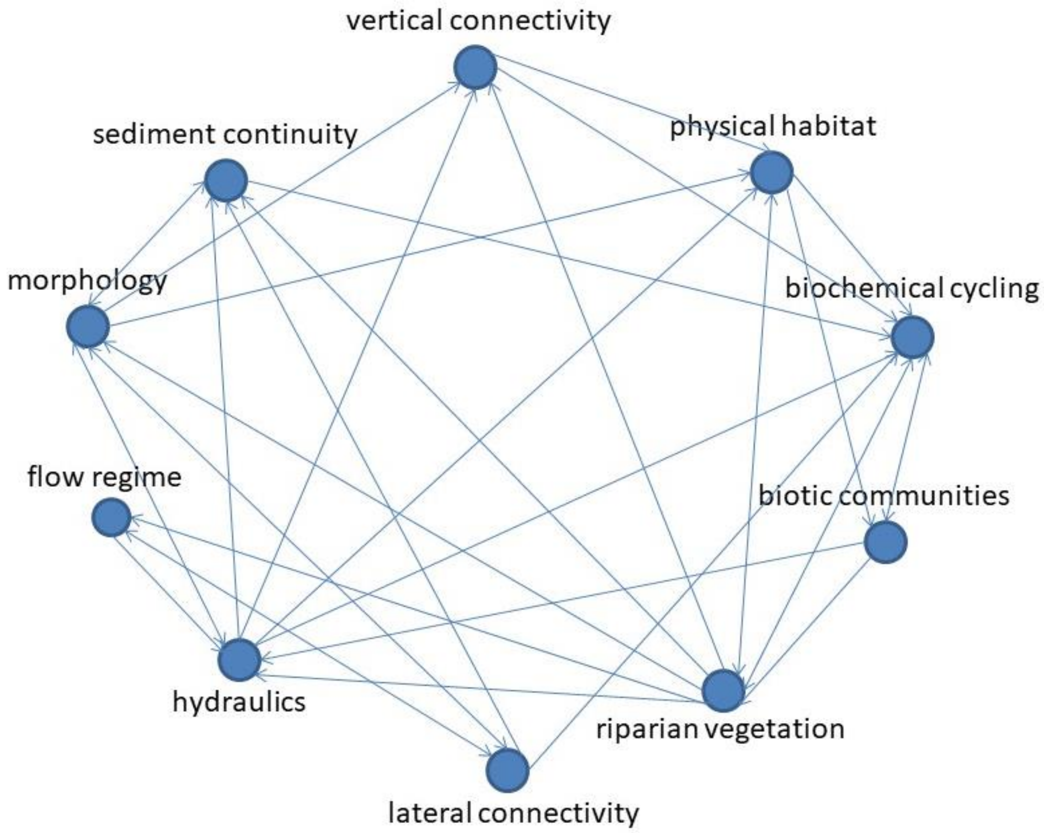

Fig. 1 Graphical representation of the interactions among the different functions (author: F. Liebault).

2.3.2 Functions' parameters

In the following paragraph we present a list of the parameters that the project partnership identified as relevant to assess the formerly described functions.

Biochemical cycling of chemical compounds

Tab. 3. Parameters suggested to assess the function.

Parameter	Unit of measure
Carbon cycle - COD	[mg/l]
Nitrogen Cycle - Total nitrogen	[mg/l]
Phosphorous cycle - Total P	[mg/l]
Oxygen - BOD5	[mg/l]
Hydrogen cycle -	
Sulfur cycle -	
Silica cycle -	

Biotic communities (Biocenosis)

Tab. 4. Parameters suggested to assess the function.

Parameter	Unit of measure
Macrozoobenthos abundance	[ind/m2]
macrozoobenthos community composition	[species number]
Fish community composition	[species number]
Biodiversity indicators [Shannon index]	[Shannon index]
Birds community composition [species number]	[species number]
Presence of rare species (birds, fish, amphibians, reptile, plants)	[species number]
Macrozoobenthos abundance	[ind/m2]

Hydraulics

Tab. 5. Parameters suggested to assess the function.

Parameter	Unit of measure
mean water depth at low, mean, high flow	[m]
maximum water depth at low, mean, high flow	[m]
wetted width at low, mean, high flow	[m]
wetted perimeter at low, mean, high flow	[m]
wetted area at low, mean, high flow	[m^2]
hydraulic radius at low, mean, high flow	[m]
variance of maximum depth	[m^2]
relation of water depth and wetted area	[-]
mean flow velocity at low, mean, high flow	[m/s]
maximum flow velocity at low, mean, high flow	[m/s]
bed slope	[-]
energy gradient	[-]
mean shear stress at low, mean, high flow	[N/m^2]
maximum shear stress at low, mean, high flow	[N/m^2]
mean specific stream power at low, mean, high flow	[N/ms]
maximum specific stream power at low, mean, high flow	[N/ms]
roughness (grain roughness, form roughness)	[$m^{1/3}/s$]

Instream flow regime

Tab. 6. Parameters suggested to assess the function.

Parameter	Unit of measure
Mean or median discharge for each month [mc/s]	[m^3/s]
Annual minima, 1-day mean [mc/s]	[m^3/s]
Annual minima, 3-day mean [mc/s]	[m^3/s]
Annual minima, 7-day mean [mc/s]	[m^3/s]

Parameter	Unit of measure
Annual minima, 30-day mean [mc/s]	[m^3/s]
Annual minima, 90-day mean [mc/s]	[m^3/s]
Annual maxima, 1-day mean [mc/s]	[m^3/s]
Annual maxima, 3-day mean [mc/s]	[m^3/s]
Annual maxima, 7-day mean [mc/s]	[m^3/s]
Annual maxima, 30-day mean [mc/s]	[m^3/s]
Annual maxima, 90-day mean [mc/s]	[m^3/s]
Number of zero-flow days [day]	[day]
Base flow index []	[]
Julian date of 1-day minimum [date]	[date]
Julian date of 1-day maximum [date]	[date]
Number of low flow pulses [count]	[count]
Mean (median) duration of low flow pulses [sum of days]	[sum of days]
Number of high flow pulses [count]	[count]
Mean (median) duration of high flow pulses [sum of days]	[sum of days]
Indicators of sub-daily alterations, HP1 [-]	[-]
Indicators of sub-daily alterations, HP2 [mc/sh]	[m^3/sh]
Minimum flow [mc/s]	[m^3/s]

Lateral connectivity

Tab. 7. Parameters suggested to assess the function.

Parameter	Unit of measure
flooding frequency	[1/a]
bank erosion rate	[m/a]
channel migration	[m/a]
channel widening	[m/a]
degree of channelization	[HyMoCARES lateral River Freedom Index]
connectivity of side channels, oxbows: discharge partition for low, mean, high flow [%]	[%]
connectivity of side channels, oxbows: duration of connection for low, mean, high flow [days per year]	[days per year]
groundwater recharge	[m^3/year]

Physical habitat

Tab. 8. Parameters suggested to assess the function.

Parameter	Unit of measure
Weighted usable area (wetted channel)	[m^2]
Area covered by natural riparian habitat	[m^2]
Weighted usable area normalised by maximum WUA among different discahrge (wetted channel) [-]	[-]

Presence and composition of riparian vegetation plant community

Tab. 9. Parameters suggested to assess the function.

Parameter	**Unit of measure**
Plant species composition	[species list]
Density	
Structure	[species composition]
Age	[year]
Leaf Area Index (LAI) [m^2/m^2]	[m^2/m^2]
Canopy Percentage Foliage Cover (CPFC)	
Height [m]	[m]
Crown size	
Stem diameter at breast height (DBH)	[m]
Riparian zone width	[m]
Cover	
Richness	[species list]
Diversity Index	[-]
Dominance	[-]

River morphology

Tab. 10. Parameters suggested to assess the function.

Parameter	**Unit of measure**
channel slope	[m/m]
active channel or bankfull width	[m]
bankfull depth	[m]
width-depth ratio	[adim]
bed elevation	[m]
channel roughness metrics	
bed relief index	[m]
braiding indexes	
sinuosity	[-]
surface grain-size distribution (percentiles in mm)	[mm]
subsurface grain-size distribution (percentiles in mm)	[mm]
scour and fill depths	[m]
morphological quality index	

Sediment continuity

Tab. 11. Parameters suggested to assess the function.

Parameter	**Unit of measure**
sedimentation in a reservoir (bedload, suspended sediments,)	[m3/year]
erosion in a reservoir (bedload, suspended sediments) m^3/year]	[m3/year]
sediment throughput (bedload, suspended sediments): frequency	[m3/year or per event]
sediment throughput (bedload, suspended sediments): quantity	[m3/year or per event]
sediment throughput (bedload, suspended sediments): quality	[m3/year or per event]
sediment velocity	[m/year]
sediment consumption	[m3/year]
trap efficiency e.g. after Brune	[%]
flushing efficiency	[Volume of sediments mobilised vs used water volume]
turbidity current - Sediment concentration	[mg/l]

Vertical connectivity

3 Management actions

As everywhere in the EU, agencies which deal with the management of rivers and floodplains have to consider a variety of management goals provided by the sectoral legal frameworks, as the EU Water Framework Directive, EU Flood Risk Directive, EU Habitats Directive, national legislation on hydropower use, etc. In many cases, implementation of these legal frameworks will result in potential conflicts. Such conflicts are often due to an insufficiently wide range of alternatives taken into account, and due to consolidated positions of stakeholder groups, that are not based on an exhaustive assessment of the effects of each alternative. The adoption of an evaluation approach based on the concept of ES may help to identify "hidden" benefits of some management actions, as well as synergies between the objectives of different stakeholders, ultimately reducing the conflict.

In order to establish the linkages between management actions and ES, we below define a set of standard management or structural measures aiming at the (ecological) restoration of rivers. Most hydromorphological restoration projects usually involve at least one of these measures. These are usually based on removing, mitigating, or compensating a pre-existing pressure. As the logical connections between a restoration action and a given ES are usually the same (though with opposite "direction") that can be established between the corresponding pressure/alteration action and the same ES, we associated to each restoration measure the corresponding alteration.

Tab. 12. List of the management actions and of the corresponding alterations studied in the HyMoCARES project.

Management action	Corresponding alteration
Sediment recharge / restoration of sediment continuity	Gravel extraction
Channel widening	Channelization
Creation of macroforms	Removal of river macroforms, making artificially homogeneous river sections
Dam removal	Dam construction
Deculverting	Culverting
Ensuring ecological flow	Water abstraction
Reintroduction of large woody debris	Removal of large woody debris
Remeandering	Straightening
Removal of bank protection	Bank protection construction
Floodplain reconnection (removal, retreat of levees)	Levees construction
Replanting of in-channel and riparian vegetation	Removal of in-channel and riparian vegetation
Weir removal	Weir construction

Sediment recharge / restoration of sediment continuity (↔ Gravel extraction)

Significant amounts of sediments with the particle size of the natural bedload of the river are artificially added to the river channel, especially in river reaches affected by channelization or former gravel mining and downstream of barriers (dams, weirs). In case the sediment transport capacity allows the formation of aggradational features (not the case in strongly narrowed channels), this measure will have significant effects, in case there is enough space between eventual constraints, on: physical habitat due to restoration of mesohabitat and pool/riffle sequences (Merz and Ochikubo Chan, 2005; Ock et al., 2013); riparian vegetation (Ock et al., 2013); morphodynamics, river morphology (Ock et al., 2013; Gaeuman et al., 2017); sediment supply (Venditti et al., 2010), lateral (if banks are not protected) and vertical connectivity.

Channel widening (↔ Channelization, channel narrowing)

Widening of river channels to restore a natural cross-section (widening, braiding) is often associated with a restoration of the channel planform (re-meandering, see below). However, it has to be highlighted that channel widening can be a restoration or an artificialization measure, depending on the specific reference conditions. Channel widening can be actively performed by the use of excavators, or passively by the removal of bank protection or the setback of the levees, which will reactivate natural morphodynamic processes leading to a widening of the river channel (Habersack and Piegay, 2007; Habersack et al., 2013). Effects of this measure are expected on physical habitat due to change in width, velocity and mesohabitat patches (Jähnig et al., 2009; Jähnig et al., 2009b), on river morphology (Habersack and Nachtnebel, 1995) and on lateral connectivity (Gumiero et al., 2013), as well as on sediment and LW supply (Hauer and Lamberti, 2017; Surian and Rinaldi, 2003) and river communities (Chovanec et al., 2002). Additionally, effects on water quality may be expected. A precondition for the river to sustainable flow in a widened bed is sufficient sediment supply. To maintain sufficient hydraulic load along the banks for preserving the dynamics of bank erosion, aggradational features such as bars are needed (Klösch et al., 2015), requiring sediment supply from upstream.

Creation of macroforms (↔ Removal of river macroforms, making artificially homogeneous river sections)

It is the artificial construction of river morphological macroforms as bars, riffles, pools. Effects are expected on physical habitat due to the modification of the hydraulic variables (De Almeida and Rodriguez, 2011) and of the substrate, on riparian vegetation, on biotic communities due to the increase in habitat diversity.

Check dam removal (Check dam construction)

Check dams are grade-control structures deployed in steep slope torrents built to trap the sediment transport (bedload and/or debris flows), generally upstream debris fans. Check dam removal will have expected effects on the sediment and LW supply to downstream river sections (Schmidt and Wilcock, 2008) due to the restored possibility of sediments to move along the river channel, which will stop the trend to river incision downstream the dam (Petts 1984). Check-dam removal is expected to improve sediment continuity (Wang et al., 2016). Sediment retention basins are check-dams with a retention basin. The removal of sediment retention basins has been considered as a type of check dam removal.

Dam removal (↔ Dam construction)

It is the complete removal or the increase of the permeability of sediment and water barriers. Effects on sediments are similar to effects expected for check dam removal. Effects on instream flow regime are broadly described in scientific literature (e.g., Poff and Hart, 2002), river morphology (Pizzuto, 2002), lateral and vertical connectivity (Giardino and Houser, 2015), and on biotic communities (Poff et al., 2007), as the developing morphology is strongly dependent on the sediment supply (Schumm, 1985; Church, 2006; 2007). Moreover, effects on biochemical cycling are expected as well. The removal of sediment retention basins has been considered within this action.

Deculverting – Culverting

Deculverting means opening up watercourses that have been buried in order to restore more natural conditions. Deculverting projects may involve a simple removal of the river roof, up to a complete reshaping of river's bed and banks (Wild et al., 2011). Positive effects or deculverting are predicted, but still unclear.

Ensuring Ecological flows (↔ Water abstraction)

Increase of minimum flow and restoration of natural variations of the flow regime. E-flow is "a hydrological regime consistent with the achievement of the environmental objectives of the WFD in natural surface water bodies" (CIS guidance n. 31, 2015). Effects are expected on Instream flow regime, on physical habitat (CIS guidance n. 31, 2015), and on the biotic communities due to the restoration of a natural regime (CIS guidance n. 31, 2015).

Reintroduction (↔ removal) of Large Woody Debris (LWD)

Placement of large woody debris and other wood structures to enhance riverine habitats (see the review by Roni et al., 2015). In many cases, the pieces of LW are fixed by cables etc. in order to prevent drift at high flow events. Placement of large woody debris nowadays represents a common and widely applied management practice with proven effects on physical habitat, on fish communities and abundance, especially for salmonids (Roni et al., 2015).

Remeandering (↔ Straightening)

Recreation of meanders in straightened and channelized rivers. Remeandering can be performed by re-activating an artificially short-cut river meander (oxbow lake), by artificially digging a new sinuous channel, or by triggering lateral erosion. Such measures will have effects on physical habitat due to the increase of depth variability and recreation of riffle/pool sequences (Klein et al., 2007; Pedersen et al., 2007), on river morphology (Sear et al., 1998), on sediment supply and LW supply (Sear et al., 1998). Effects are expected on river confinement, on biochemical cycling and biotic communities due to an increase in nutrient retention time (Bukaveckas 2007)

Removal of bank protection (↔ Bank protection construction)

Removal of bank protection structures (e.g., riprap) is expected to have effects on sediment and large wood entrainment, physical habitat (Rohde et al., 2005), riparian vegetation due to the restoration of a riparian ecosystem (Rohde et al., 2005), lateral connectivity (Chovanec et al., 2002), and on the river communities (Chovanec et al., 2002).

Floodplain reconnection (removal, retreat of levees) (dykes) (↔ Levees construction)

Floodplain reconnection (removal, retreat of levees) may be performed either without removal of bank protection, or in parallel with the removal of bank protection. In case bank protection remains, the effect of the Floodplain reconnection (removal, retreat of levees) consists in the re-establishment of the lateral connectivity between the river and the floodplain, thus greatly increasing flooding frequency of the floodplain. After dyke removal at high discharge a portion of river flow will occur in the floodplain, which reduces shear stress on the river bottom, and thus reduces river bed incision.

Replanting (↔ removal) of in-channel and riparian vegetation

This action consists in the omission of the removal of vegetation in and near river active channel, or active planting of typical riparian and floodplain trees and bushes (e.g. willows, alder, tamarisk). Expected effects on physical habitat due to the removal of vegetation are the increase of floodplain heterogeneity, the increase of flow velocity and shear stress (Vargas-Luna et al., 2015), the change in sediment supply and LW supply by reduce the sedimentation (Wu and He, 2009), the change in river morphology (Gurnell 2014), the change in biotic communities and in biochemical cycling. Omission of vegetation removal in some instances requires parallel widening of the river channel in order to ensure the same flow capacity of the river channel.

Weir removal (↔ Weir construction)

It is the removal, lowering or modification of weirs and check dams to restore longitudinal continuity. In HyMoCARES we adopted the following definitions (for further details, see Piton et al., 2017):

- weir: a grade-control structure deployed in large and medium gravel-bed rivers with relatively gentle slopes;

Sediment retention basins are check-dams with a retention basin built to trap the sediment transport (bedload and/or debris flows), generally upstream debris fans. The removal of sediment retention basins has been considered as a type of check dam removal.

Weir removal is a pivotal management measure to restore longitudinal continuity for sediment transfer and for fish migration. Check-dam removal is expected to improve sediment continuity from steep-slope tributaries (Wang et al., 2016). Many national laws impose that weirs have to be permeable for fish migration. Effects may be expected on downstream sediment and LW supply due to the restoration of the continuity and of erosion/deposition processes, on physical habitat due to the change in velocity and substrate, on river morphology, on biotic communities due to the recreation of habitat. A weir may also be the gate of a hydropower plant, which strongly affects the sediment transfer.

4 Linkages between management actions, hydromorphological and biological functions, and ecosystem services

The relationship between management actions, hydromorphological and biological processes and functions, and riverine ecosystem services has rarely been analyzed in literature so far. Thorp et al. (2010) quantitatively linked some hydromorphological traits with habitat and niche complexity and finally with a partial list of ecosystem services. Although they used a different classification system of processes, functions and ES, the relationships that they proposed have been partially adopted in a modified way by the HyMoCARES classification system. In particular, the authors highlighted the strong relationships between river morphology, Instream flow regime and availability of ecosystem services such as plants resources for agricultural purposes, water for drinking and non-drinking purpose, water-related recreational activities, and natural and cultural heritage. In addition to the ecosystem services, in the HyMoCARES project we defined the linkages between hydromorphological functions and ecological status, since it has to be assessed as required by European and national laws.

Tab. 13. HyMoCARES river ES list (taken from HyMoCARES D.T1.1.1) and ecological status.

Ecosystem service
Cultivated crops
Plant resources for agricultural use - Pasture
Surface water for drinking purpose
Groundwater for drinking purpose
Surface water for non-drinking purposes in industry and agriculture
Groundwater for non-drinking purposes in industry and agriculture
Plant-based resources from agriculture, short rotation coppice, forestry
Self-purification
Reduction of greenhouse gas emission / carbon sequestration
Flood risk mitigation
Drought risk mitigation
Soil formation in floodplains
Regulating temperature/Cooling (water bodies and ground)
Habitat-related services
Aesthetics of landscape
Natural and cultural heritage
Education, Science
Water-related activities
Hydropower
Navigation
Sediments for construction
Ecological status

In the HyMoCARES project linkages have been defined by a panel of experts on the basis of their knowledge and of the existing literature. In many cases, the literature available to define linkages between hydromorphological and biological functions and ecosystem services was too sparse, thus the linkages definition is based mainly or exclusively on expert opinion.

In this section we provide a brief description of each of the linkages between the management actions, the hydromorphological and ecological functions, and the ecosystems services. We grouped the linkages by management action, following the alphabetical order of actions in chapter 3. Firstly, for each management action, we highlighted the **direct** linkages between the action and the targeted function (first level linkage). In the description of the linkages, we provided suggestions for the **indirect** effects of the action on the different functions. The linkages are classified as second level linkage (2 linkages distance from the action), third level linkage (3 linkages distance from the action) and fourth level linkage (4 linkages distance from the action). Secondly, for each management action we showed the linkages between the functions (directly and indirectly connected with the action) and the ecosystem services. The aim is to underline which ecosystem services will be targeted by each management action. To link functions and ES we partially followed the methodology proposed by Campagne et al. (2017). For that purpose, we developed one matrix (see Annex 1) and send it to all partners to ask for an opinion about the linkages (0-5 score transformed in presence/absence). We received 29 replies and on the basis of this linkages we define the linkages between functions and ES. The framework has been finally validated by an expert panel selected within the HyMoCARES partnership. For each action, we showed which services are more directly related with the action and how many functions will influence each service.

4.1 Sediment recharge / restoration of sediment continuity

Biochemical cycling of chemical compounds (1st level)

Direct effects are expected due to contaminants delivery from trapped sediments (negative effect on water quality). Positive effects are expected due to the recovering of the biotic communities. The sediment supply influences the exchanges with the hyporheic zone with known effects on nutrient cycling (Maazouzi et al., 2013).

Tab. 14. Linkages between Sediment recharge / restoration of sediment continuity and hydromorphological and biological functions, with direct or indirect linkage defined by experts' panel, distance from the action represented by the number of steps and the number of outgoing linkages.

Action	**Function**	**Linkage**	**Level**
Sediment recharge / restoration of sediment continuity	Biochemical cycling of chemical compounds	Direct	1
	Biotic communities	Indirect	2
	Instream flow regime	Indirect	4
	Hydraulics	Indirect	3
	Lateral connectivity	Indirect	3
	Physical habitat	Indirect	3
	Presence and composition of riparian vegetation	Indirect	4
	River morphology	Indirect	2
	Sediment continuity	Direct	1
	Vertical connectivity	Indirect	3

Biotic communities

Indirect effects are expected due to change in the physical habitat and biochemical cycling (water quality).

Hydraulics

Indirect effects are expected due to changes in morphology.

Instream flow regime

Indirect effects through changes in lateral connectivity (water retention in floodplains).

Lateral connectivity

Indirect effects are expected due to changes in morphology due to possible lateral shifting of the river channel.

Physical habitat

The effects are mainly through hydraulics (change of hydraulic patterns), morphology (increase of habitat heterogeneity) and biogeochemical cycling of chemical compounds. Sediment replenishment is important to restore the aquatic habitat (Kondolf et al., 2014) and increase sediment diversity, which is fundamental to sustain the life cycle of several aquatic species (e.g., Riebe et al., 2014). A high concentration of suspended solids can have a negative impact on several aquatic species, in particular on salmonids (Kjelland et al., 2015). Gravel augmentation is known to trigger increase in macroinvertebrate diversity and biomass (Merz et al., 2005); in the same time, it could increase the availability of spawning areas for salmonids (mainly) or breeding areas for some bird species.

Presence and composition of riparian vegetation

The effect is not direct but linked to the decreased distance to the groundwater table, to the increase of the frequency and magnitude of the flooding events in the riparian areas, and to the reactivation of geomorphological lateral dynamics. If the channel constraints allow the supplied sediment to form steady or migrating bars in the river channel, the bare sediment surfaces and variability of grain sizes associated with sediment deposition provide habitat for pioneer vegetation. Bar accretion goes along with bank erosion, which provides woody debris and ensures rejuvenation of the vegetation cover

River morphology

The quantity and quality of the sediment supply co-determines the channel morphology (e.g. Schumm, 1985; Church, 2006). If not impeded by narrowing channel constraints, replenished sediment may form aggradational channel features in the river bed, transforming the morphology from a narrow, straight and immobile type towards a wider, alternated bar or braided type which provides the dynamics of a shifting landscape mosaic, which the life cycles of many riverine species rely on (Robinson et al., 2002).

Sediment continuity

By artificially increasing the sediment supply to a reach, sediment replenishment will increase bedload transport downstream from the injection site (Gaueman et al., 2017). It is also recognized that the addition of fine gravels to coarser gravel beds will increase the mobility of the substrate and subsequently the bed material transport rate of the replenished reach (Venditi et al., 2010). If gravel replenishment is sufficiently important to reactivate a morphological activity along the restored reach, sediment input from bank erosion should increase.

Vertical connectivity (3rd level)

The direct effects are not relevant or negligible. Due to changes in river morphology, sediment replenishment improves the development of large bedforms relative to the flow depth, and may contribute to improve exchanges of water, nutrients, and organic matters between the surface and the hyporheic zone (Malard et al., 2002; Malard et al., 2017).

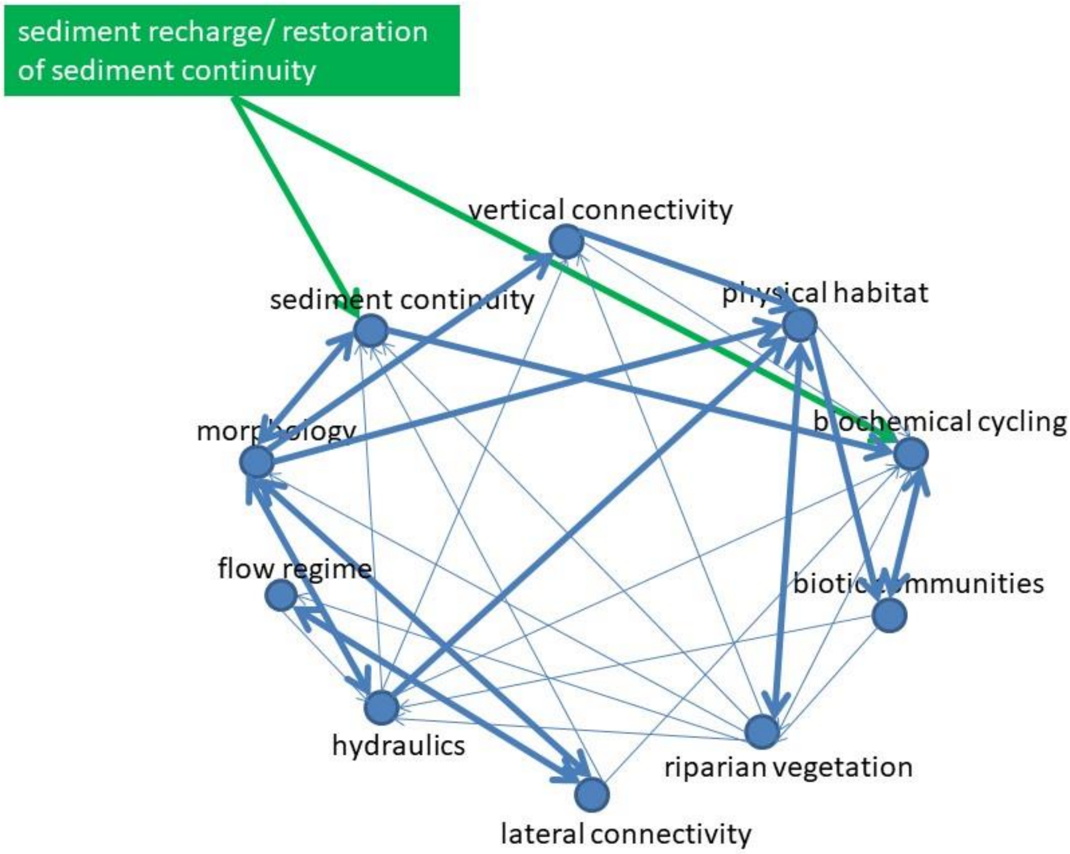

Fig. 2 Graphical representation of the interactions among the functions (author: F. Liebault).

4.1.1 Function – ecosystem services linkages

Biochemical cycling of chemical compounds – Ecological status

This function does not affect directly ecosystem services, but it influences the biotic communities and the ecological status.

Biotic communities - Natural and cultural heritage of the river and floodplain ecosystem

It is relevant due to the importance of rivers as biodiversity reserve and presence of relevant species (e.g., umbrella species).

Biotic communities - Water-related activities

The presence and abundance of several species are a pre-condition for some water-related activities, in particular for angling and bird-watching. Different types of angling have different requirements in relation to biotic communities.

Biotic communities – Ecological status

The community composition influences the ecological status of the river.

Hydraulics – Regulating Temperature, cooling

The hydraulic variables directly influence the temperature and the cooling capacity of the river.

Hydraulics – Water related activities

The hydraulic variables directly influence specific water related activities such as boating and rafting (see Carolli et al., 2017).

Lateral connectivity - Drought risk mitigation

Drought risk is naturally mitigated through water storage, e.g. in groundwater and in wetlands. The amount of water that can feed these natural storage systems is influenced by the connectivity between the river channel and its floodplain. Bank surface layer clogging in some of cases causing elevated water table and thus in cases of floods, increased total recharge amount to the aquifer (Chen et al., 2013).

Lateral connectivity - Flood risk mitigation

The degree of lateral connectivity influences peak flow attenuation downstream, due to temporary storage in the floodplain, flood wave celerity reduction and to de-synchronization of the timings of sub-catchment flood waves (Dixon et al. 2016). It has to be highlighted that restoration of lateral connectivity may not always have positive effects on flood risk downstream, as in some cases it may re-synchronize flood waves that had been shifted due to artificialization, therefore a case-by-case assessment is necessary. It should also be recognized that in steep slope alpine valleys, the temporary storage capacity in the floodplain may be often insufficient to significantly reduce peak flows. Lateral connectivity affects flood risk depending on bank hydrogeological characteristics, sediment permeability, ground saturation levels, e.g. saturated river banks increase lateral connectivity between river and floodplain and in consequence flood risk. Flood risk reduction in this context is possible with bank layers with high water infiltration rate.

Lateral connectivity - Groundwater for drinking purpose

Increase of the recharge amount to the aquifer increases with increased lateral connectivity (increased fluid exchange rate).

Lateral connectivity - Groundwater for non-drinking purpose

Increase of the recharge amount to the aquifer increases with increased lateral connectivity (increased fluid exchange rate).

Physical habitat - Habitat-related services

Physical habitat provides the physical drivers and the fundamental ecological niches to sustain species life-cycle.

Physical habitat - Natural and cultural heritage of the river and floodplain ecosystem

Physical drivers are fundamental to sustain the life cycle of species relevant for natural and cultural heritage (e.g., flagship species).

Presence and composition of riparian vegetation - Aesthetics of landscape

The presence of riparian vegetation increases the aesthetic value.

Presence and composition of riparian vegetation - Reduction of greenhouse gas emission

Riparian vegetation reduces GHG emission by carbon fixation.

Presence and composition of riparian vegetation - Regulating temperature

Temperature changes in presence of vegetation (Zardo et al., 2017). Additional possible effects at the local scale on water temperature are due to shading.

Presence and composition of riparian vegetation - Retention of nutrients

Riparian vegetation assimilates and retains nutrients, changing the timing of nutrient diffusion and availability in the river habitat (e.g., nutrients introduced in the river during autumn by the fall of the leaves).

Presence and composition of riparian vegetation – Ecological status

Presence and composition of riparian vegetation influences the river ecological status.

River morphology - Aesthetics of landscape

Natural morphologies (braiding river, anastomosing river) may increase aesthetic value in comparison with more artificial river morphologies.

River morphology - Natural and cultural heritage of the river and floodplain ecosystem

It is important for the high natural and cultural value of river types that deserve conservation (e.g., braiding rivers in Europe).

River morphology - Sediments for construction

The effects are not relevant or negligible.

River morphology - Water-related activities

Different river types support different water activities (e.g., white-water sports in high-gradient streams, paddling in low-gradient rivers).

River morphology – Ecological status

River morphology vegetation influences the river ecological status and it has to be assessed in the Water Framework Directive,

Sediment continuity

Although it is directly influenced by the management action, the sediment continuity does not directly influence any ES but it has a strong effect on river morphology.

Vertical connectivity - Drought risk mitigation

Hyporheic zone characteristics affect groundwater-surface water exchange rate and consequently water availability for different purposes.

Vertical connectivity - Groundwater for drinking purpose

Vertical connectivity affects surface water mainly in the context of water quality (degree of water clarity/suspended matter amount) through water exchange between shallow groundwater and river (depending also on type of substrate, river morphology, hydraulics).

Vertical connectivity – Groundwater for non-drinking purposes

The effects are relevant. industry/agriculture water availability depends on aquifer-river water exchange level/groundwater level.

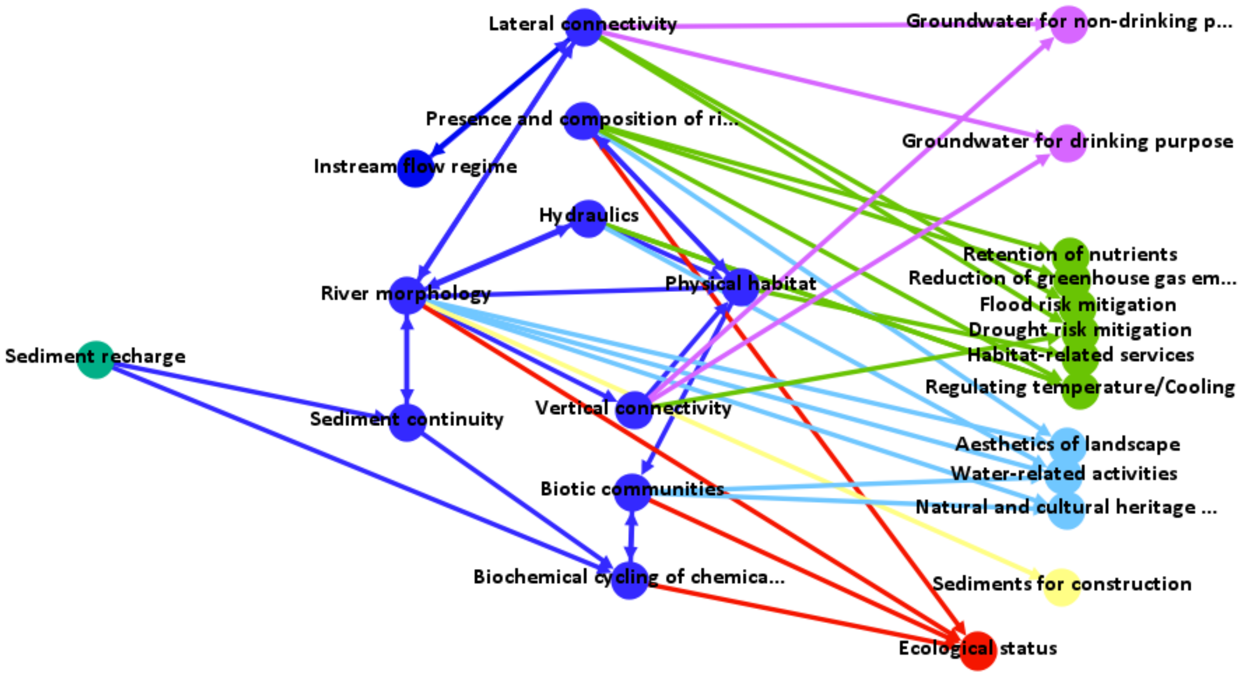

Fig. 3 Graphical representation of the framework for the sediment recharge / restoration of sediment continuity. The blue color represent the functions and the linkages between functions and actions. The pink color represents Provisioning services and their linkage with the functions, the green color represents Regulation and mainteinance services and their linkage with the functions, light blue color represents Cultural services and their linkage with the functions, and the yellow color represents the usages of abiotic natural capital and their linkage with the functions. In red we showed the ecological status and its linkages with the functions.

4.2 Channel widening

Tab. 15 Linkages between Channel widening and hydromorphological and biological functions, with direct or indirect linkage defined by experts' panel, distance from the action represented by the number of steps and the number of outgoing linkages.

Action	Function	Linkage	Level
Channel widening	Biochemical cycling of chemical compounds	No	
	Biotic communities	Indirect	3
	Hydraulics	Indirect	2
	Instream flow regime	No	
	Lateral connectivity	Indirect	2
	Physical habitat	Indirect	2
	Presence and composition of riparian vegetation	No	
	River morphology	Direct	1
	Sediment continuity	Indirect	2
	Vertical connectivity	Indirect	2

Biochemical cycling of chemical compounds

There are no relevant effects of channel widening on biochemical cycling.

Biotic communities

The effects are indirect and mainly through physical habitat. Channel widening has likely positive effect on macroinvertebrate and fish, but these effects are hard to disentangle from other effects.

Hydraulics

The effects are mainly due to changes in river morphology. Channel widening will tend to decrease flow depth and flow velocity for a given discharge, and then modify the sediment transport capacity (shear stress) of the reach. The change in river hydraulic conditions consequently affects the level of bank erosion dynamics (extended lower half riverbank sediment deposits due to reduced water velocities).

Instream flow regime

In general terms the impact of this measure on Instream flow regime is limited.

Lateral connectivity

The effects are not direct and mainly through morphology.

Physical habitat

The effects are not direct and mainly through morphology and hydraulics. Channel widening improves habitat diversity and increases the number of available ecological niches.

Presence and composition of riparian vegetation

The effects are not direct and not relevant. The effects are on the physical habitat.

River morphology

Channel widening decreases the bed shear stresses, stabilizing formerly incising river beds and promoting the emergence of aggradational features such as bars and riffles. Bars increase the hydraulic load along the banks, there causing further widening if not impeded by bank protection. A precondition for stabilising the river bed and sustaining width increase is sufficient sediment supply.

Sediment continuity

The effects are mainly through morphology. By increasing the channel flow capacity, channel widening is likely to induce a decrease of water depth for a given flow discharge, and may induce a decrease of sediment transport capacity, and subsequently sediment deposition. Channel widening associated with Floodplain reconnection (removal, retreat of levees) and/or bank protection can have a positive effect on sediment supply from bank erosion, by restoring the lateral mobility of active channels. For a review, see Piegay et al. (2005).

Vertical connectivity

The effects are not direct and mainly through morphology. Channel widening affects hydraulic conditions by reducing velocities, affecting the riverbed layer thickness which hinders the vertical hyporheic flow. In general, channel widening triggers the development of macroforms and enhance vertical exchanges. Provided sufficient sediment supply from upstream, channel widening allows increased bed dynamics which prevent from the increased bed armouring, often observed as a result of narrowing in the degrading state. The coupled sediment deposition and partial aggradation leads to an increase in the grain size variability, dynamic gravel bars etc. enhancing vertical connectivity in the hyporheic zone.

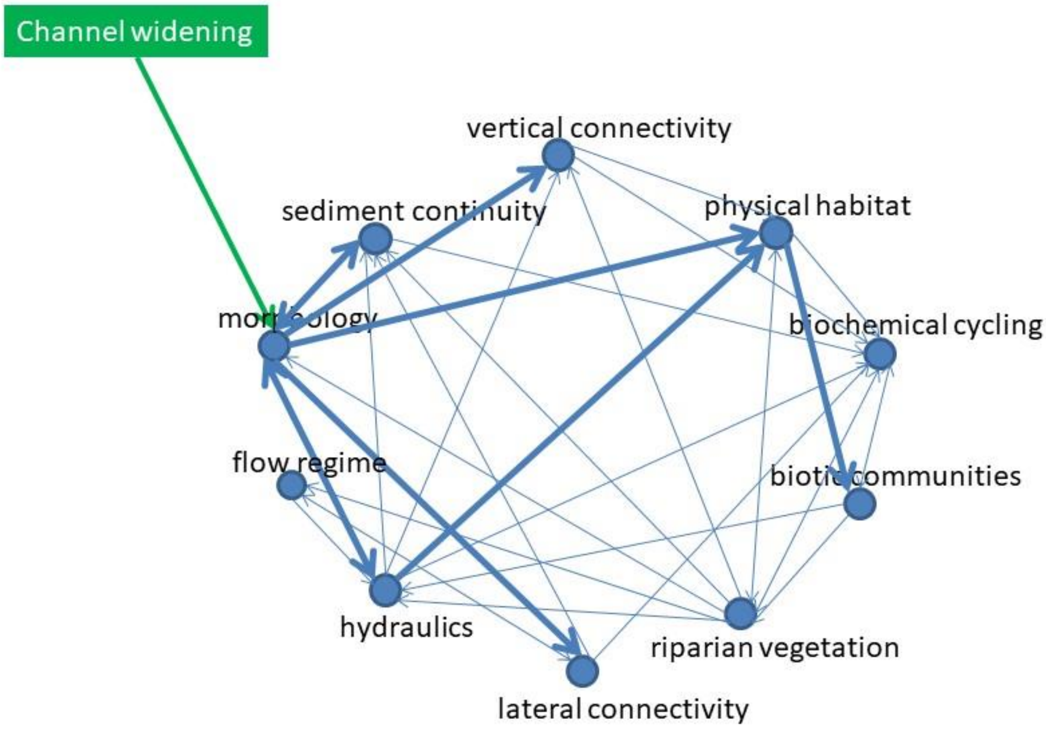

Fig. 4 Graphical representation of the interactions among functions (author: F. Liebault).

4.2.1 Function – ecosystem services linkages

Biotic communities - Natural and cultural heritage of the river and floodplain ecosystem

It is relevant due to the importance of rivers as biodiversity reserve and presence of relevant species (e.g., umbrella species).

Biotic communities - Water-related activities

The presence and abundance of several species are a pre-condition for some water-related activities, in particular for angling and bird-watching. Different types of angling have different requirements in relation to biotic communities.

Biotic communities – Ecological status

The community composition influences the ecological status of the river.

Hydraulics – Regulating Temperature, cooling

The hydraulic variables directly influence the temperature and the cooling capacity of the river.

Hydraulics – Water related activities

The hydraulic variables directly influence specific water related activities such as boating and rafting (see Carolli et al., 2017).

Physical habitat - Habitat-related services

Physical habitat provides the physical drivers and the fundamental ecological niches to sustain species life-cycle.

Physical habitat - Natural and cultural heritage of the river and floodplain ecosystem

Physical drivers are fundamental to sustain the life cycle of species relevant for natural and cultural heritage (e.g., flagship species).

River morphology - Aesthetics of landscape

Natural morphologies (braiding river, anastomosing river) may increase aesthetic value in comparison with more artificial river morphologies.

River morphology – Cultivated crops

Changes in the river morphology due to artificial widening of the channel can lead to a decrease of the area available for cultivation. On the opposite, river channelization lead to an increase in available arable area.

River morphology - Natural and cultural heritage of the river and floodplain ecosystem

It is important for the high natural and cultural value of river types that deserve conservation (e.g., braiding rivers in Europe).

River morphology – Plant resource for agricultural use - pasture

Changes in the river morphology due to artificial widening of the channel can lead to a decrease of area available for pasture and other agricultural activities. On the opposite, river channelization lead to an increase in available area.

River morphology – Plant-based resources from agriculture, short rotation coppice, forestry

Changes in the river morphology due to artificial widening of the channel can lead to a decrease of area available for forest and other agricultural activities. On the opposite, river channelization lead to an increase in available area.

River morphology - Sediments for construction

Specific river morphologies can improve sediment deposition, thus increase the sediments available for construction.

River morphology - Water-related activities

Different river types support different water activities (e.g., white-water sports in high-gradient streams, paddling in low-gradient rivers).

River morphology – Ecological status

River morphology vegetation influences the river ecological status and it has to be assessed in the Water Framework Directive.

Sediment continuity

Although it is directly influenced by the management action, the sediment continuity does not directly influence any ES but it has a strong effect on river morphology.

Vertical connectivity - Drought risk mitigation

Hyporheic zone characteristics affect groundwater-surface water exchange rate and consequently water availability for different purposes.

Vertical connectivity - Groundwater for drinking purpose

Vertical connectivity affects surface water mainly in the context of water quality (degree of water clarity/suspended matter amount) through water exchange between shallow groundwater and river (depending also on type of substrate, river morphology, hydraulics).

Vertical connectivity – Groundwater for non-drinking purposes

The effects are relevant if industry/agriculture water availability depends on aquifer-river water exchange level/groundwater level.

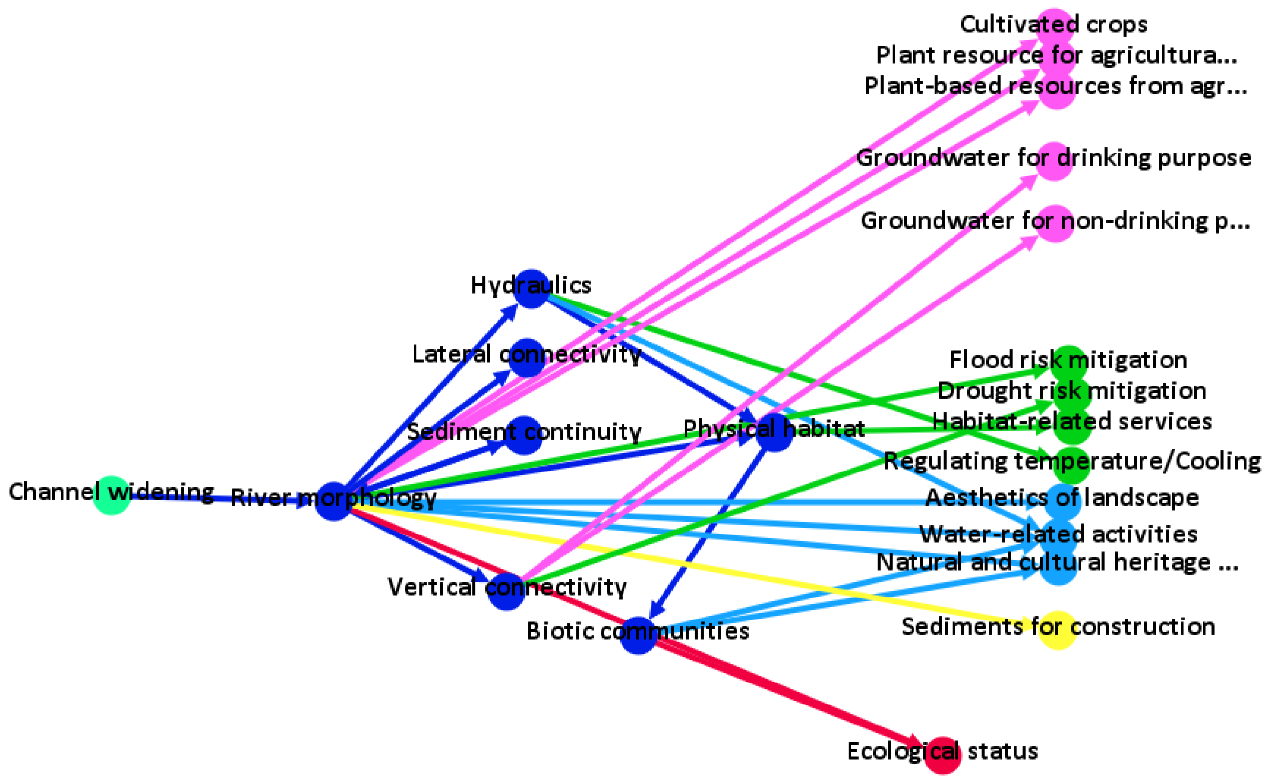

Fig. 5 Graphical representation of the framework for the channel widening. The blue color represent the functions and the linkages between functions and actions. The pink color represents Provisioning services and their linkage with the functions, the green color represents Regulation and mainteinance services and their linkage with the functions, light blue color represents Cultural services and their linkage with the functions, and the yellow color represents the usages of abiotic natural capital and their linkage with the functions. In red we showed the ecological status and its linkages with the functions.

4.3 Check dam removal

Tab. 16. Linkages between check dam removal and hydromorphological and biological functions, , with direct or indirect linkage defined by experts' panel, distance from the action represented by the number of steps and the number of outgoing linkages.

Action	Function	Linkage	Level
Check dam removal	Biochemical cycling of chemical compounds	No	
	Biotic communities	Direct	1
	Hydraulics	Indirect	2
	Instream flow regime	Indirect	3
	Lateral connectivity	Indirect	2
	Physical habitat	Indirect	2
	Presence and composition of riparian vegetation	Indirect	3
	River morphology	Direct	1
	Sediment continuity	Direct	1
	Vertical connectivity	Indirect	2

Biotic communities (1st level)

The effects are mainly through the physical habitat.

Hydraulics

Dam removal restores river morphology, thus indirectly changes the hydraulic variables of the river.

Instream flow regime

The effects are through lateral connectivity.

Lateral connectivity

The effects are due to changes in river morphology (lateral shifting of the river channel).

Physical habitat

The effects are indirect and due to changes in hydraulics, river morphology and biochemical cycling (e.g. oxygen and temperature).

Presence and composition of riparian vegetation

The effects are indirect and mainly due to the changes in physical habitat because of the creation and destruction of floodplain habitat, effects on the groundwater level which influence vegetation water supply.

River morphology (1st level)

The effects are due to the restoration of river dynamics and the increase of channel slope in case of dam removal. It is influenced by the alteration of the sediment supply and transport.

Sediment continuity (1st level)

Check dam removal has a direct positive effect on sediment continuity, by removing obstructions to the downstream propagation of bedload, by releasing sediment previously stored behind the dam and by the destabilization of slopes. Such actions will increase the sediment transport downstream, by increasing the sediment supply to the reach (Randle et al., 2015). It influences greatly river morphology.

Vertical connectivity

The effects are indirect and mainly through aggradation which leads to the raising of the groundwater table.

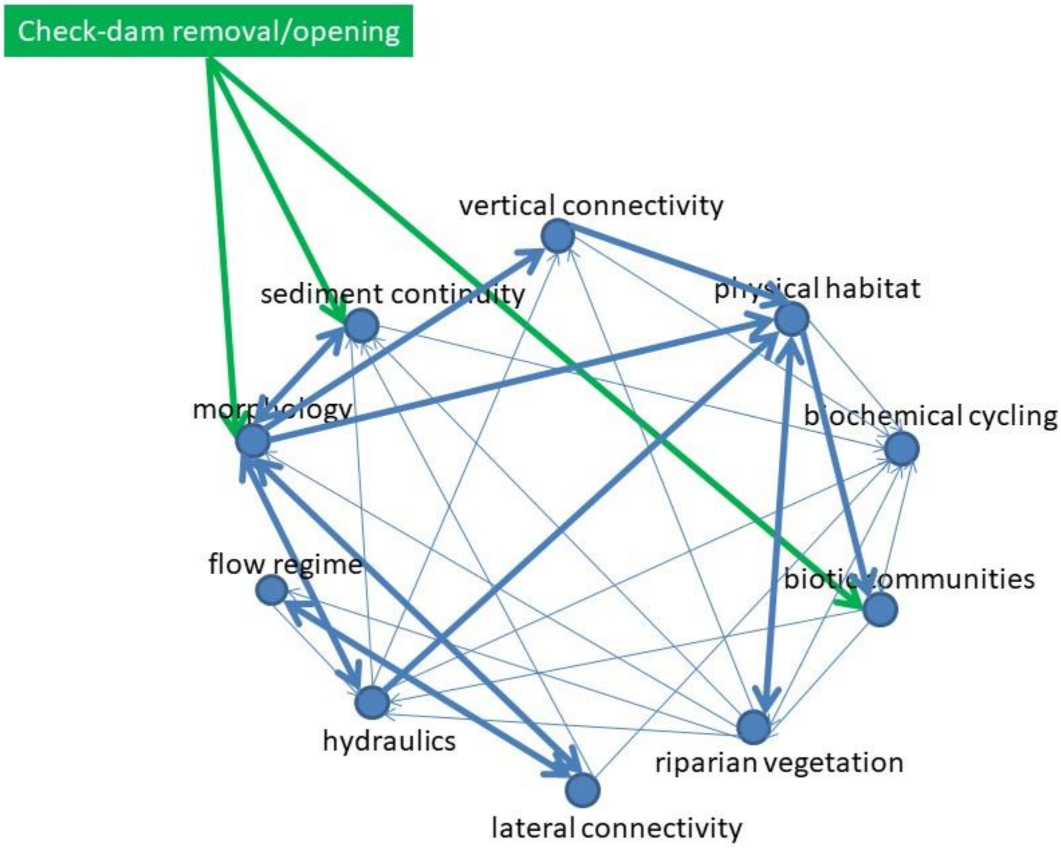

Fig. 6. Graphical representation of the interactions among functions (author: F. Liebault).

4.3.1 Function – ecosystem services linkages

Biotic communities - Natural and cultural heritage of the river and floodplain ecosystem

It is relevant due to the importance of rivers as biodiversity reserve and presence of relevant species (e.g., umbrella species).

Biotic communities - Water-related activities

The presence and abundance of several species are a pre-condition for some water-related activities, in particular for angling and bird-watching. Different types of angling have different requirements in relation to biotic communities.

Biotic communities – Ecological status

The community composition influences the ecological status of the river.

Hydraulics – Regulating Temperature, cooling

The hydraulic variables directly influence the temperature and the cooling capacity of the river.

Hydraulics – Water related activities

The hydraulic variables directly influence specific water related activities such as boating and rafting (see Carolli et al., 2017).

Lateral connectivity - Drought risk mitigation

Drought risk is naturally mitigated through water storage, e.g. in groundwater and in wetlands. The amount of water that can feed these natural storage systems is influenced by the connectivity between the river channel and its floodplain. Bank surface layer clogging in some of cases causing elevated water table and thus in cases of floods, increased total recharge amount to the aquifer (Chen et al., 2013).

Lateral connectivity - Flood risk mitigation

The degree of lateral connectivity influences peak flow attenuation downstream, due to temporary storage in the floodplain, flood wave celerity reduction and to de-synchronization of the timings of sub-catchment flood waves (Dixon et al. 2016). It has to be highlighted that restoration of lateral connectivity may not always have positive effects on flood risk downstream, as in some cases it may re-synchronize flood waves that had been shifted due to artificialization, therefore a case-by-case assessment is necessary. It should also be recognized that in steep slope alpine valleys, the temporary storage capacity in the floodplain may be often insufficient to significantly reduce peak flows. Lateral connectivity affects flood risk depending on bank hydrogeological characteristics, sediment permeability, ground saturation levels, e.g. saturated river banks increase lateral connectivity between river and floodplain and in consequence flood risk. Flood risk reduction in this context is possible with bank layers with high water infiltration rate.

Lateral connectivity - Groundwater for drinking purpose

Increase of the recharge amount to the aquifer increases with increased lateral connectivity (increased fluid exchange rate).

Lateral connectivity - Groundwater for non-drinking purpose

Increase of the recharge amount to the aquifer increases with increased lateral connectivity (increased fluid exchange rate).

Physical habitat - Habitat-related services

Physical habitat provides the physical drivers and the fundamental ecological niches to sustain species life-cycle.

Physical habitat - Natural and cultural heritage of the river and floodplain ecosystem

Physical drivers are fundamental to sustain the life cycle of species relevant for natural and cultural heritage (e.g., flagship species).

Presence and composition of riparian vegetation - Aesthetics of landscape

The presence of riparian vegetation increases the aesthetic value.

Presence and composition of riparian vegetation - Reduction of greenhouse gas emission

Riparian vegetation reduces GHG emission by carbon fixation.

Presence and composition of riparian vegetation - Regulating temperature

Temperature changes in presence of vegetation (Zardo et al., 2017). Additional possible effects at the local scale on water temperature are due to shading.

Presence and composition of riparian vegetation - Retention of nutrients

Riparian vegetation assimilates and retains nutrients, changing the timing of nutrient diffusion and availability in the river habitat (e.g., nutrients introduced in the river during autumn by the fall of the leaves).

Presence and composition of riparian vegetation – Ecological status

Presence and composition of riparian vegetation influences the river ecological status.

River morphology - Aesthetics of landscape

Natural morphologies (braiding river, anastomosing river) may increase aesthetic value in comparison with more artificial river morphologies.

River morphology - Education, Science

It is important for the description and understanding of fundamental geomorphological processes

River morphology - Flood risk mitigation

The effect is still unclear (see Sholtes and Doyle, 2010). Large river-bed rivers may retain water and mitigate floods, but there is not agreement in literature about the effects of morphology on flood risk mitigation in Alpine rivers (e.g., Sholtes and Doyle, 2010).

River morphology - Natural and cultural heritage of the river and floodplain ecosystem

It is important for the high natural and cultural value of river types that deserve conservation (e.g., braiding rivers in Europe).

River morphology - Sediments for construction

Specific river morphologies can improve sediment deposition, thus increase the sediments available for construction.

River morphology - Water-related activities

Different river types support different water activities (e.g., white-water sports in high-gradient streams, paddling in low-gradient rivers).

River morphology – Ecological status

River morphology vegetation influences the river ecological status and it has to be assessed in the Water Framework Directive,

Sediment continuity

The sediment continuity has a strong effect on river morphology.

Vertical connectivity - Drought risk mitigation

Hyporheic zone characteristics affect groundwater-surface water exchange rate and consequently water availability for different purposes.

Vertical connectivity - Groundwater for drinking purpose

Vertical connectivity affects surface water mainly in the context of water quality (degree of water clarity/suspended matter amount) through water exchange between shallow groundwater and river (depending also on type of substrate, river morphology, hydraulics).

Vertical connectivity – Groundwater for non-drinking purposes

The effects are relevant if industry/agriculture water availability depends on aquifer-river water exchange level/groundwater level.

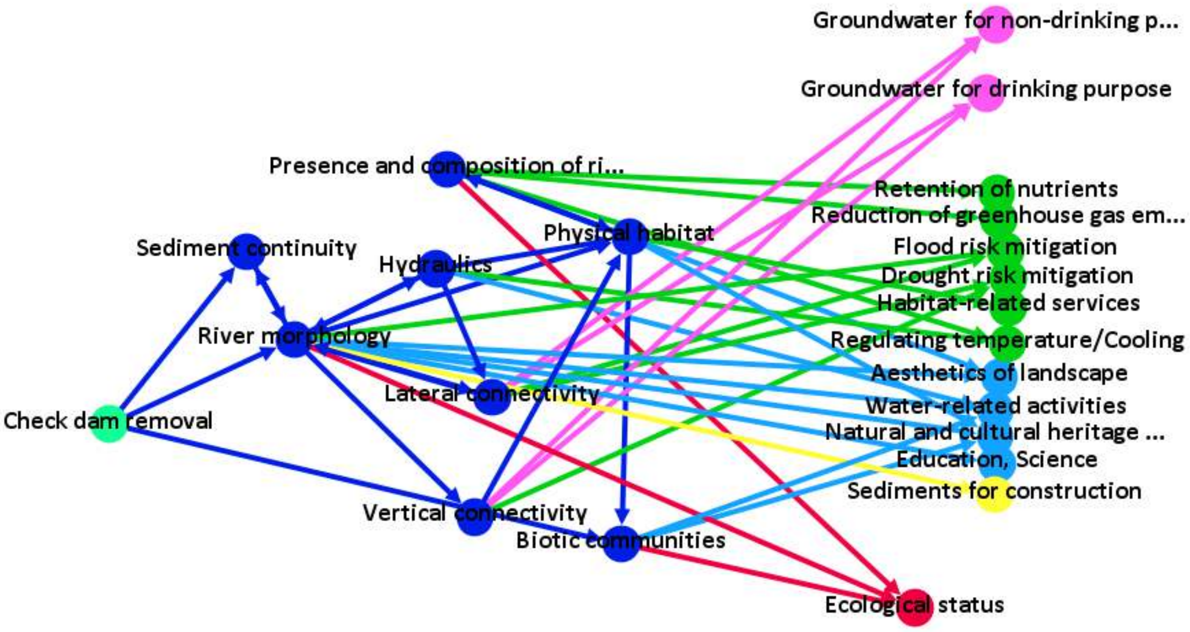

Fig. 7 Graphical representation of the framework for check dam removal. The blue color represent the functions and the linkages between functions and actions. The pink color represents Provisioning services and their linkage with the functions, the green color represents Regulation and mainteinance services and their linkage with the functions, light blue color represents Cultural services and their linkage with the functions, and the yellow color represents the usages of abiotic natural capital and their linkage with the functions. In red we showed the ecological status and its linkages with the functions.

4.4 Creation of macroforms

Tab. 17. Linkages between Creation of macroforms and hydromorphological and biological functions, with direct or indirect linkage defined by experts' panel, distance from the action represented by the number of steps and the number of outgoing linkages.

Action	Function	Linkage	Level
Creation of macroforms	Biochemical cycling of chemical compounds	No	
	Biotic communities	Indirect	3
	Hydraulics	Indirect	2
	Instream flow regime	No	
	Lateral connectivity	No	
	Physical habitat	Indirect	2
	Presence and composition of riparian vegetation	No	
	River morphology	Direct	1
	Sediment continuity	No	
	Vertical connectivity	Indirect	2

Biochemical cycling of chemical compounds

The effect of creation of macroforms on the chemical cycling are not relevant or negligible.

Biotic communities

The effect of creation of macroforms on the biotic communities is not direct. An expected positive effect is due to habitat diversification (see below).

Hydraulics

The effect of creation of macroforms on the biotic communities is not direct and mainly through river morphology.

Instream flow regime

The effect of creation of macroforms on the Instream flow regime is not relevant or negligible.

Lateral connectivity

The effect of creation of macroforms on lateral connectivity is not relevant or negligible.

Physical habitat

Although the effect is not direct and mainly due to changes in morphology and hydraulics, the creation of macroforms improves the habitat diversification and increase the number of ecological niches that can be occupied by river and riparian species.

Presence and composition of riparian vegetation

The effect of creation of macroforms on presence and composition of riparian vegetation is not relevant or negligible.

River morphology (1st level)

The morphological appearance is directly changed by the created macroforms, while the sustainability of the created macroforms and morphology depends on the boundary conditions such as quantity and quality (grain size) of sediment supply, channel constraints, discharge, slope as well as the succession of vegetation.

Sediment continuity

The effect of creation of macroforms on sediment continuity is not relevant or negligible.

Vertical connectivity

The effect of creation of macroforms on vertical connectivity is not direct. However, due to changes in river morphology, Creation of macroforms affects the riverbed bottom permeability with (sediment fraction dependent) potential riverbed colmatation. Strong effects on exchange between surface and the hyporheic zone are predicted.

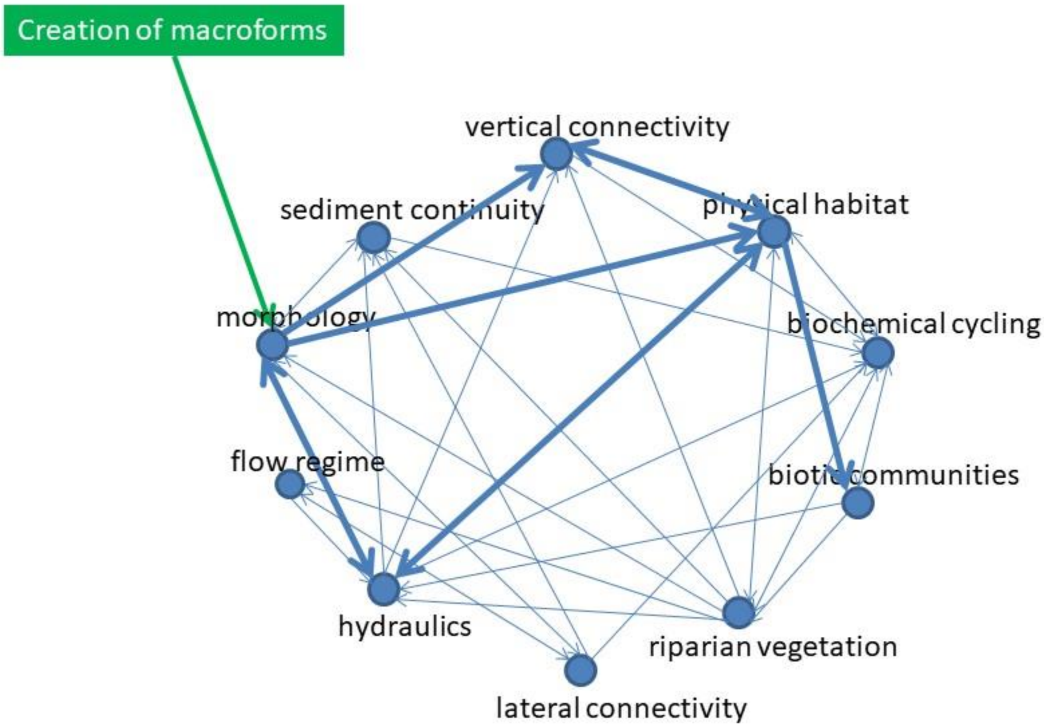

Fig. 8 Graphical representation of the interactions among functions (author: F. Liebault).

4.4.1 Function – ecosystem services linkages

Biotic communities - Natural and cultural heritage of the river and floodplain ecosystem

It is relevant due to the importance of rivers as biodiversity reserve and presence of relevant species (e.g., umbrella species).

Biotic communities - Water-related activities

The presence and abundance of several species are a pre-condition for some water-related activities, in particular for angling and bird-watching. Different types of angling have different requirements in relation to biotic communities.

Biotic communities – Ecological status

The community composition influences the ecological status of the river.

Hydraulics – Regulating Temperature, cooling

The hydraulic variables directly influence the temperature and the cooling capacity of the river.

Hydraulics – Water related activities

The hydraulic variables directly influence specific water related activities such as boating and rafting (see Carolli et al., 2017).

Physical habitat - Habitat-related services

Physical habitat provides the physical drivers and the fundamental ecological niches to sustain species life-cycle.

Physical habitat - Natural and cultural heritage of the river and floodplain ecosystem

Physical drivers are fundamental to sustain the life cycle of species relevant for natural and cultural heritage (e.g., flagship species).

River morphology - Aesthetics of landscape

Natural morphologies (braiding river, anastomosing river) may increase aesthetic value in comparison with more artificial river morphologies.

River morphology - Natural and cultural heritage of the river and floodplain ecosystem

It is important for the high natural and cultural value of river types that deserve conservation (e.g., braiding rivers in Europe).

River morphology - Sediments for construction

Specific river morphologies can improve sediment deposition, thus increase the sediments available for construction.

River morphology - Water-related activities

Different river types support different water activities (e.g., white-water sports in high-gradient streams, paddling in low-gradient rivers).

River morphology – Ecological status

River morphology vegetation influences the river ecological status and it has to be assessed in the Water Framework Directive, *Vertical connectivity - Drought risk mitigation*

Hyporheic zone characteristics affect groundwater-surface water exchange rate and consequently water availability for different purposes.

Vertical connectivity - Groundwater for drinking purpose

Vertical connectivity affects surface water mainly in the context of water quality (degree of water clarity/suspended matter amount) through water exchange between shallow groundwater and river (depending also on type of substrate, river morphology, hydraulics).

Vertical connectivity – Groundwater for non-drinking purposes

The effects are relevant if industry/agriculture water availability depends on aquifer-river water exchange level/groundwater level.

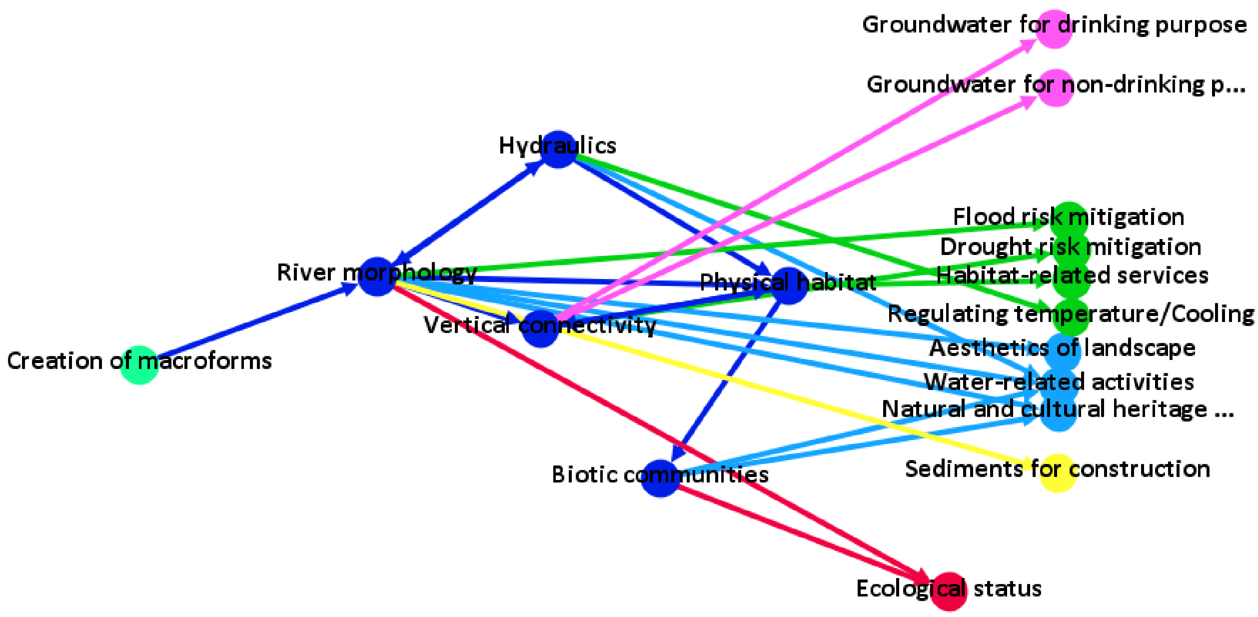

Fig. 9 Graphical representation of the framework for the creation of macroforms. The blue colour represents the functions and the linkages between functions and actions. The pink colour represents Provisioning services and their linkage with the functions, the green colour represents Regulation and mainteinance services and their linkage with the functions, light blue colour represents Cultural services and their linkage with the functions, and the yellow colour represents the usages of abiotic natural capital and their linkage with the functions. In red we showed the ecological status and its linkages with the functions.

4.5 Dam removal

Tab. 18. Linkages between Dam removal and hydromorphological and biological functions, , with direct or indirect linkage defined by experts' panel, distance from the action represented by the number of steps and the number of outgoing linkages.

Action	Function	Linkage	Level
Dam removal	Biochemical cycling of chemical compounds	No	
	Biotic communities	Direct	1
	Hydraulics	Indirect	2
	Instream flow regime	Direct	1
	Lateral connectivity	Indirect	2
	Physical habitat	Indirect	2
	Presence and composition of riparian vegetation	Indirect	3
	River morphology	Direct	1
	Sediment continuity	Direct	1
	Vertical connectivity	Indirect	2

Biochemical cycling of chemical compounds

Although some effects are described in literature (restoring transport of nutrients, Zhou et al., 2013; effects on nutrient retention and cycling, Stanley et al., 2002), they have been considered not relevant.

Biotic communities (1st level)

Dam removal restores longitudinal connectivity for fish (e.g., Jungwirth et al., 2000) with positive effects of dam removal on fish community and macroinvertebrates (e.g., Hansen and Hayes, 2012).

Hydraulics

Dam removal restores natural ins-stream flow regime and river morphology, thus indirectly changes the hydraulic variables of the river.

Instream flow regime (1st level)

A restoration of a natural or near-natural Instream flow regime is expected.

Lateral connectivity

The effects are due to changes in river morphology. Dam removal affects the lateral connectivity especially in the case of high discharges/floods after the removal of the dam, since there is additional sediment coming from upstream section(s). Also, removal of the dam usually causes the water level to change influencing the level of lateral flow exchange (river - lateral groundwater).

Physical habitat

The dam removal changes the physical habitat immediately upstream the dam, with a (partial) restoration of the typical river dynamics. Downstream the removal, the effect is indirect and due to changes in hydraulics, river morphology and biochemical cycling (e.g. oxygen and temperature).

Presence and composition of riparian vegetation

The presence (or removal) of a dam and of the corresponding water impoundment upstream affects the average water level and consequently affects riparian vegetation location, composition and age structure. Downstream the dam the effects are indirect and mainly due to the changes in physical habitat.

River morphology (1st level)

Dam removal upstream effects are due to the restoration of river dynamics, and downstream through flow regime and sediment availability. Both, downstream of the dam and upstream (at the place of the reservoir) the dam removal restores the flow regime and sediment transfer, allowing the formation of an undisturbed or less disturbed river morphology if eventual additional artificial constraints provide enough space. It is influenced by the alteration of the sediment supply and transport.

Sediment continuity (1st level)

Dam removal has a direct positive effect on sediment continuity, by removing obstructions to the downstream propagation of bedload, and by releasing sediment previously stored behind the dam. Such actions will increase the sediment transport downstream, by increasing the sediment supply to the reach (Randle et al., 2015). It influences greatly river morphology.

Vertical connectivity

The effects are mainly through river morphology. Dam removal affects depositions/erosion of sediments with direct effects on the riverbed layers' substrate composition, and consequently on hyporheic exchanges.

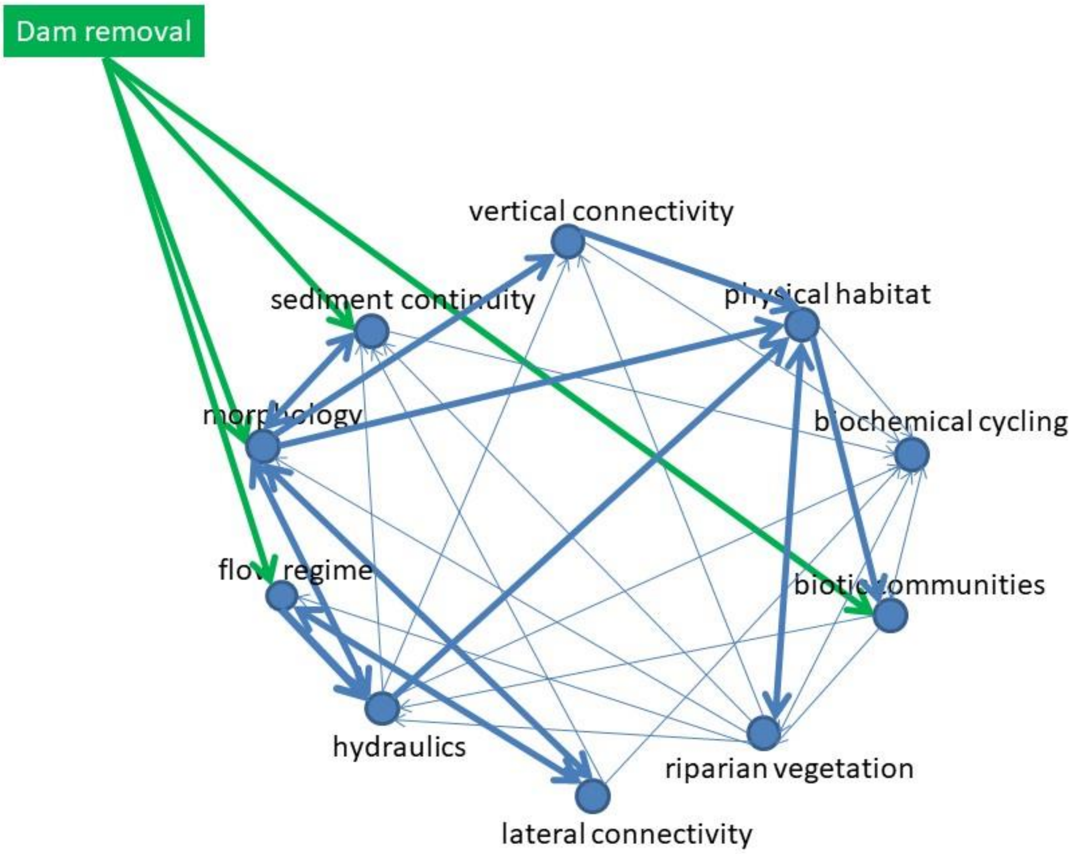

Fig. 10 Graphical representation of the interactions among functions (author: F. Liebault).

4.5.1 Function – ecosystem services linkages

Biotic communities - Natural and cultural heritage of the river and floodplain ecosystem

It is relevant due to the importance of rivers as biodiversity reserve and presence of relevant species (e.g., umbrella species).

Biotic communities - Water-related activities

The presence and abundance of several species are a pre-condition for some water-related activities, in particular for angling and bird-watching. Different types of angling have different requirements in relation to biotic communities.

Biotic communities – Ecological status

The community composition influences the ecological status of the river.

Hydraulics – Regulating Temperature, cooling

The hydraulic variables directly influence the temperature and the cooling capacity of the river.

Hydraulics – Water related activities

The hydraulic variables directly influence specific water related activities such as boating and rafting (see Carolli et al., 2017).

Instream flow regime - Aesthetics of landscape

The Instream flow regime has an important impact on the aesthetical appreciation of the river landscape. One of the most relevant components of the regime in this context is the frequency of occurrence of very low flows (temporary rivers or gravel bed rivers with limited extension of channels with flowing water may be less attractive for the general public). Another important aspect is the "sound of the river" associated to a given flow rate (and affected by river morphology) which is inherently part of the experience of a river landscape.

Instream flow regime - Drought risk mitigation

Flow regime (quantity and timing) mitigate drought. especially through groundwater recharge.

Instream flow regime - Education, Science

It is important to make population aware of why, when and where rivers are dangerous. The study and understand the flow regime raise awareness in the population about risk and hazard connected with rivers.

Instream flow regime - Flood risk mitigation

The high flows components of the flow regime (in terms of quantity and timing) have a strong and obvious influence on flood risk.

Instream flow regime – Hydropower

Flow regime influences the quantity of water available for production.

Instream flow regime - Regulating temperature

Flow regime (water quantity) may regulate temperature locally with heating/cooling effect.

Instream flow regime - Surface water for drinking purpose

Flow regime influences the water quantity and the timing of the water available for this service.

Instream flow regime – Surface water for non-drinking purposes

Flow regime influences the water quantity and the timing of the water available for this service.

Instream flow regime - Water-related activities

Flow regime influences the water quantity and the timing of the water available for this service.

Instream flow regime – Ecological status

The flow regime is fundamental to sustain the life cycle of species, thus ensuring a good ecological status (Poff et al., 1997).

Lateral connectivity - Drought risk mitigation

Drought risk is naturally mitigated through water storage, e.g. in groundwater and in wetlands. The amount of water that can feed these natural storage systems is influenced by the connectivity between the river channel and its floodplain. Bank surface layer clogging in some of cases causing elevated water table and thus in cases of floods, increased total recharge amount to the aquifer (Chen et al., 2013).

Lateral connectivity - Flood risk mitigation

The degree of lateral connectivity influences peak flow attenuation downstream, due to temporary storage in the floodplain, flood wave celerity reduction and to de-synchronization of the timings of sub-catchment flood waves (Dixon et al. 2016). It has to be highlighted that restoration of lateral connectivity may not always have positive effects on flood risk downstream, as in some cases it may re-synchronize flood waves that had been shifted due to artificialization, therefore a case-by-case assessment is necessary. It should also be recognized that in steep slope alpine valleys, the temporary storage capacity in the floodplain may be often insufficient to significantly reduce peak flows. Lateral connectivity affects flood risk depending on bank hydrogeological characteristics, sediment permeability, ground saturation levels, e.g. saturated river banks increase lateral connectivity between river and floodplain and in consequence flood risk. Flood risk reduction in this context is possible with bank layers with high water infiltration rate.

Lateral connectivity - Groundwater for drinking purpose

Increase of the recharge amount to the aquifer increases with increased lateral connectivity (increased fluid exchange rate).

Lateral connectivity - Groundwater for non-drinking purpose

Increase of the recharge amount to the aquifer increases with increased lateral connectivity (increased fluid exchange rate).

Physical habitat - Habitat-related services

Physical habitat provides the physical drivers and the fundamental ecological niches to sustain species life-cycle.

Physical habitat - Natural and cultural heritage of the river and floodplain ecosystem

Physical drivers are fundamental to sustain the life cycle of species relevant for natural and cultural heritage (e.g., flagship species).

Presence and composition of riparian vegetation - Aesthetics of landscape

The presence of riparian vegetation increases the aesthetic value.

Presence and composition of riparian vegetation - Reduction of greenhouse gas emission

Riparian vegetation reduces GHG emission by carbon fixation.

Presence and composition of riparian vegetation - Regulating temperature

Temperature changes in presence of vegetation (Zardo et al., 2017). Additional possible effects at the local scale on water temperature are due to shading.

Presence and composition of riparian vegetation - Retention of nutrients

Riparian vegetation assimilates and retains nutrients, changing the timing of nutrient diffusion and availability in the river habitat (e.g., nutrients introduced in the river during autumn by the fall of the leaves).

Presence and composition of riparian vegetation – Ecological status

Presence and composition of riparian vegetation influences the river ecological status.

River morphology - Aesthetics of landscape

Natural morphologies (braiding river, anastomosing river) may increase aesthetic value in comparison with more artificial river morphologies.

River morphology - Education, Science

It is important for the description and understanding of fundamental geomorphological processes

River morphology - Flood risk mitigation

The effect is still unclear (see Sholtes and Doyle, 2010). Large river-bed rivers may retain water and mitigate floods, but there is not agreement in literature about the effects of morphology on flood risk mitigation in Alpine rivers (e.g., Sholtes and Doyle, 2010).

River morphology - Natural and cultural heritage of the river and floodplain ecosystem

It is important for the high natural and cultural value of river types that deserve conservation (e.g., braiding rivers in Europe).

River morphology - Sediments for construction

Specific river morphologies can improve sediment deposition, thus increase the sediments available for construction.

River morphology - Water-related activities

Different river types support different water activities (e.g., white-water sports in high-gradient streams, paddling in low-gradient rivers).

River morphology – Ecological status

River morphology vegetation influences the river ecological status and it has to be assessed in the Water Framework Directive,

Vertical connectivity - Drought risk mitigation

Hyporheic zone characteristics affect groundwater-surface water exchange rate and consequently water availability for different purposes.

Vertical connectivity - Groundwater for drinking purpose

Vertical connectivity affects surface water mainly in the context of water quality (degree of water clarity/suspended matter amount) through water exchange between shallow groundwater and river (depending also on type of substrate, river morphology, hydraulics).

Vertical connectivity – Groundwater for non-drinking purposes

The effects are relevant if industry/agriculture water availability depends on aquifer-river water exchange level/groundwater level.

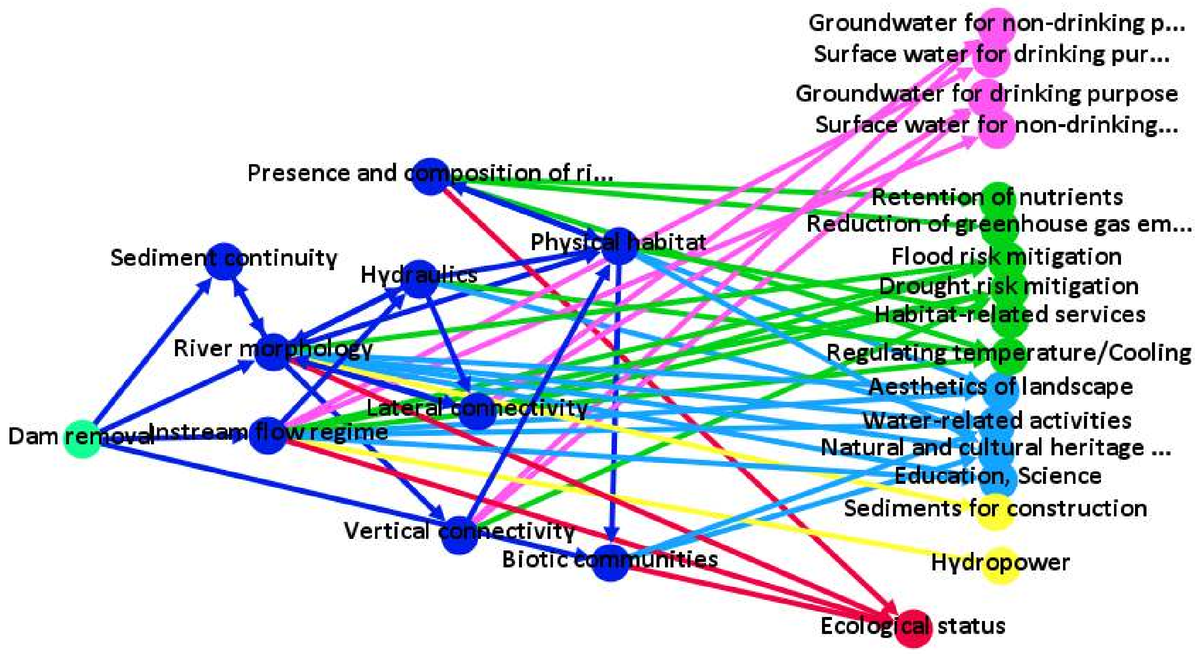

Fig. 11 Graphical representation of the framework for dam removal. The blue colour represents the functions and the linkages between functions and actions. The pink colour represents Provisioning services and their linkage with the

functions, the green colour represents Regulation and mainteinance services and their linkage with the functions, light blue colour represents Cultural services and their linkage with the functions, and the yellow colour represents the usages of abiotic natural capital and their linkage with the functions. In red we showed the ecological status and its linkages with the functions.

4.6 Deculverting

Tab. 19. Linkages between Deculverting and hydromorphological and biological functions, with direct or indirect linkage defined by experts' panel, distance from the action represented by the number of steps and the number of outgoing linkages.

Action	Function	Linkage	Level
Deculverting	Biochemical cycling of chemical compounds	Indirect	2
	Biotic communities	Direct	1
	Hydraulics	Indirect	2
	Instream flow regime	Indirect	2
	Lateral connectivity	Direct	1
	Physical habitat	Direct	1
	Presence and composition of riparian vegetation	Indirect	2
	River morphology	Direct	1
	Sediment continuity	Indrect	2
	Vertical connectivity	Indirect	2

Biochemical cycling of chemical compounds

The effects are mainly through vegetation and vertical connectivity. Restoring river association with the surrounding environment (floodplain, terrestrial) by deculverting can reestablish the natural cycle of chemical compounds and nutrients, also affecting temperature and processes related to solar light.

Biotic communities (1st level)

Deculverting affects all the main biological cycles (e.g. photosynthesis) thus strongly affecting all the aquatic communities. Restore river habitat and association with the surrounding environment improve river and riparian biotic communities (Wild et al., 2011). The effects are due to changes in physical habitat and in the biochemical cycles.

Hydraulics

Effects on hydraulic variables are mainly due to changes in morphology. Deculverting leads to a strong effect decrease of flow velocity and flow depth.

Instream flow regime

The effects of deculverting on Instream flow regime are through lateral connectivity.

Lateral connectivity (1st level)

Deculverting improves sediment flux exchange through lateral erosion. Also, deculverting could potentially cause increase of river roughness causing (potential) water level elevation and increased possibility of sediment and water exchange with neighboring floodplain.

Physical habitat (1st level)

Deculverting improves the habitat diversity and increases the number of ecological niches that can be occupied by river and riparian species. It is directly influenced by the action, but influenced by other function as well (e.g., morphology, hydraulics). Expected relevant effects are due to changes in water temperature.

Presence and composition of riparian vegetation

The effects are linked to the reactivation of the biochemical processes associated with solar lights (in particular photosynthesis), to the increase of the connection with the floodplain and to restoration of river morphology.

River morphology (1st level)

Considering that a flow in a culvert is not perceived as a river, the replacement of a culvert by an open channel section is a major change in the morphological appearance. The re-establishment of a more natural river morphology depends on eventual new channel constrainment.

Sediment continuity

The effects are through the river morphology. When culverted reaches are associated with a “bottleneck effect” for sediment and large woody debris transport, deculverting should enhance sediment continuity. Conversely, when culverted reaches are associated with a flushing effect for sediment, deculverting may increase sediment deposition along the reach.

Vertical connectivity

The effects are through river morphology. Deculverting causes increased permeability of river bottom layer, encouraging the exchanges between groundwater and riverbed, which was non-existent prior to deculverting because of river bottom impermeability.

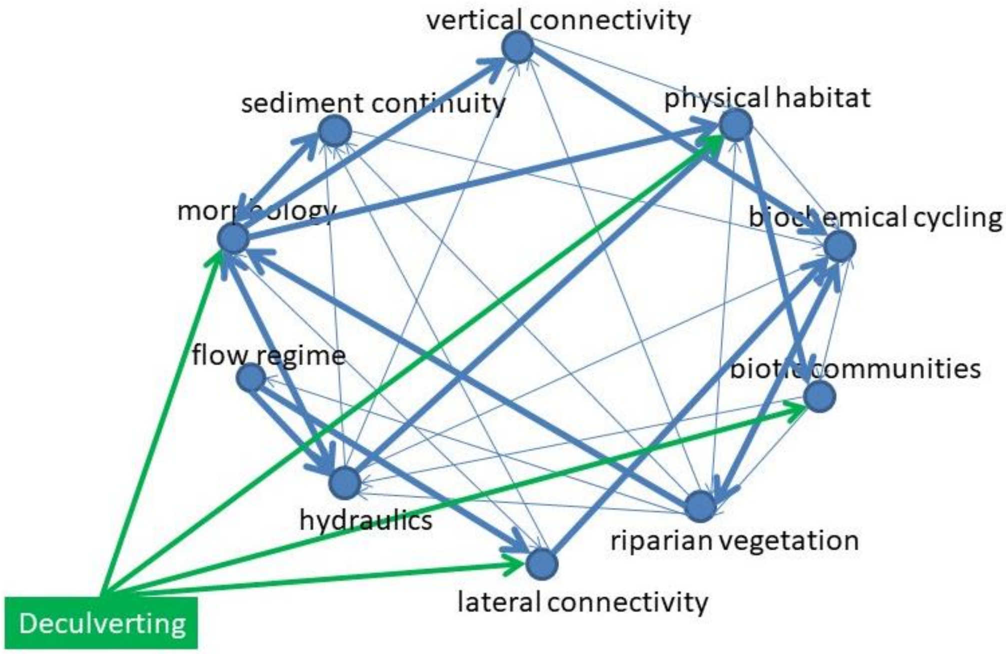

Fig. 12 Graphical representation of the interactions among functions (author: F. Liébault).

4.6.1 Function – ecosystem services linkages

Biochemical cycling of chemical compounds – Ecological status

This function does not affect directly ecosystem services, but it influences the biotic communities and the ecological status.

Biotic communities - Natural and cultural heritage of the river and floodplain ecosystem

It is relevant due to the importance of rivers as biodiversity reserve and presence of relevant species (e.g., umbrella species).

Biotic communities - Water-related activities

The presence and abundance of several species are a pre-condition for some water-related activities, in particular for angling and bird-watching. Different types of angling have different requirements in relation to biotic communities.

Biotic communities – Ecological status

The community composition influences the ecological status of the river.

Hydraulics – Regulating Temperature, cooling

The hydraulic variables directly influence the temperature and the cooling capacity of the river.

Hydraulics – Water related activities

The hydraulic variables directly influence specific water related activities such as boating and rafting (see Carolli et al., 2017).

Lateral connectivity - Drought risk mitigation

Drought risk is naturally mitigated through water storage, e.g. in groundwater and in wetlands. The amount of water that can feed these natural storage systems is influenced by the connectivity between the river channel and its floodplain. Bank surface layer clogging in some of cases causing elevated water table and thus in cases of floods, increased total recharge amount to the aquifer (Chen et al., 2013).

Lateral connectivity - Flood risk mitigation

The degree of lateral connectivity influences peak flow attenuation downstream, due to temporary storage in the floodplain, flood wave celerity reduction and to de-synchronization of the timings of sub-catchment flood waves (Dixon et al. 2016). It has to be highlighted that restoration of lateral connectivity may not always have positive effects on flood risk downstream, as in some cases it may re-synchronize flood waves that had been shifted due to artificialization, therefore a case-by-case assessment is necessary. It should also be recognized that in steep slope alpine valleys, the temporary storage capacity in the floodplain may be often insufficient to significantly reduce peak flows. Lateral connectivity affects flood risk depending on bank hydrogeological characteristics, sediment permeability, ground saturation levels, e.g. saturated river banks increase lateral connectivity between river and floodplain and in consequence flood risk. Flood risk reduction in this context is possible with bank layers with high water infiltration rate.

Lateral connectivity - Groundwater for drinking purpose

Increase of the recharge amount to the aquifer increases with increased lateral connectivity (increased fluid exchange rate).

Lateral connectivity - Groundwater for non-drinking purpose

Increase of the recharge amount to the aquifer increases with increased lateral connectivity (increased fluid exchange rate).

Physical habitat - Habitat-related services

Physical habitat provides the physical drivers and the fundamental ecological niches to sustain species life-cycle.

Physical habitat - Natural and cultural heritage of the river and floodplain ecosystem

Physical drivers are fundamental to sustain the life cycle of species relevant for natural and cultural heritage (e.g., flagship species).

Presence and composition of riparian vegetation - Aesthetics of landscape

The presence of riparian vegetation increases the aesthetic value.

Presence and composition of riparian vegetation - Reduction of greenhouse gas emission

Riparian vegetation reduces GHG emission by carbon fixation.

Presence and composition of riparian vegetation - Regulating temperature

Temperature changes in presence of vegetation (Zardo et al., 2017). Additional possible effects at the local scale on water temperature are due to shading.

Presence and composition of riparian vegetation - Retention of nutrients

Riparian vegetation assimilates and retains nutrients, changing the timing of nutrient diffusion and availability in the river habitat (e.g., nutrients introduced in the river during autumn by the fall of the leaves).

Presence and composition of riparian vegetation – Ecological status

Presence and composition of riparian vegetation influences the river ecological status.

River morphology - Aesthetics of landscape

Natural morphologies (braiding river, anastomosing river) may increase aesthetic value in comparison with more artificial river morphologies.

River morphology - Natural and cultural heritage of the river and floodplain ecosystem

It is important for the high natural and cultural value of river types that deserve conservation (e.g., braiding rivers in Europe).

River morphology - Sediments for construction

Specific river morphologies can improve sediment deposition, thus increase the sediments available for construction.

River morphology - Water-related activities

Different river types support different water activities (e.g., white-water sports in high-gradient streams, paddling in low-gradient rivers).

River morphology – Ecological status

River morphology vegetation influences the river ecological status and it has to be assessed in the Water Framework Directive,

Sediment continuity

Although it is directly influenced by the management action, the sediment continuity does not influence any ES. It has a strong effect on river morphology.

Vertical connectivity - Drought risk mitigation

Hyporheic zone characteristics affect groundwater-surface water exchange rate and consequently water availability for different purposes.

Vertical connectivity - Groundwater for drinking purpose

Vertical connectivity affects surface water mainly in the context of water quality (degree of water clarity/suspended matter amount) through water exchange between shallow groundwater and river (depending also on type of substrate, river morphology, hydraulics).

__Vertical connectivity – Groundwater for non-drinking purposes__

The effects are relevant if industry/agriculture water availability depends on aquifer-river water exchange level/groundwater level.

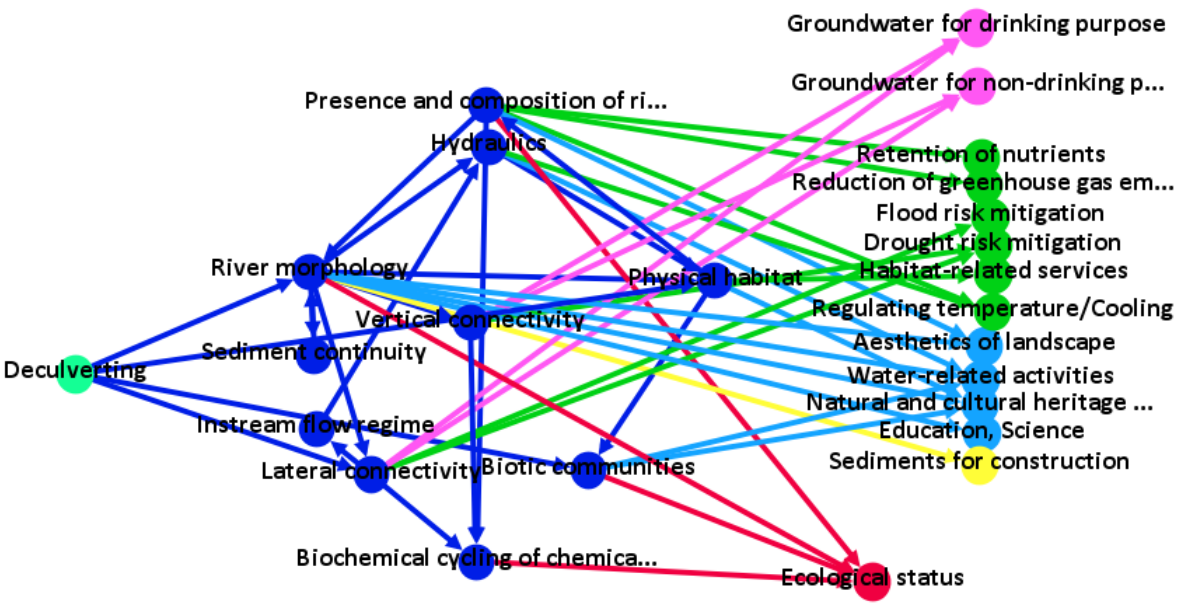

Fig. 13 Graphical representation of the framework for deculverting. The blue colour represents the functions and the linkages between functions and actions. The pink colour represents Provisioning services and their linkage with the functions, the green colour represents Regulation and mainteinance services and their linkage with the functions, light blue colour represents Cultural services and their linkage with the functions, and the yellow colour represents the usages of abiotic natural capital and their linkage with the functions. In red we showed the ecological status and its linkages with the functions.

4.7 Ensuring ecological flows

Tab. 20. Linkages between Ensuring ecological flows and hydromorphological and biological functions, with direct or indirect linkage defined by experts' panel, distance from the action represented by the number of steps and the number of outgoing linkages.

Action	Function	Linkage	Level
Ensuring ecological flows	Biochemical cycling of chemical compounds	Indirect	4
	Biotic communities	Indirect	4
	Hydraulics	Indirect	2
	Instream flow regime	Direct	1
	Lateral connectivity	No	
	Physical habitat	Indirect	3
	Presence and composition of riparian vegetation	No	
	River morphology	Indirect	3
	Sediment continuity	Indirect	4
	Vertical connectivity	No	

Biochemical cycling of chemical compounds

The effects are mainly due to physical habitat. The restoration of the natural flow regime has positive effects on nutrient cycling (CIS Guidance 2015; nitrogen: Poff et al, 1997) and the natural variations of the flow regime affects nutrients dynamics in lowland floodplain-river systems (Baldwin and Mitchell, 2000).

Biotic Communities

Expected positive effects of the restored regime on biotic communities (for the effects of flow regime alterations, see Bunn and Arthington, 2002), due both to the increase of physical habitat suitability (see below).

Hydraulics

Changes in hydraulic variables are due to changes in river morphology and flow regime.

Instream flow regime (1st level)

Ensuring ecological flows have direct positive effects on the flow regime by changing the variability, timing, duration and rate of change of the flow regime (see Poff et al., 1997).

Lateral connectivity

The effects are not relevant.

Physical habitat

The effects are due to changes in river morphology and hydraulic variables. Ecological flows mitigate the effects of low flows on temperature and dissolved oxygen (CIS Guidance 2015) and help to mitigate the alterations of the river thermal regime induced by hydropeaking (Zolezzi et al., 2010).

Presence and composition of riparian vegetation

The effects are not relevant or negligible.

River morphology

The effects are not direct but mainly through hydraulics. Duration, intensity and frequency of hydrological alterations related to ecological flows are the key processes which determine the river morphology. Hydrograph alterations may trigger sediment turnover in the channel, scouring, overbank deposition, channel migration, change in sediment composition and many other morphological processes (Merritt et al., 2010). Ecological flows should be defined dynamically, so that e.g. they vary seasonally, allow floods to pass almost undisturbed and keep sufficient shear stress so that sediment transport is ongoing and an adequate river morphology is following.

Sediment continuity

Generally, ecological flows are concerning water discharges below the incipient motion for bedload transport, and their effect on coarse sediment transport should be very low. However, a possible positive effect (through morphology) should be observed for the flushing of fine deposits in river channels (channel clogging). When the implementation of ecological flows includes Instream flow magnitudes which are relevant for bedload transport and previously altered, then the measure can enhance sediment continuity downstream.

Vertical connectivity

The effects are negligible or not relevant.

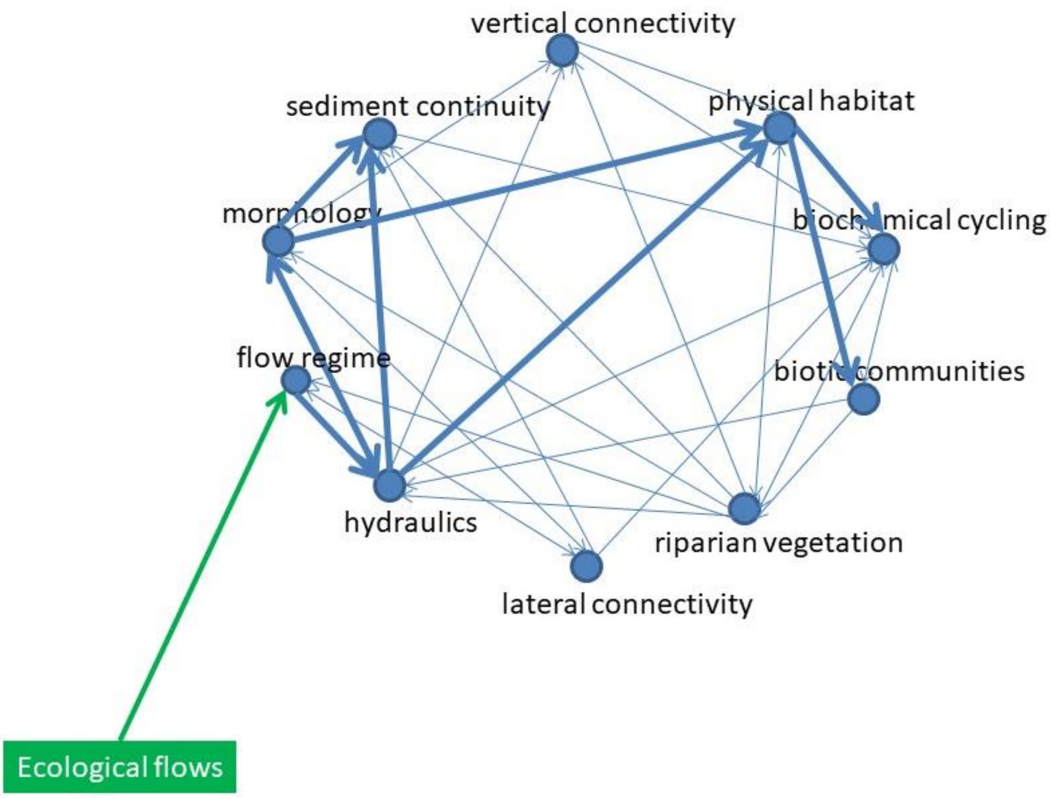

Fig. 14 Graphical representation of the interactions among functions (author: F. Liebault).

4.7.1 Function – ecosystem services linkages

Biochemical cycling of chemical compounds – Ecological status

This function does not affect directly ecosystem services, but it influences the biotic communities and the ecological status.

Biotic communities - Natural and cultural heritage of the river and floodplain ecosystem

It is relevant due to the importance of rivers as biodiversity reserve and presence of relevant species (e.g., umbrella species).

Biotic communities - Water-related activities

The presence and abundance of several species are a pre-condition for some water-related activities, in particular for angling and bird-watching. Different types of angling have different requirements in relation to biotic communities.

Biotic communities – Ecological status

The community composition influences the ecological status of the river.

Hydraulics – Navigation

Changes in the water depth and water velocity influence river navigability.

Hydraulics – Regulating Temperature, cooling

The hydraulic variables directly influence the temperature and the cooling capacity of the river.

Hydraulics – Water related activities

The hydraulic variables directly influence specific water related activities such as boating and rafting (see Carolli et al., 2017).

Instream flow regime - Aesthetics of landscape

The Instream flow regime has an important impact on the aesthetical appreciation of the river landscape. One of the most relevant components of the regime in this context is the frequency of occurrence of very low flows (temporary rivers or gravel bed rivers with limited extension of channels with flowing water may be less attractive for the general public). Another important aspect is the "sound of the river" associated to a given flow rate (and affected by river morphology) which is inherently part of the experience of a river landscape.

Instream flow regime - Drought risk mitigation

Flow regime (quantity and timing) mitigate drought. especially through groundwater recharge.

Instream flow regime - Education, Science

It is important to make population aware of why, when and where rivers are dangerous. The study and understand the flow regime raise awareness in the population about risk and hazard connected with rivers.

Instream flow regime - Flood risk mitigation

The high flows components of the flow regime (in terms of quantity and timing) have a strong and obvious influence on flood risk.

Instream flow regime - Groundwater for drinking purpose

Flow regime influences water quantity available for infiltration in the groundwater.

Instream flow regime - Groundwater for non-drinking purpose

Flow regime influences water quantity available for infiltration in the groundwater.

Instream flow regime – Hydropower

Flow regime influences the quantity of water available for production.

Instream flow regime - Regulating temperature/Cooling

Flow regime (water quantity) may regulate temperature locally with heating/cooling effect.

Instream flow regime - Surface water for drinking purpose

Flow regime influences the water quantity and the timing of the water available for this service.

Instream flow regime – Surface water for non-drinking purposes

Flow regime influences the water quantity and the timing of the water available for this service.

Instream flow regime - Water-related activities

Flow regime influence the water quantity and the timing of the water available for this service.

Instream flow regime – Ecological status

The flow regime is fundamental to sustain the life cycle of species, thus ensuring a good ecological status (Poff et al., 1997).

Physical habitat - Habitat-related services

Physical habitat provides the physical drivers and the fundamental ecological niches to sustain species life-cycle.

Physical habitat - Natural and cultural heritage of the river and floodplain ecosystem

Physical drivers are fundamental to sustain the life cycle of species relevant for natural and cultural heritage (e.g., flagship species).

River morphology - Aesthetics of landscape

Natural morphologies (braiding river, anastomosing river) may increase aesthetic value in comparison with more artificial river morphologies.

River morphology - Natural and cultural heritage of the river and floodplain ecosystem

It is important for the high natural and cultural value of river types that deserve conservation (e.g., braiding rivers in Europe).

River morphology - Sediments for construction

Specific river morphologies can improve sediment deposition, thus increase the sediments available for construction.

River morphology - Water-related activities

Different river types support different water activities (e.g., white-water sports in high-gradient streams, paddling in low-gradient rivers).

River morphology – Ecological status

River morphology vegetation influences the river ecological status and it has to be assessed in the Water Framework Directive.

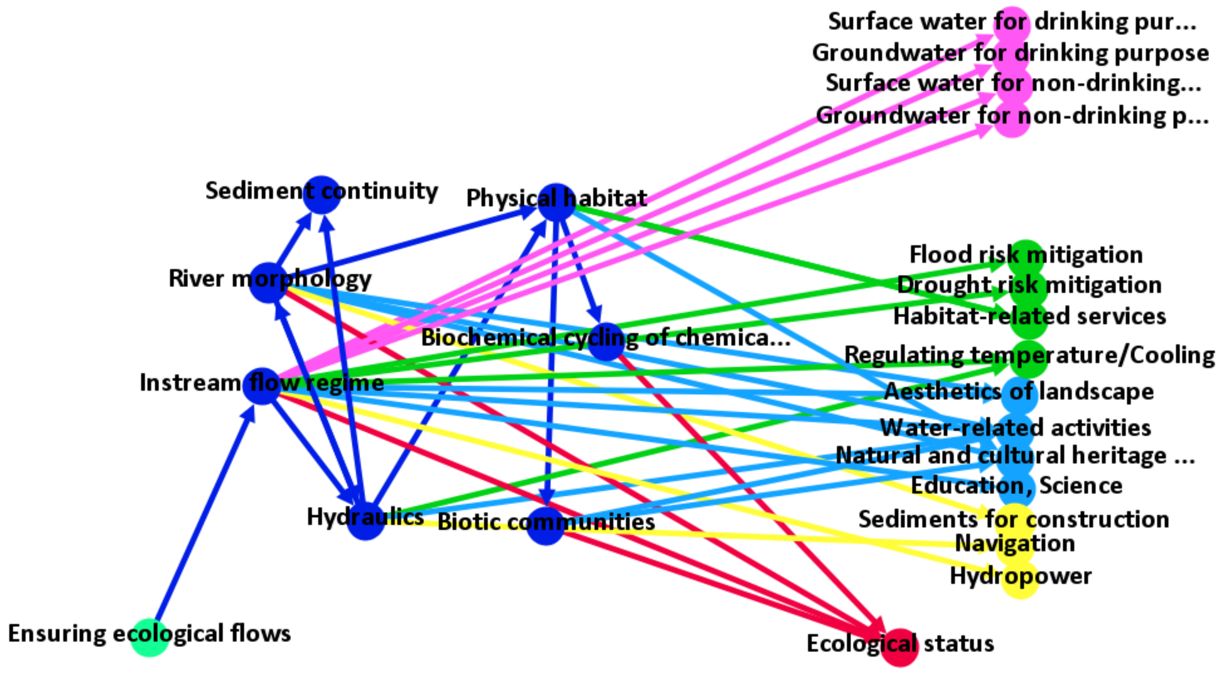

Fig. 15 Graphical representation of the framework for ensuring ecological flow. The blue color represent the functions and the linkages between functions and actions. The pink colour represents Provisioning services and their linkage with the functions, the green colour represents Regulation and mainteinance services and their linkage with the functions, light blue colour represents Cultural services and their linkage with the functions, and the yellow colour represents the usages of abiotic natural capital and their linkage with the functions. In red we showed the ecological status and its linkages with the functions.

4.8 Reintroduction of large woody debris

Tab. 21. Linkages between Reintroduction of large woody debris (LWD) and hydromorphological and biological functions, with direct or indirect linkage defined by experts' panel, distance from the action represented by the number of steps and the number of outgoing linkages.

Action	Function	Linkage	Level
Reintroduction of large woody debris	Biochemical cycling of chemical compounds	No	
	Biotic communities	Indirect	3
	Hydraulics	Indirect	2
	Instream flow regime	No	
	Lateral connectivity	No	
	Physical habitat	Indirect	2
	Presence and composition of riparian vegetation	No	
	River morphology	Direct	1
	Sediment continuity	Direct	1
	Vertical connectivity	Indirect	2

Biochemical cycling of chemical compounds

The effect of the reintroduction of LWD on the chemical cycling are not relevant or negligible.

Biotic communities

The effect of the reintroduction of LWD on the biotic communities is not direct. An expected positive effect is due to habitat diversification (see below).

Hydraulics

The effect of the reintroduction of LWD on the biotic communities is not direct and mainly through river morphology.

Instream flow regime

The effect of the reintroduction of LWD on the Instream flow regime is not relevant or negligible.

Lateral connectivity

The effect of the reintroduction of LWD on lateral connectivity is not relevant or negligible.

Physical habitat

Although the effect is not direct and mainly due to changes in morphology, hydraulics. The reintroduction of LWD improves the habitat diversification and increase the number of ecological niches that can be occupied by river and riparian species.

Presence and composition of riparian vegetation

The effect of the reintroduction of LWD on presence and composition of riparian vegetation is not relevant or negligible.

River morphology (1st level)

The morphological appearance is directly changed by the created macroforms, while the sustainability of the created macroforms and morphology depends on the boundary conditions such as quantity and quality (grain size) of sediment supply, channel constraints, discharge, slope as well as the succession of vegetation.

Sediment continuity (1st level)

The reintroduction of LWD may locally change the sediment continuity. However, a direct effect on ecosystem services is not expected.

Vertical connectivity

The effect of the reintroduction of LWD on vertical connectivity is not direct. However, due to changes in river morphology, the reintroduction of LWD affects the riverbed bottom permeability with (sediment fraction dependent) potential riverbed colmatation. Strong effects on exchange between surface and the hyporheic zone are predicted.

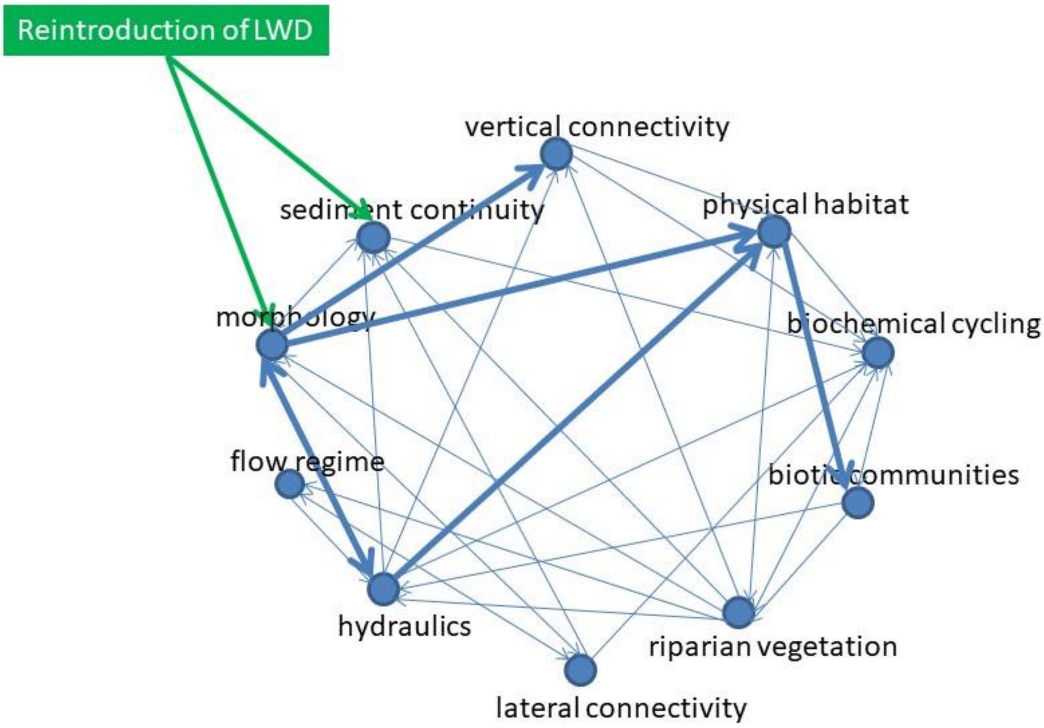

Fig. 16 Graphical representation of the interactions among functions (author: F. Liébault).

4.8.1 Function – ecosystem services linkages

Biotic communities - Natural and cultural heritage of the river and floodplain ecosystem

It is relevant due to the importance of rivers as biodiversity reserve and presence of relevant species (e.g., umbrella species).

Biotic communities - Water-related activities

The presence and abundance of several species are a pre-condition for some water-related activities, in particular for angling and bird-watching. Different types of angling have different requirements in relation to biotic communities.

Biotic communities – Ecological status

The community composition influences the ecological status of the river.

Hydraulics – Regulating Temperature, cooling

The hydraulic variables directly influence the temperature and the cooling capacity of the river.

Hydraulics – Water related activities

The hydraulic variables directly influence specific water related activities such as boating and rafting (see Carolli et al., 2017).

Physical habitat - Habitat-related services

Physical habitat provides the physical drivers and the fundamental ecological niches to sustain species life-cycle.

Physical habitat - Natural and cultural heritage of the river and floodplain ecosystem

Physical drivers are fundamental to sustain the life cycle of species relevant for natural and cultural heritage (e.g., flagship species).

River morphology - Aesthetics of landscape

Natural morphologies (braiding river, anastomosing river) may increase aesthetic value in comparison with more artificial river morphologies.

River morphology - Flood risk mitigation

The effect is still unclear (see Sholtes and Doyle, 2010). There is not a clear agreement in literature about the effects of morphology on flood risk mitigation in Alpine rivers (e.g., Sholtes and Doyle, 2010).

River morphology - Natural and cultural heritage of the river and floodplain ecosystem

It is important for the high natural and cultural value of river types that deserve conservation (e.g., braiding rivers in Europe).

River morphology - Sediments for construction

Specific river morphologies can improve sediment deposition, thus increase the sediments available for construction.

River morphology - Water-related activities

Different river types support different water activities (e.g., white-water sports in high-gradient streams, paddling in low-gradient rivers).

River morphology – Ecological status

River morphology vegetation influences the river ecological status and it has to be assessed in the Water Framework Directive,

Vertical connectivity - Drought risk mitigation

Hyporheic zone characteristics affect groundwater-surface water exchange rate and consequently water availability for different purposes.

Vertical connectivity - Groundwater for drinking purpose

Vertical connectivity affects surface water mainly in the context of water quality (degree of water clarity/suspended matter amount) through water exchange between shallow groundwater and river (depending also on type of substrate, river morphology, hydraulics).

Vertical connectivity – Groundwater for non-drinking purposes

The effects are relevant if industry/agriculture water availability depends on aquifer-river water exchange level/groundwater level.

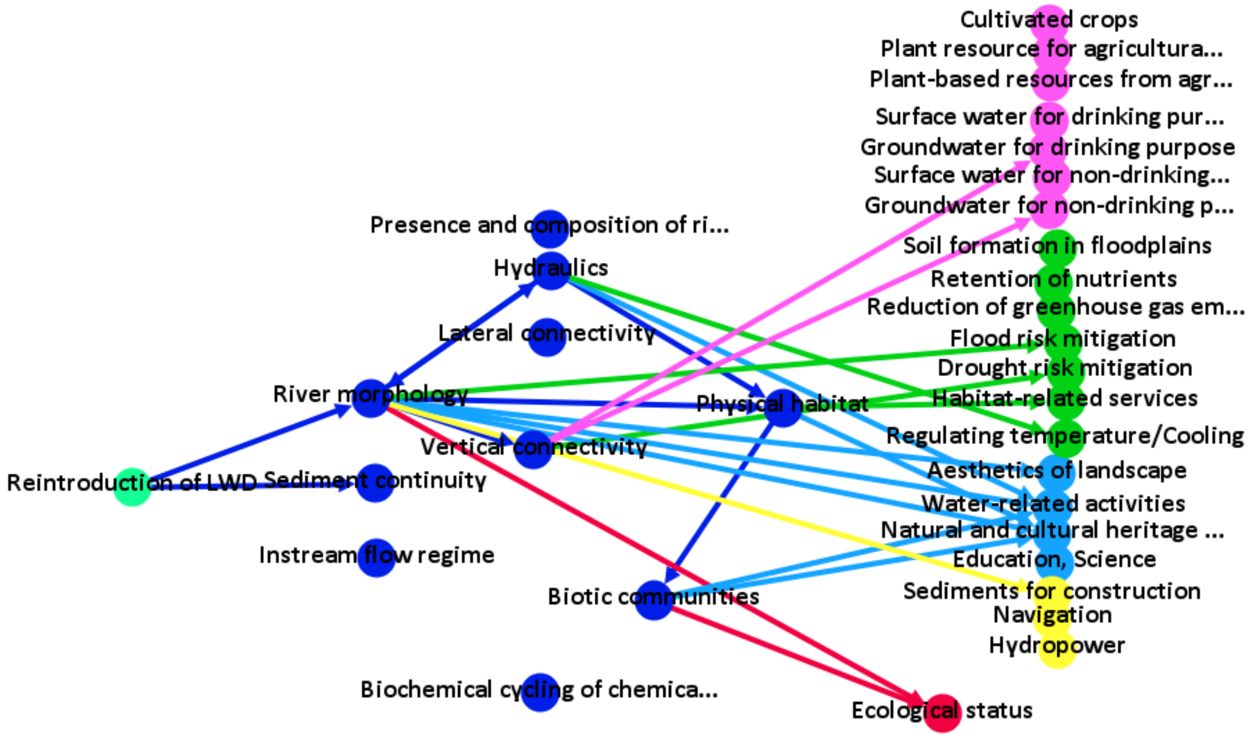

Fig. 17 Graphical representation of the framework for the reintroduction of LWD. The blue colour represents the functions and the linkages between functions and actions. The pink colour represents Provisioning services and their linkage with the functions, the green colour represents Regulation and mainteinance services and their linkage with the functions, light blue colour represents Cultural services and their linkage with the functions, and the yellow colour represents the usages of abiotic natural capital and their linkage with the functions. In red we showed the ecological status and its linkages with the functions.

4.9 Remeandering

Tab. 22. Linkages between Remeandering and hydromorphological and biological functions, with direct or indirect linkage defined by experts' panel, distance from the action represented by the number of steps and the number of outgoing linkages.

Action	Function	Linkage	Level
Remeandering	Biochemical cycling of chemical compounds	No	
	Biotic communities	Indirect	3
	Hydraulics	Indirect	2
	In-stream flow regime	No	
	Lateral connectivity	Indirect	2
	Physical habitat	Indirect	2
	Presence and composition of riparian vegetation	Indirect	3
	River morphology	Direct	1
	Sediment continuity	Indirect	2
	Vertical connectivity	No	

Biochemical cycling of chemical compounds

The effects are indirect and not relevant.

Biotic communities

The effects of remeandering on biotic communities are indirect. The effects are due to modification of the river morphology and physical habitat (e.g., improve macroinvertebrate community diversity and biomass, Nakano and Nakamura, 2006).

Hydraulics

The effects are not direct. Changes in river morphology change the hydraulic variables.

In-stream flow regime

The effects of remeandering on the in-stream flow regime are negligible or not relevant.

Lateral connectivity

The effects are mainly through morphology. Recreation of meanders affects hydraulic conditions in the river and causes important differences of connectivity with floodplain in the direction perpendicular to river.

Physical habitat

Recreation of meanders changes the hydraulic properties of a river (e.g. velocities, velocities depth distribution, turbulences, etc.), improving habitat diversity. In the same time the creation of new niches and habitat along river banks is expected. Effects are through morphology, hydraulics and riparian vegetation.

Presence and composition of riparian vegetation

The effects are indirect and mainly through physical habitat. If established meanders are allowed to migrate, point bars developing at the inner banks of river bends provide bare sediment for the recruitment of pioneer vegetation. The outer banks are scoured from bank erosion, there undermining the rootstock of mature trees and hence delivering woody debris into the channel.

River morphology (1st level)

The effects are directly on river morphology. Remeandering increases the river length and decreases the channel slope, promoting the emergence of aggradational features such as bars and riffles. If the re-established meanders are allowed to migrate, point bars develop at the inner banks of river bends, while the outer banks are scoured from bank erosion.

Sediment continuity

Through changes in morphology, remeandering may have a positive effect on sediment supply by reactivating sediment exchanges between the active channel and the floodplain (Piegay et al., 1997). However, a direct effect on ecosystem services is not expected.

Vertical connectivity

The effects of remeandering are negligible or not relevant.

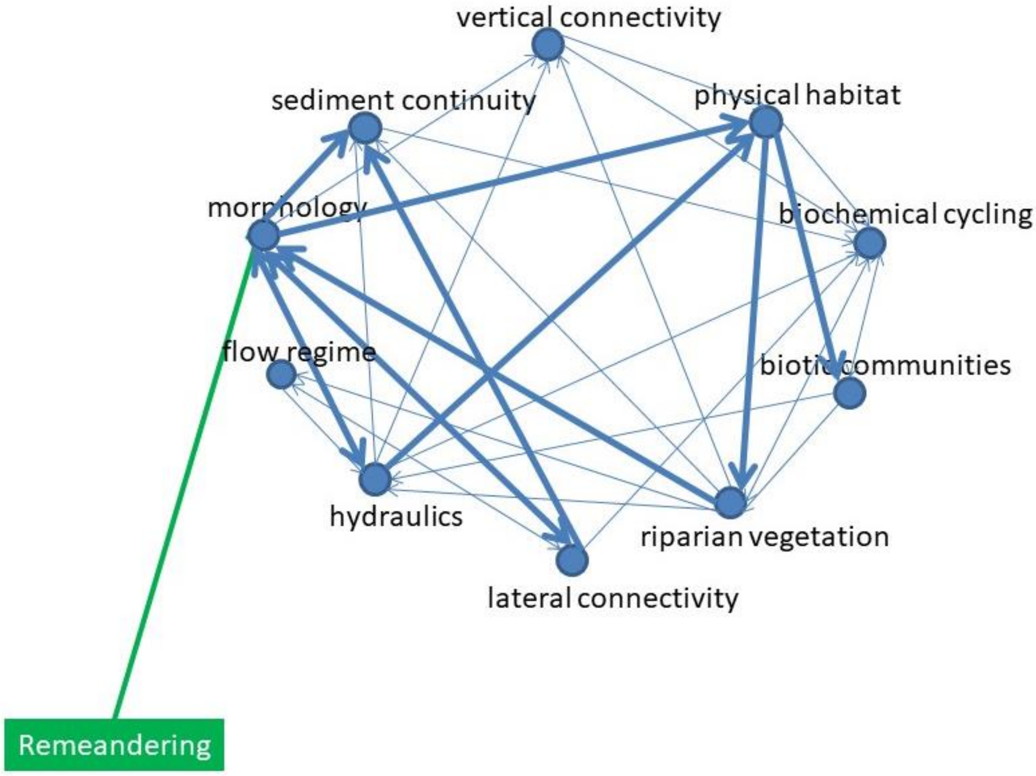

Fig. 18 Graphical representation of the interactions among functions (author: F. Liébault).

4.9.1 Function – ecosystem services linkages

Biotic communities - Natural and cultural heritage of the river and floodplain ecosystem

It is relevant due to the importance of rivers as biodiversity reserve and presence of relevant species (e.g., umbrella species).

Biotic communities - Water-related activities

The presence and abundance of several species are a pre-condition for some water-related activities, in particular for angling and bird-watching. Different types of angling have different requirements in relation to biotic communities.

Biotic communities – Ecological status

The community composition influences the ecological status of the river.

Hydraulics – Regulating Temperature, cooling

The hydraulic variables directly influence the temperature and the cooling capacity of the river.

Hydraulics – Water related activities

The hydraulic variables directly influence specific water related activities such as boating and rafting (see Carolli et al., 2017).

Lateral connectivity - Drought risk mitigation

Drought risk is naturally mitigated through water storage, e.g. in groundwater and in wetlands. The amount of water that can feed these natural storage systems is influenced by the connectivity between the river channel and its floodplain. Bank surface layer clogging in some of cases causing elevated water table and thus in cases of floods, increased total recharge amount to the aquifer (Chen et al., 2013).

Lateral connectivity - Flood risk mitigation

The degree of lateral connectivity influences peak flow attenuation downstream, due to temporary storage in the floodplain, flood wave celerity reduction and to de-synchronization of the timings of sub-catchment flood waves (Dixon et al. 2016). It has to be highlighted that restoration of lateral connectivity may not always have positive effects on flood risk downstream, as in some cases it may re-synchronize flood waves that had been shifted due to artificialization, therefore a case-by-case assessment is necessary. It should also be recognized that in steep slope alpine valleys, the temporary storage capacity in the floodplain may be often insufficient to significantly reduce peak flows. Lateral connectivity affects flood risk depending on bank hydrogeological characteristics, sediment permeability, ground saturation levels, e.g. saturated river banks increase lateral connectivity between river and floodplain and in consequence flood risk. Flood risk reduction in this context is possible with bank layers with high water infiltration rate.

Lateral connectivity - Groundwater for drinking purpose

Increase of the recharge amount to the aquifer increases with increased lateral connectivity (increased fluid exchange rate).

Lateral connectivity - Groundwater for non-drinking purpose

Increase of the recharge amount to the aquifer increases with increased lateral connectivity (increased fluid exchange rate).

Physical habitat - Habitat-related services

Physical habitat provides the physical drivers and the fundamental ecological niches to sustain species life-cycle.

Physical habitat - Natural and cultural heritage of the river and floodplain ecosystem

Physical drivers are fundamental to sustain the life cycle of species relevant for natural and cultural heritage (e.g., flagship species).

Presence and composition of riparian vegetation - Aesthetics of landscape

The presence of riparian vegetation increases the aesthetic value.

Presence and composition of riparian vegetation - Reduction of greenhouse gas emission

Riparian vegetation reduces GHG emission by carbon fixation.

Presence and composition of riparian vegetation - Regulating temperature

Temperature changes in presence of vegetation (Zardo et al., 2017). Additional possible effects at the local scale on water temperature are due to shading.

Presence and composition of riparian vegetation - Retention of nutrients

Riparian vegetation assimilates and retains nutrients, changing the timing of nutrient diffusion and availability in the river habitat (e.g., nutrients introduced in the river during autumn by the fall of the leaves).

Presence and composition of riparian vegetation – Ecological status

Presence and composition of riparian vegetation influences the river ecological status.

River morphology - Aesthetics of landscape

Natural morphologies (braiding river, anastomosing river) may increase aesthetic value in comparison with more artificial river morphologies.

River morphology - Natural and cultural heritage of the river and floodplain ecosystem

It is important for the high natural and cultural value of river types that deserve conservation (e.g., braiding rivers in Europe).

River morphology - Sediments for construction

Specific river morphologies can improve sediment deposition, thus increase the sediments available for construction.

River morphology - Water-related activities

Different river types support different water activities (e.g., white-water sports in high-gradient streams, paddling in low-gradient rivers).

River morphology – Ecological status

River morphology vegetation influences the river ecological status and it has to be assessed in the Water Framework Directive.

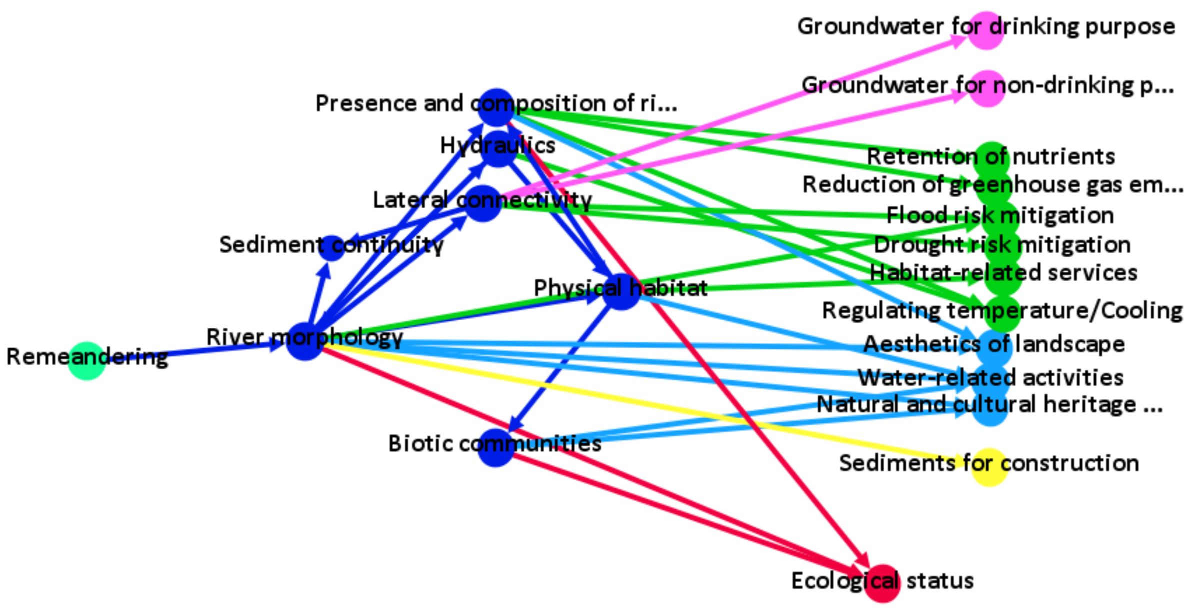

Fig. 19 Graphical representation of the framework for remeandering. The blue color represent the functions and the linkages between functions and actions. The pink colour represents Provisioning services and their linkage with the functions, the green colour represents Regulation and mainteinance services and their linkage with the functions, light blue colour represents Cultural services and their linkage with the functions, and the yellow colour represents the usages of abiotic natural capital and their linkage with the functions. In red we showed the ecological status and its linkages with the functions.

4.10 Removal of bank protection

Tab. 23. Linkages between Removal of bank protection and hydromorphological and biological functions, with linkage presence/absence defined by experts' panel. Linkage weight is defined by mean score resulting from the analysis of the expert-based matrices.

Action	Function	Linkage	Level
Removal of bank protection	Biochemical cycling of chemical compounds	Indirect	5
	Biotic communities	Indirect	4
	Hydraulics	Indirect	3
	Instream flow regime	No	
	Lateral connectivity	Direct	1
	Physical habitat	Indirect	3
	Presence and composition of riparian vegetation	Indirect	4
	River morphology	Indirect	2
	Sediment continuity	Indirect	2
	Vertical connectivity	Indirect	3

Biochemical cycling of chemical compounds

The effects are through biotic communities. The presence of bank protections could negatively affect the buffer capacity of the soil community of natural riparian area, both interrupting the subsurface flows and preventing the rooting system of vegetation to develop, with possible effects on nutrient inputs.

Biotic communities

The effects are due to changes in physical habitat and biochemical cycling. The removal of bank protection restores the natural macroinvertebrate communities (e.g., Hirabayashi et al., 2008) and helps to restore natural fish communities (e.g., Shields et al., 2000)

Hydraulics

Indirect effects are due to changes in morphology.

Instream flow regime

The effects of this action on the Instream flow regime are negligible or not relevant.

Lateral connectivity (1st level)

This action affects directly the lateral connectivity since the banks without protection are subjected to bank erosion and extended overbank flooding potentially causing (bare cultivated) flushing of floodplain soils in the direction river-floodplain.

Physical habitat

The effects are mainly through hydraulics, morphology. The creation of new ecological niches and habitat along the river banks is expected and the removal of bank protection could provide refugia for fish and macroinvertebrate (e.g., shady areas, overhanging roots).

Presence and composition of riparian vegetation

The indirect effects are due to changes in morphology. The removal of bank protections allows the recreation of the natural succession of vegetation in the riparian areas, leads to channel shifting and changes in the groundwater table.

River morphology

The removal of artificial channel constraints allows lateral erosion, which provides space for wider morphologies such as the alternate bars or braiding type. An increased width may stabilize formerly incising riverbeds, and promote the emergence of aggradational features such as bars and riffles. A precondition for self-dynamic widening through bank erosion is sufficient sediment supply.

Sediment continuity

Bank protection removal will increase sediment supply to stream channel, and subsequently increase sediment transport downstream.

Vertical connectivity

As an indirect effect, changes in river morphology can lead to aggradation and changes in groundwater level

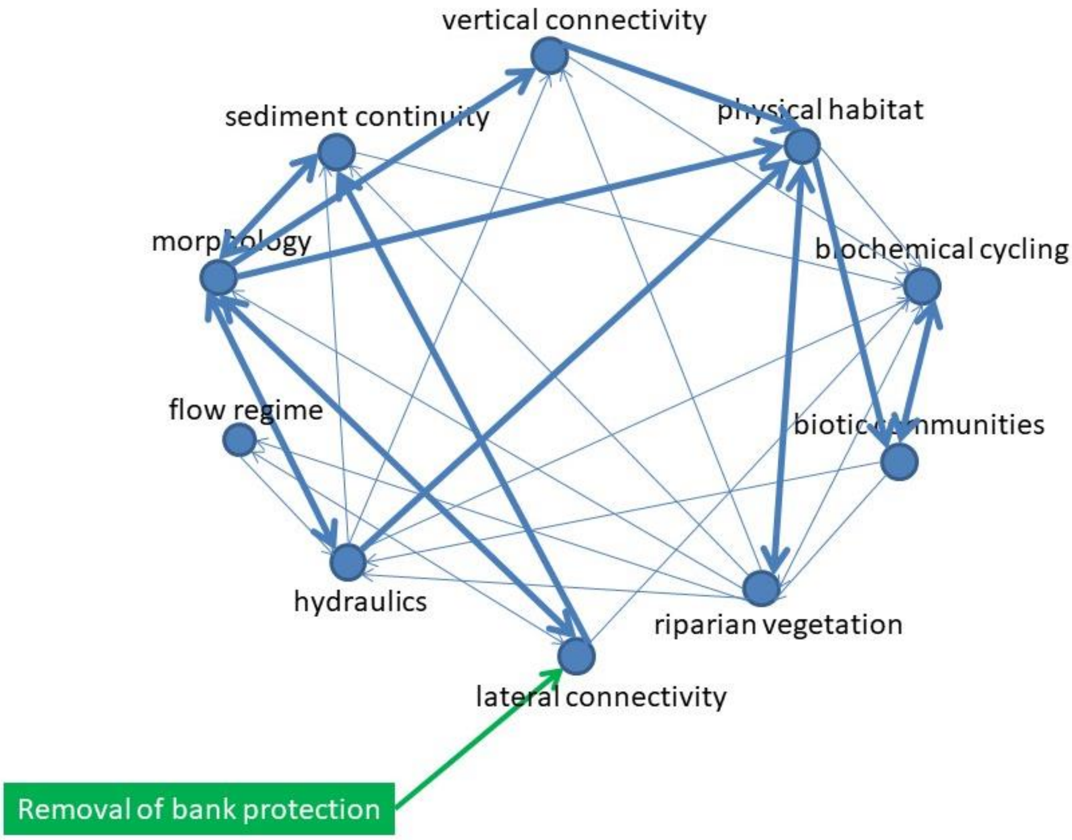

Fig. 20 Graphical representation of the interactions among functions (author: F. Liebault).

4.10.1 Function – ecosystem services linkages

Biochemical cycling of chemical compounds – Ecological status

This function does not affect directly ecosystem services, but it influences the physical habitat, the biotic communities and the ecological status.

Biotic communities - Natural and cultural heritage of the river and floodplain ecosystem

It is relevant due to the importance of rivers as biodiversity reserve and presence of relevant species (e.g., umbrella species).

Biotic communities - Water-related activities

The presence and abundance of several species are a pre-condition for some water-related activities, in particular for angling and bird-watching. Different types of angling have different requirements in relation to biotic communities.

Biotic communities – Ecological status

The community composition influences the ecological status of the river.

Hydraulics – Regulating Temperature, cooling

The hydraulic variables directly influence the temperature and the cooling capacity of the river.

Hydraulics – Water related activities

The hydraulic variables directly influence specific water related activities such as boating and rafting (see Carolli et al., 2017).

Lateral connectivity - Drought risk mitigation

Drought risk is naturally mitigated through water storage, e.g. in groundwater and in wetlands. The amount of water that can feed these natural storage systems is influenced by the connectivity between the river channel and its floodplain. Bank surface layer clogging in some of cases causing elevated water table and thus in cases of floods, increased total recharge amount to the aquifer (Chen et al., 2013).

Lateral connectivity - Flood risk mitigation

The degree of lateral connectivity influences peak flow attenuation downstream, due to temporary storage in the floodplain, flood wave celerity reduction and to de-synchronization of the timings of sub-catchment flood waves (Dixon et al. 2016). It has to be highlighted that restoration of lateral connectivity may not always have positive effects on flood risk downstream, as in some cases it may re-synchronize flood waves that had been shifted due to artificialization, therefore a case-by-case assessment is necessary. It should also be recognized that in steep slope alpine valleys, the temporary storage capacity in the floodplain may be often insufficient to significantly reduce peak flows. Lateral connectivity affects flood risk depending on bank hydrogeological characteristics, sediment permeability, ground saturation levels, e.g. saturated river banks increase lateral connectivity between river and floodplain and in consequence flood risk. Flood risk reduction in this context is possible with bank layers with high water infiltration rate.

Lateral connectivity - Groundwater for drinking purpose

Increase of the recharge amount to the aquifer increases with increased lateral connectivity (increased fluid exchange rate).

Lateral connectivity - Groundwater for non-drinking purpose

Increase of the recharge amount to the aquifer increases with increased lateral connectivity (increased fluid exchange rate).

Physical habitat - Habitat-related services

Physical habitat provides the physical drivers and the fundamental ecological niches to sustain species life-cycle.

Physical habitat - Natural and cultural heritage of the river and floodplain ecosystem

Physical drivers are fundamental to sustain the life cycle of species relevant for natural and cultural heritage (e.g., flagship species).

Presence and composition of riparian vegetation - Aesthetics of landscape

The presence of riparian vegetation increases the aesthetic value.

Presence and composition of riparian vegetation - Reduction of greenhouse gas emission

Riparian vegetation reduces GHG emission by carbon fixation.

Presence and composition of riparian vegetation - Regulating temperature

Temperature changes in presence of vegetation (Zardo et al., 2017). Additional possible effects at the local scale on water temperature are due to shading.

Presence and composition of riparian vegetation - Retention of nutrients

Riparian vegetation assimilates and retains nutrients, changing the timing of nutrient diffusion and availability in the river habitat (e.g., nutrients introduced in the river during autumn by the fall of the leaves).

Presence and composition of riparian vegetation – Ecological status

Presence and composition of riparian vegetation influences the river ecological status.

River morphology - Aesthetics of landscape

Natural morphologies (braiding river, anastomosing river) may increase aesthetic value in comparison with more artificial river morphologies.

River morphology - Education, Science

It is important for the description and understanding of fundamental geomorphological processes

River morphology - Natural and cultural heritage of the river and floodplain ecosystem

It is important for the high natural and cultural value of river types that deserve conservation (e.g., braiding rivers in Europe).

River morphology - Sediments for construction

Specific river morphologies can improve sediment deposition, thus increase the sediments available for construction.

River morphology - Water-related activities

Different river types support different water activities (e.g., white-water sports in high-gradient streams, paddling in low-gradient rivers).

River morphology – Ecological status

River morphology vegetation influences the river ecological status and it has to be assessed in the Water Framework Directive,

Vertical connectivity - Drought risk mitigation

Hyporheic zone characteristics affect groundwater-surface water exchange rate and consequently water availability for different purposes.

Vertical connectivity - Groundwater for drinking purpose

Vertical connectivity affects surface water mainly in the context of water quality (degree of water clarity/suspended matter amount) through water exchange between shallow groundwater and river (depending also on type of substrate, river morphology, hydraulics).

Vertical connectivity – Groundwater for non-drinking purposes

The effects are relevant if industry/agriculture water availability depends on aquifer-river water exchange level/groundwater level.

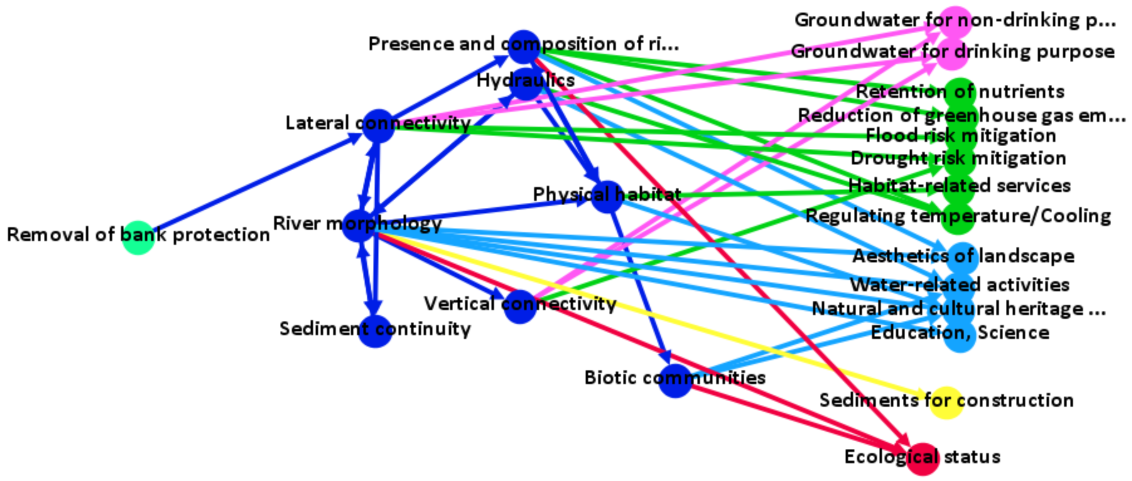

Fig. 21 Graphical representation of the framework for removal of bank protection. The blue color represent the functions and the linkages between functions and actions. The pink colour represents Provisioning services and their linkage with the functions, the green colour represents Regulation and mainteinance services and their linkage with the functions, light blue colour represents Cultural services and their linkage with the functions, and the yellow colour represents the usages of abiotic natural capital and their linkage with the functions. In red we showed the ecological status and its linkages with the functions.

4.11 Floodplain reconnection through removal or retreat of levees

Tab. 24. Linkages between Floodplain reconnection (removal, retreat of levees) and hydromorphological functions and biological, with direct or indirect linkage defined by experts' panel, distance from the action represented by the number of steps and the number of outgoing linkages.

Action	Function	Linkage	Level
Removal of levees	Biochemical cycling of chemical compounds	Indirect	2
	Biotic Communities	Indirect	4
	Hydraulics	Indirect	3
	Instream flow regime	Indirect	2
	Lateral connectivity	Direct	1
	Physical habitat	Indirect	4
	Presence and composition of riparian vegetation	Indirect	5
	River morphology	Indirect	4
	Sediment continuity	No	
	Vertical connectivity	Indirect	3

Biochemical cycling of chemical compounds

The direct effects of this action are through lateral connectivity. The floodplain reconnection (removal, retreat of levees) could allow the inundation of the floodplain and activate some biogeochemical processes.

Biotic communities

Positive indirect effects through physical habitat on the population of amphibians and dragonflies have been demonstrated in literature (Chovanec et al., 2002). An improvement in fish population is expected as well (Jungwirth et al., 2002), mainly due to the recreation of lateral spawning and resting habitats.

Hydraulics

Indirect effects are due to changes in instream flow regime. Water depth decrease during floods due to floodplain exchanges.

Instream flow regime

Indirect effects are due to changes in lateral connectivity. On the basis of the literature on numerical modelling, restoration of floodplain connectivity usually has limited effects on peak flow discharge for mountain (i.e. high slope) rivers and streams, even in case of extensive restoration measures (Dixon et al., 2016; Kreis et al., 2005; Sholtes and Doyle, 2011). For lowland rivers floodplain reconnection can have a relevant effect on downstream water retention during floods, depending on the extension of the reconnected floodplain and on the characteristics of the river network.

Lateral connectivity (1st level)

Floodplain reconnection (removal, retreat of levees) has two major relevance to lateral connectivity: the first one is to allow the extended flooding of the floodplain while reducing the shear stress on river bottom layers, the second one is related to extended floodplain bare soil erosion in case of floods.

Physical habitat

The effects are mainly through hydraulics and morphology. Floodplain reconnection (removal, retreat of levees) trigger the creation of new habitats in the reconnected floodplains (e.g. oxbow lakes).

Presence and composition of riparian vegetation

The indirect effects are due to changes in the physical habitat. The presence and the composition of vegetation in the reconnected floodplains could be strongly affected by the increase of the frequency and intensity of the flooding events modified by the Floodplain reconnection (removal, retreat of levees).

River morphology

In addition to the effects on river morphology of an increased lateral mobility, the Floodplain reconnection (removal, retreat of levees) decreases the water depth and hence the bed shear stresses during flood events. This effect may turn a formerly degrading riverbed into a stable bed, eventually with aggradational features such as bars or riffles.

Sediment continuity

The direct effects of this action are not relevant or negligible.

Vertical connectivity

The direct effects are through hydraulics. The reconnection with the floodplain allows groundwater recharge A possible indirect effect removal of levee affects the vertical connectivity when there is an income of sediments from subsequent bank erosion (flood discharges), and consequently a potential alteration of fluid exchange between shallow groundwater and river.

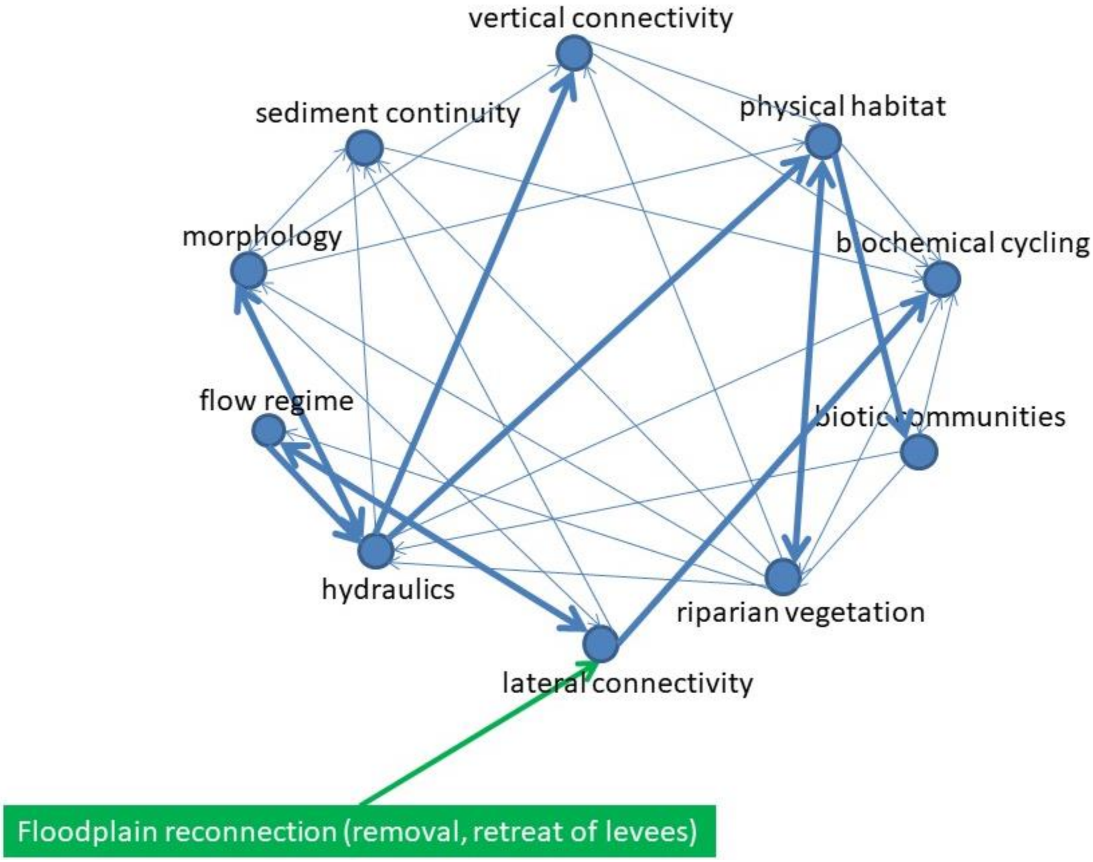

Fig. 22 Graphical representation of the interactions among functions (author: F. Liébault).

4.11.1Functions – ecosystem services linkages

Biochemical cycling of chemical compounds – Ecological status

This function does not affect directly ecosystem services, but it influences the physical habitat, the biotic communities and the ecological status.

Biotic communities - Natural and cultural heritage of the river and floodplain ecosystem

It is relevant due to the importance of rivers as biodiversity reserve and presence of relevant species (e.g., umbrella species).

Biotic communities - Water-related activities

The presence and abundance of several species are a pre-condition for some water-related activities, in particular for angling and bird-watching. Different types of angling have different requirements in relation to biotic communities.

Biotic communities – Ecological status

The community composition influences the ecological status of the river.

Hydraulics – Regulating Temperature, cooling

The hydraulic variables directly influence the temperature and the cooling capacity of the river.

Hydraulics – Water related activities

The hydraulic variables directly influence specific water related activities such as boating and rafting (see Carolli et al., 2017).

Lateral connectivity - Drought risk mitigation

Drought risk is naturally mitigated through water storage, e.g. in groundwater and in wetlands. The amount of water that can feed these natural storage systems is influenced by the connectivity between the river channel and its floodplain. Bank surface layer clogging in some of cases causing elevated water table and thus in cases of floods, increased total recharge amount to the aquifer (Chen et al., 2013).

Lateral connectivity - Flood risk mitigation

The degree of lateral connectivity influences peak flow attenuation downstream, due to temporary storage in the floodplain, flood wave celerity reduction and to de-synchronization of the timings of sub-catchment flood waves (Dixon et al. 2016). It has to be highlighted that restoration of lateral connectivity may not always have positive effects on flood risk downstream, as in some cases it may re-synchronize flood waves that had been shifted due to artificialization, therefore a case-by-case assessment is necessary. It should also be recognized that in steep slope alpine valleys, the temporary storage capacity in the floodplain may be often insufficient to significantly reduce peak flows. Lateral connectivity affects flood risk depending on bank hydrogeological characteristics, sediment permeability, ground saturation levels, e.g. saturated river banks increase lateral connectivity between river and floodplain and in consequence flood risk. Flood risk reduction in this context is possible with bank layers with high water infiltration rate.

Lateral connectivity - Groundwater for drinking purpose

Increase of the recharge amount to the aquifer increases with increased lateral connectivity (increased fluid exchange rate).

Lateral connectivity - Groundwater for non-drinking purpose

Increase of the recharge amount to the aquifer increases with increased lateral connectivity (increased fluid exchange rate).

Physical habitat - Habitat-related services

Physical habitat provides the physical drivers and the fundamental ecological niches to sustain species life-cycle.

Physical habitat - Natural and cultural heritage of the river and floodplain ecosystem

Physical drivers are fundamental to sustain the life cycle of species relevant for natural and cultural heritage (e.g., flagship species).

Presence and composition of riparian vegetation - Aesthetics of landscape

The presence of riparian vegetation increases the aesthetic value.

Presence and composition of riparian vegetation - Reduction of greenhouse gas emission

Riparian vegetation reduces GHG emission by carbon fixation.

Presence and composition of riparian vegetation - Regulating temperature

Temperature changes in presence of vegetation (Zardo et al., 2017). Additional possible effects at the local scale on water temperature are due to shading.

Presence and composition of riparian vegetation - Retention of nutrients

Riparian vegetation assimilates and retains nutrients, changing the timing of nutrient diffusion and availability in the river habitat (e.g., nutrients introduced in the river during autumn by the fall of the leaves).

Presence and composition of riparian vegetation – Ecological status

Presence and composition of riparian vegetation influences the river ecological status.

River morphology - Aesthetics of landscape

Natural morphologies (braiding river, anastomosing river) may increase aesthetic value in comparison with more artificial river morphologies.

River morphology - Education, Science

It is important for the description and understanding of fundamental geomorphological processes

River morphology - Natural and cultural heritage of the river and floodplain ecosystem

It is important for the high natural and cultural value of river types that deserve conservation (e.g., braiding rivers in Europe).

River morphology - Sediments for construction

Specific river morphologies can improve sediment deposition, thus increase the sediments available for construction.

River morphology - Water-related activities

Different river types support different water activities (e.g., white-water sports in high-gradient streams, paddling in low-gradient rivers).

River morphology – Ecological status

River morphology vegetation influences the river ecological status and it has to be assessed in the Water Framework Directive,

Vertical connectivity - Drought risk mitigation

Hyporheic zone characteristics affect groundwater-surface water exchange rate and consequently water availability for different purposes.

Vertical connectivity - Groundwater for drinking purpose

Vertical connectivity affects surface water mainly in the context of water quality (degree of water clarity/suspended matter amount) through water exchange between shallow groundwater and river (depending also on type of substrate, river morphology, hydraulics).

Vertical connectivity – Groundwater for non-drinking purposes

The effects are relevant if industry/agriculture water availability depends on aquifer-river water exchange level/groundwater level.

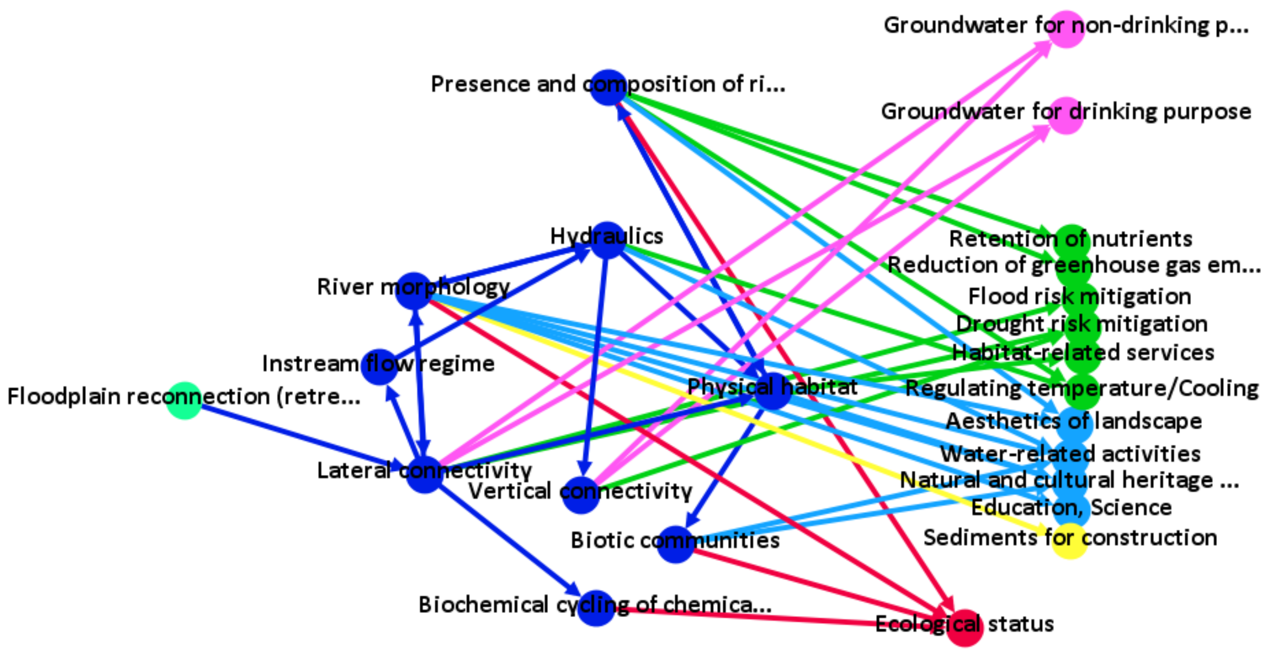

Fig. 23 Graphical representation of the framework for Floodplain reconnection (removal, retreat of levees). The blue colour represents the functions and the linkages between functions and actions. The pink colour represents Provisioning services and their linkage with the functions, the green colour represents Regulation and mainteinance services and their linkage with the functions, light blue colour represents Cultural services and their linkage with the functions, and the yellow colour represents the usages of abiotic natural capital and their linkage with the functions. In red we showed the ecological status and its linkages with the functions.

4.12Replanting of in channel and riparian vegetation

Tab. 25. Linkages between Replanting of in-channel and riparian vegetation and hydromorphological and biological functions, with direct or indirect linkage defined by experts' panel, distance from the action represented by the number of steps and the number of outgoing linkages.

Action	Function	Linkage	Level
Replanting of in-channel and riparian vegetation	Biochemical cycling of chemical compounds	Indirect	2
	Biotic Communities	Indirect	3
	Hydraulics	Indirect	2
	Instream flow regime	No	
	Lateral connectivity	Indirect	3
	Physical habitat	Indirect	2
	Presence and composition of riparian vegetation	Direct	1
	River morphology	Indirect	2
	Sediment continuity	Indirect	2
	Vertical connectivity	Indirect	3

Biochemical cycling of chemical compounds

The effects are mainly through the composition of the river and riparian plant community. Vegetation, especially riparian, is the main driver of the nutrient cycling in river habitat (e.g., Sabater et al., 2000; McMillan et al., 2014).

Biotic Communities

The effects are mainly through the physical habitat. Replanting vegetation has positive effects on river communities, e.g. macroinvertebrate communities (Sweeney 1993).

Hydraulics

The effects are mainly through the river morphology. Vegetation changes the roughness coefficient and, consequently, several hydraulic variables.

Instream flow regime

The effects are not relevant or negligible. Possible effects on flood peak attenuation are still unclear. On the contrary, floodplain reforestation is usually the action that can influence most the flood peaks downstream (Dixon et al., 2016)

Lateral connectivity

The effects are mainly through river morphology. Depending on vegetation stem diameter, stem spacing/plant density, (Da Silva et al. 2015), plant elastic module, height and geometric shape (Klösch et al., 2017), replanting of in-channel vegetation affects, velocities, increases (especially larger fractions) sediment settling, affects water level (rising) and in more probable event of flooding, lateral sediment exchange with floodplain.

Physical habitat

The effects are mainly through river morphology and hydraulics. Replanting of in-channel vegetation affects flow velocity and in general change the hydraulic properties of the river habitat.

Presence and composition of riparian vegetation (1st level)

This action directly affects the presence and the composition of riparian vegetation.

River morphology

The effects are mainly through presence of river and riparian vegetation. Riparian vegetation affects the river morphology by increasing the hydraulic roughness (affecting also sediment transport), and by increasing the bank stability through root reinforcement, which decreases the bank retreat rates. Accordingly, replanted vegetation is suspected to promote narrowing of the active channel, even if mature trees may destabilize banks given their weight component in the failure surface or due to wind throw.

Sediment continuity

The effects are indirect. In-channel vegetation establishment increases channel roughness and subsequently reduces sediment transport capacity, enhancing sediment deposition (Corenblit et al., 2007). Vegetation establishment in the floodplain will increase bank stability (and subsequently reduce sediment input from bank erosion), and increase flow resistance near the banks, which may enhance vegetation encroachment in active channels and possibly induce active channel narrowing (Liébault and Piégay, 2002, Pautou et al., 1997).

Vertical connectivity

The effects are mainly through river morphology. Depending on vegetation stem diameter, stem spacing/plant density, (Da Silva et al. 2015), plant elastic module, height and geometric shape (Klösch et al., 2017), replanting of in-channel vegetation Replanting of in-channel vegetation causes the alteration of groundwater flow patterns through the bed of the river (hyporheic exchange/percolation hindering).

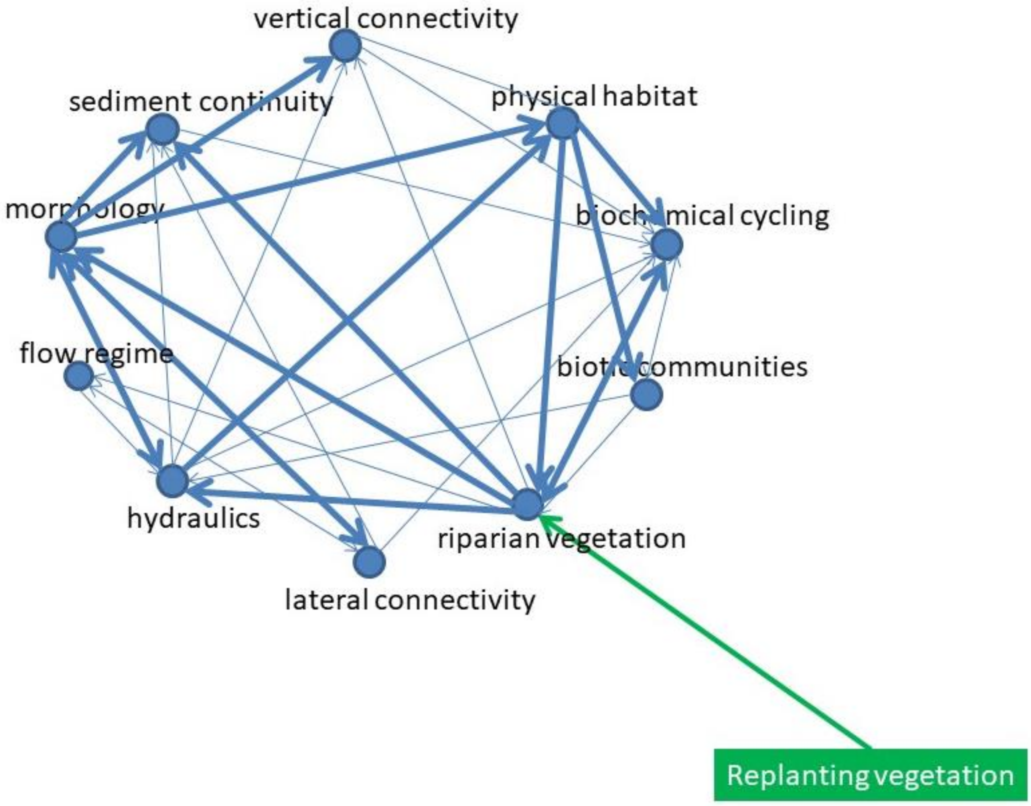

Fig. 24 Graphical representation of the interactions among functions (author: F. Liebault).

4.12.1Functions – ecosystem services linkages

Biochemical cycling of chemical compounds – Ecological status

This function does not affect directly ecosystem services, but it influences the physical habitat, the biotic communities and the ecological status.

Biotic communities - Natural and cultural heritage of the river and floodplain ecosystem

It is relevant due to the importance of rivers as biodiversity reserve and presence of relevant species (e.g., umbrella species).

Biotic communities - Water-related activities

The presence and abundance of several species are a pre-condition for some water-related activities, in particular for angling and bird-watching. Different types of angling have different requirements in relation to biotic communities.

Biotic communities – Ecological status

The community composition influences the ecological status of the river.

Hydraulics – Regulating Temperature, cooling

The hydraulic variables directly influence the temperature and the cooling capacity of the river.

Hydraulics – Water related activities

The hydraulic variables directly influence specific water related activities such as boating and rafting (see Carolli et al., 2017).

Lateral connectivity - Drought risk mitigation

Drought risk is naturally mitigated through water storage, e.g. in groundwater and in wetlands. The amount of water that can feed these natural storage systems is influenced by the connectivity between the river channel and its floodplain. Bank surface layer clogging in some of cases causing elevated water table and thus in cases of floods, increased total recharge amount to the aquifer (Chen et al., 2013).

Lateral connectivity - Flood risk mitigation

The degree of lateral connectivity influences peak flow attenuation downstream, due to temporary storage in the floodplain, flood wave celerity reduction and to de-synchronization of the timings of sub-catchment flood waves (Dixon et al. 2016). It has to be highlighted that restoration of lateral connectivity may not always have positive effects on flood risk downstream, as in some cases it may re-synchronize flood waves that had been shifted due to artificialization, therefore a case-by-case assessment is necessary. It should also be recognized that in steep slope alpine valleys, the temporary storage capacity in the floodplain may be often insufficient to significantly reduce peak flows. Lateral connectivity affects flood risk depending on bank hydrogeological characteristics, sediment permeability, ground saturation levels, e.g. saturated river banks increase lateral connectivity between river and floodplain and in consequence flood risk. Flood risk reduction in this context is possible with bank layers with high water infiltration rate.

Physical habitat - Habitat-related services

Physical habitat provides the physical drivers and the fundamental ecological niches to sustain species life-cycle.

Physical habitat - Natural and cultural heritage of the river and floodplain ecosystem

Physical drivers are fundamental to sustain the life cycle of species relevant for natural and cultural heritage (e.g., flagship species).

Presence and composition of riparian vegetation - Aesthetics of landscape

The presence of riparian vegetation increases the aesthetic value.

Presence and composition of riparian vegetation - Flood risk mitigation

Vegetation mitigates flood risk by changing hydraulic characteristic of the riparian area and the floodplain. Wood transport may increase flood risk. Riparian vegetation increases flow resistance, and subsequently water depth for a given flow discharge, resulting in an increased flooding risk in the vicinity of the reforested reach.

Presence and composition of riparian vegetation - Plant-based resources from agriculture, short rotation coppice, forestry

Riparian plants can be used for biomass production.

Presence and composition of riparian vegetation - Reduction of greenhouse gas emission

Riparian vegetation reduces GHG emission by carbon fixation.

Presence and composition of riparian vegetation - Regulating temperature

Temperature changes in presence of vegetation (Zardo et al., 2017). Additional possible effects at the local scale on water temperature are due to shading.

Presence and composition of riparian vegetation - Retention of nutrients

Riparian vegetation assimilates and retains nutrients, changing the timing of nutrient diffusion and availability in the river habitat (e.g., nutrients introduced in the river during autumn by the fall of the leaves).

Presence and composition of riparian vegetation – Ecological status

Presence and composition of riparian vegetation influences the river ecological status.

River morphology - Aesthetics of landscape

Natural morphologies (braiding river, anastomosing river) may increase aesthetic value in comparison with more artificial river morphologies.

River morphology - Natural and cultural heritage of the river and floodplain ecosystem

It is important for the high natural and cultural value of river types that deserve conservation (e.g., braiding rivers in Europe).

River morphology - Sediments for construction

Specific river morphologies can improve sediment deposition, thus increase the sediments available for construction.

River morphology - Water-related activities

Different river types support different water activities (e.g., white-water sports in high-gradient streams, paddling in low-gradient rivers).

River morphology – Ecological status

River morphology vegetation influences the river ecological status and it has to be assessed in the Water Framework Directive.

Vertical connectivity - Drought risk mitigation

Hyporheic zone characteristics affect groundwater-surface water exchange rate and consequently water availability for different purposes.

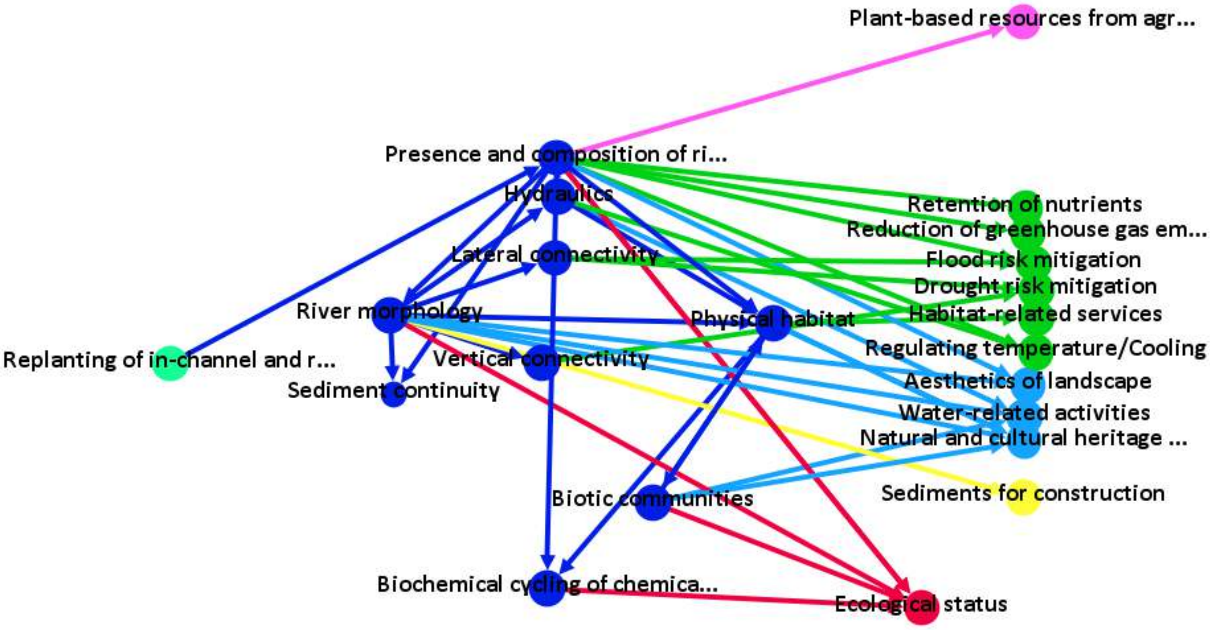

Fig. 25 Graphical representation of the framework for replanting of in-channel and riparian vegetation. The blue colour represents the functions and the linkages between functions and actions. The pink colour represents Provisioning services and their linkage with the functions, the green colour represents Regulation and mainteinance services and their linkage with the functions, light blue colour represents Cultural services and their linkage with the functions, and the yellow colour represents the usages of abiotic natural capital and their linkage with the functions. In red we showed the ecological status and its linkages with the functions.

4.13 Weir removal

Tab. 26. Linkages between Weir removal and hydromorphological and biological functions, with direct or indirect linkage defined by experts' panel, distance from the action represented by the number of steps and the number of outgoing linkages.

Action	Function	Linkage	Level
Weir removal	Biochemical cycling of chemical compounds	No	
	Biotic communities	Direct	1
	Hydraulics	Indirect	2
	Instream flow regime	No	
	Lateral connectivity	No	
	Physical habitat	Indirect	2
	Presence and composition of riparian vegetation	No	
	River morphology	Direct	1
	Sediment continuity	No	
	Vertical connectivity	No	

Biochemical cycling of chemical compounds

The direct effects are not relevant or negligible.

Biotic Communities (1st level)

The removal of weir is very important to restore river continuity, especially for migratory species as salmons (De Leaniz, 2008) and eels.

Hydraulics

The effects of this action on hydraulics are indirect. Possible effects are through morphological changes.

Instream flow regime

The effects of this action on the Instream flow regime are negligible or not relevant.

Lateral connectivity

The direct effects are not relevant or negligible.

Physical habitat

The effects are mainly through hydraulics, morphology. Weir removal restores Instream natural flow dynamics, favouring species naturally found in the river, and it improves habitat diversity especially upstream (Bunn and Arthington, 2002).

Presence and composition of riparian vegetation

The direct effects are not relevant.

River morphology (1st level)

In the downstream river section, which suffered from sediment starvation, the re-established sediment supply and river stage fluctuations cause aggradation and related lateral dynamics. Bar accretion or migration may go along with erosion of riverbanks. In former diversion channels with residual flow, deposited sediment and encroached vegetation may be remobilised and replaced by a more dynamic pattern (including bars with bare sediment). Upstream, the morphology changes from the impounded reservoir to a free flowing river. The re-established transfer of sediment may enable morphodynamics and the emergence of related morphologic channel features (bars, riffles, cut banks) and to the modification of channel slope.

Sediment continuity

Weir removal temporary increases the sediment supply by releasing sediment artificially stored behind the weir, but the effect on sediment transport is very short-lasting.

Vertical connectivity

The effects of this action on the vertical connectivity are not relevant. Possible indirect effects are due to morphological changes.

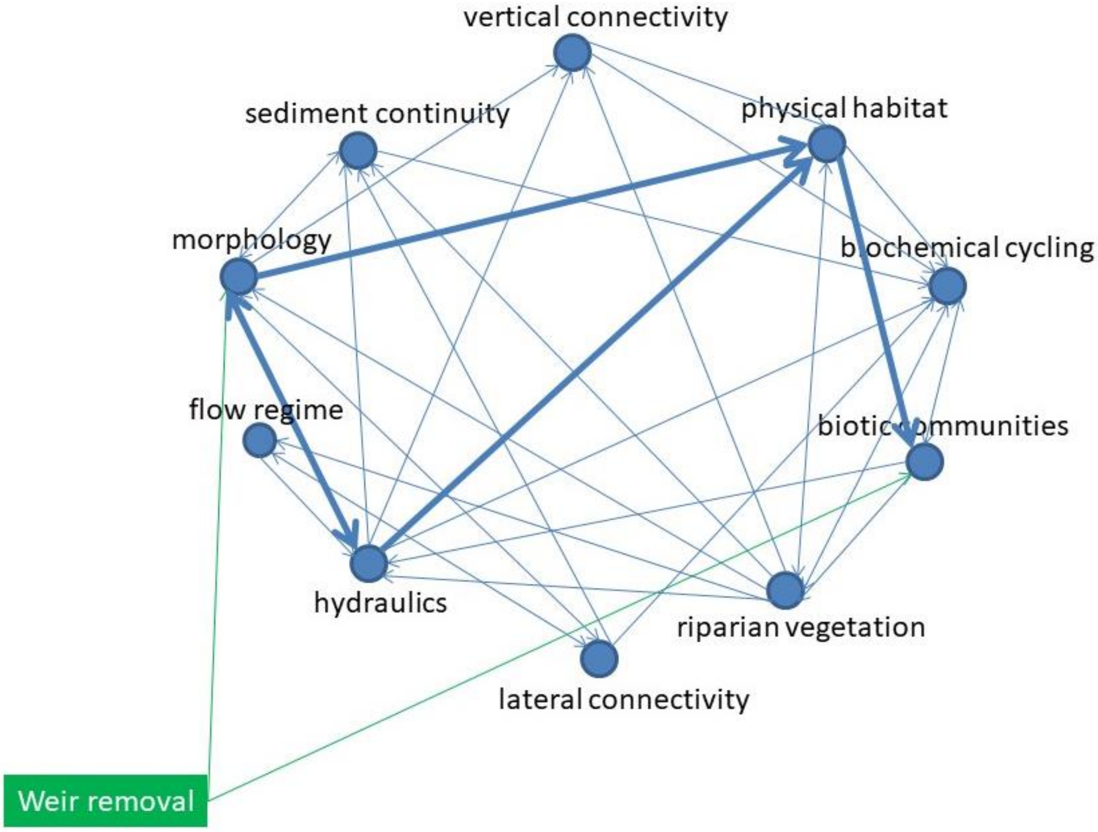

Fig. 26 Graphical representation of the interactions among functions (author: F. Liébault).

4.13.1Function – ecosystem services linkages

Biotic communities - Natural and cultural heritage of the river and floodplain ecosystem

It is relevant due to the importance of rivers as biodiversity reserve and presence of relevant species (e.g., umbrella species).

Biotic communities - Water-related activities

The presence and abundance of several species are a pre-condition for some water-related activities, in particular for angling and bird-watching. Different types of angling have different requirements in relation to biotic communities.

Biotic communities – Ecological status

The community composition influences the ecological status of the river.

Hydraulics – Regulating Temperature, cooling

The hydraulic variables directly influence the temperature and the cooling capacity of the river.

Hydraulics – Water related activities

The hydraulic variables directly influence specific water related activities such as boating and rafting (see Carolli et al., 2017).

Physical habitat - Habitat-related services

Physical habitat provides the physical drivers and the fundamental ecological niches to sustain species life-cycle.

Physical habitat - Natural and cultural heritage of the river and floodplain ecosystem

Physical drivers are fundamental to sustain the life cycle of species relevant for natural and cultural heritage (e.g., flagship species).

River morphology - Aesthetics of landscape

Natural morphologies (braiding river, anastomosing river) may increase aesthetic value in comparison with more artificial river morphologies.

River morphology - Education, Science

It is important for the description and understanding of fundamental geomorphological processes

River morphology - Natural and cultural heritage of the river and floodplain ecosystem

It is important for the high natural and cultural value of river types that deserve conservation (e.g., braiding rivers in Europe).

River morphology - Sediments for construction

Specific river morphologies can improve sediment deposition, thus increase the sediments available for construction.

River morphology - Water-related activities

Different river types support different water activities (e.g., white-water sports in high-gradient streams, paddling in low-gradient rivers).

River morphology – Ecological status

River morphology vegetation influences the river ecological status and it has to be assessed in the Water Framework Directive,

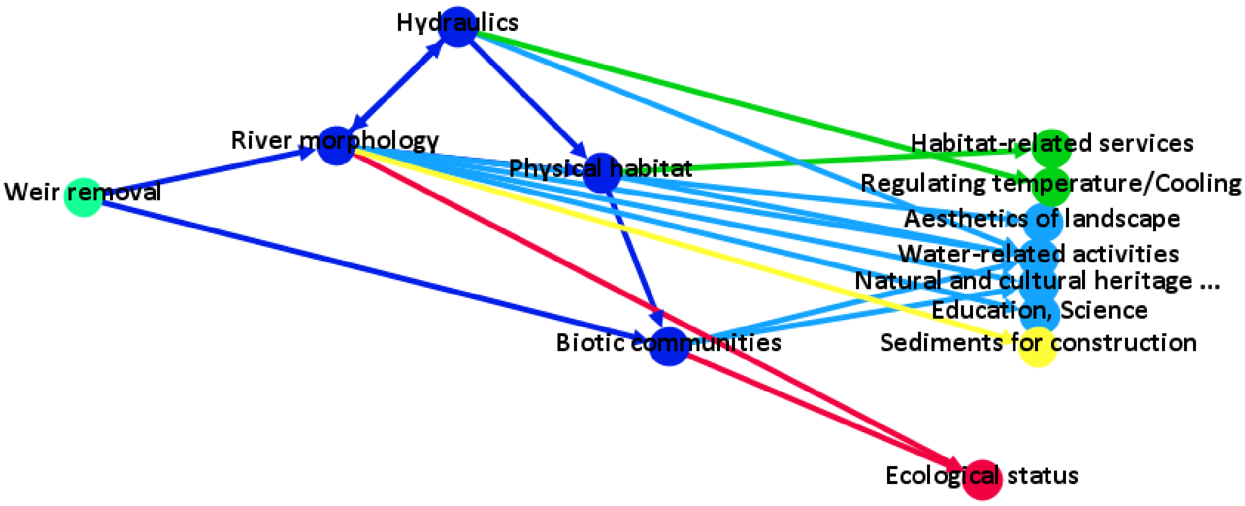

Fig. 27 Graphical representation of the framework for weir removal. The blue colour represents the functions and the linkages between functions and actions. The pink colour represents Provisioning services and their linkage with the functions, the green colour represents Regulation and mainteinance services and their linkage with the functions, light blue colour represents Cultural services and their linkage with the functions, and the yellow colour represents the usages of abiotic natural capital and their linkage with the functions. In red we showed the ecological status and its linkages with the functions.

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Annex 1

Matrix 1 (first part) which links functions and ecosystem services (provisioning services group). We asked to each partner to fill the matrix with a scoring system ranging from 0 (no relevance) to 5 (high relevance) (Campagne et al., 2017).

Function: / Effect on:	Cultivated crops	Plant resources for agricultural use - Pasture	Surface water for drinking purpose	Groundwater for drinking purpose	Surface water for non-drinking purposes in industry and agriculture	Groundwater for non-drinking purposes in industry and agriculture	Plant-based resources from agriculture, short rotation coppice, forestry
In-stream flow regime							
Sediment continuity							
Hydraulics							
Presence and composition of riparian vegetation							
River morphology							
Vertical connectivity							
Lateral connectivity							
Physical habitat							
Biochemical cycling of chemical compounds							
Biotic Communities							

Matrix 1 (second part) which links functions and ecosystem services (regulating and mainteinance services group). We asked to each partner to fill the matrix with a scoring system ranging from 0 (no relevance) to 5 (high relevance) (Campagne et al., 2017).

Effect on: / Function:	Retention of nutrients	Reduction of greenhouse gas emission / carbon sequestration	Flood risk mitigation (flooding and risk related to morphological dynamics of	Drought risk mitigation	Soil formation in floodplains	Regulating temperature/Cooling (water bodies and ground)	Habitat- related services
In-stream flow regime							
Sediment continuity							
Hydraulics							
Presence and composition of riparian vegetation							
River morphology							
Vertical connectivity							
Lateral connectivity							
Physical habitat							
Biochemical cycling of chemical compounds							
Biotic Communities							

Matrix 1 (third part) which links functions and ecosystem services (cultural services group). We asked to each partner to fill the matrix with a scoring system ranging from 0 (no relevance) to 5 (high relevance) (Campagne et al., 2017).

Effect on: / Function:	Aesthetics of landscape	Natural and cultural heritage of the river and floodplain ecosystem	Education, Science	Water-related activities	Hydropower	Navigation	Sediments for construction
In-stream flow regime							
Sediment continuity							
Hydraulics							
Presence and composition of riparian vegetation							
River morphology							
Vertical connectivity							
Lateral connectivity							
Physical habitat							
Biochemical cycling of chemical compounds							
Biotic Communities							