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REFORM

REstoring rivers FOR effective catchment Management

Deliverable D5.3 Part 1 – Main report

Title Effects of climate and land use changes on river ecosystems and restoration practices. Part 1 Main report

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PU	Public	X
PP	Restricted to other programme participants (including the Commission Services)	
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CO	Confidential, only for members of the consortium (including the Commission Services)	

Summary

Rivers are highly complex ecosystems with interrelated processes between physical, chemical and biological components. River restoration efforts are put in place to overcome pressures from the development sector to improve river process and function, nevertheless, river restoration tends to encounter obstacles as a result of these societal demands. To stop restoration projects falling short of their objectives, there is a need to demonstrate and predict the effects of human activities on these components spatially and temporally. The overall aim of this document is to provide guidance and tools for river managers to analyse the potential effects of degradation, restoration, climate and land use change to optimise benefits between cross-sectoral river services and ecological requirements whilst considering climate change effects. Failure to plan across the full array of ecological and socioeconomic co-benefits can have undesirable and unanticipated consequences.

The motives, pressures and restoration measures for the dominant sectors are summarised in this document to identify the potential for interactions between pressures and restoration measures (benefits and losses for different conservation features). Guidance, tools and models to identify options for restoration and multiple-benefits are overviewed with focus on the potential effects of climate and land use changes on river processes. Specific emphasis is on synergistic strategies to assist project managers with decision making, problem solving and planning strategies to identify suitable Programme of Measures (PoM) to support future RBMP cycles and the tuning of the WFD with other directives (Habitats, Birds, Flood, Groundwater, Renewable Energy, Sustainable Transport).

Synergies in river restoration occur when benefits can be found for both ecosystem services and the environment, whereas a trade-off occurs when one changes at the expense of another. Adopting a 'synergy and trade-off' approach to river restoration is discussed with specific focus on soft engineering techniques in relation to climate change enabling planners to consider the links in integrated freshwater conservation planning and overcome constraints that might hinder other (or multiple) sectors. Synergistic approaches are now emerging in river restoration and cross-sectoral interactions, and are supported by various policy documents. For example, synergies between flood-risk and river management or between hydropower development and restoration of longitudinal connectivity for fisheries. Flood-risk management is perhaps the policy with the best potential for synergies with other aspects of water management, provided that adequate strategies are implemented (CIS 2007). Working with natural processes & nature-based restoration are key features of the strategy to overcome climate change impacts whilst providing multiple-benefits thus, allowing important opportunities for synergies between directives such as EU Floods Directive, WFD, Habitats Directive and Birds Directive, amongst others.

The main methods promoted in this document are hydro-economic models, cross-impact balance analysis and the nested-DPSIR framework.

- **Hydro-economic modelling** can support integrated river basin management and they represent regional scale hydrological, engineering, environmental and economic aspects of water resources systems within a single framework. The complexity of interactions between water and the economy can be captured through formal, mathematical models linking relevant hydrological and biogeochemical processes to economic 'laws' of supply and demand underlying the provision of scarce water services (Brouwer & Hofkes 2008). Integrated hydro-economic models can suggest least-cost combinations of actions to attain specified goals and examine how alternative choices will affect different interests. In summary it can be argued that hydro-economic modelling is especially suitable to address water quantity issues, but

that it is much more difficult to make the link with WFD environmental objectives that are ecological in nature. The main bottleneck in full application of hydro-economic modelling is to integrate type-specific pressure-impact relationships where hydrological regime is linked with ecological status.

- **Cross-impact Balance Analysis** creates a hypermatrix and can be applied by river managers to anticipate the potential impacts of possible hydrological changes on stream channel morphology, ecological function and services provision (Slawson 2014). CIB analysis is a helpful approach that can give a number of options for plausible future scenarios. It is based on a qualitative judgement scale and relies on expert judgement across a number of disciples, the benefit here is that CIB is not data dependant, however, expert judgement can result in bias and strongly influence any outcome.
- **The nested-DPSIR framework** is a conceptual tool that identifies key relationships between society and the environment and should be applied in the early stages of project planning. It aims to reconcile conflicting interests between societal and the ecological needs of rivers, in addition to land uses change by capturing key relationships between society and the environment, encouraging decision-makers to think about the challenges at a larger scale, across multiple sectors. At a catchment scale the nested-DPSIR can identify restoration potential and aid decisions for PoM objectives. The outcome from a CIB Analysis can be used alongside DPSIR to explore synergies and new opportunities.

Weighted prioritisation matrices are easily understood, simple to apply and have the advantage of allowing various alternatives to be compared numerically. Scoring is based on existing information, both quantitative and qualitative, and incorporates the opinions of stakeholders, ecological specialists and economists. Physical, chemical and biological aspects of broad-scale processes of freshwater rivers and interfaces between connecting ecosystems, such as natural habitat continuum from upstream to downstream catchments and between river and its surrounding land use are considered during the scoring. Nevertheless, there are a few disadvantages to this method, mainly because the evaluation procedure depends heavily on the weightings assigned and these can be subjective and open to bias.

Conclusions and recommendations from this document are:

- *In many scenarios the domains of environment, society and institutions are disconnected and sustainability is compromised*
- *Identifying relevant political and economic incentives can help overcome the inadequate budget situation for restoration*
- *Simple decision support methods are generally easier to use, but lack a full understanding of the economic and social interactions, while complex models incorporate these aspects but suffer from data paucity and need huge investments to achieve the required input*
- *Optimising ecosystem services in conjunction with the ecosystem approach appears to be a useful mechanism for selecting the best management options, but to convince other users of the importance of ecological services requires ecological and socio-economic information at a catchment scale and the more fundamental economic data to support the dialogue.*
- *Adopting a synergy approach to river restoration will maximise multiple benefits between sectors and ecosystem form and function, tools such as DPSIR help identify synergies but its application by river managers is generally lacking*

- *The consequences of climate change e.g. through more extreme discharge regimes create a moving target for planning and implementation and require an anticipating and adaptive strategy*
- *Identifying the impacts of different sectors and the potential synergies should be part of the project planning cycle and be inherent in the identification and formulation phases of the project development.*

Case studies to support the processes described are provide in Part 2 of the deliverable.

Acknowledgements

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Table of Definitions

DPSIR Framework Driver, Pressure, State, Impact, Response	A causal framework for describing the interactions between society and the environment to assists decision-makers.
Driver (Driving force)	Social, demographic and economic developments in societies and the corresponding changes in lifestyles, overall levels of consumption and production patterns. Applied to rivers, we consider driving forces as any anthropogenic activity that may have environmental effects on river structure or functioning, with prime drivers being agriculture, industry, urbanization, transport and energy production.
Pressure	Includes the release of substances (emissions), physical and biological agents, the use of resources and the use of land. Pressures are direct consequences of drivers transported and transformed into a variety of processes which provoke changes in environmental conditions (for example changes in flow or in the water chemistry of surface and groundwater bodies).
State	Abiotic condition of soil, air and water, as well as the biotic condition (biodiversity) at ecosystem/habitat, species/community and genetic levels. Represents the external manifestation or expression of the river ecosystem in terms of how it appears and functions.
Impact	Consequences for human and ecosystem health, resource availability and biodiversity from adverse environmental conditions. In practice, impacts reflect the negative environmental effects of pressures (e.g. fish killed, ecosystem modified).
Response	Actions taken by groups or individuals in society and government to prevent, compensate, ameliorate or adapt to changes in the state of the environment by seeking to •Control drivers or pressures through regulation, prevention, or mitigation •Directly maintain or restore the state of the environment •Deliberately "do nothing"
Synergy	A scenario that involves mutual benefits gained by two sectors as a result of a collaboration or improvement or enhancement of ecological or environmental characteristics by one or both sectors (improving aesthetics and saving money).
Trade-off	'The exchange of one thing for another of more-or-less equal value'. Ecological, social and economic trade-offs occur in river restoration planning and practise. Investing in one of these factors could potentially detract (or benefit) from actions in another sector.
Soft engineering	The use of ecological principles to reduce the impacts on ecological features. Soft engineering is achieved by using vegetation and other materials to soften the land-water interface, thereby improving ecological features without compromising the engineered integrity of the shoreline or river edges.

1. Introduction

1.1 Background

Global effects of climate change are becoming increasingly more evident (IPCC 2007) and are expected to have a major impact on water resources in Europe. It is predicted that climate change will increase the occurrence of extreme events (i.e. flood and droughts) and will therefore have a strong influence on habitats, communities, species and individual organisms in the future (Levitus et al. 2000; Parmesan & Yohe 2003; Root et al. 2003; FSBI 2007). There are a number of European Directives to support the ecological health of rivers such as the Water Framework Directive (WFD (2000/60/EC)), Habitats Directive (HD (92/43/EEC)) and Groundwater Directive (GWD (2006/118/EC)), in addition to global initiatives such as Agenda 21 of the Rio Convention and the Convention of Biological Diversity. These have driven the management of inland waters towards rehabilitation of rivers and lakes to improve the aquatic environment for biodiversity and allow for sustainable exploitation of the resources (Eden & Tunstall 2006; Pasternack 2008; Hobbs et al. 2011). Consequently, nature conservation, and in particular river restoration, are increasingly considered as part of a much wider framework of environmental policy and practice (Arlinghaus et al. 2002). Nevertheless, the aims of restoration activities in Europe are influenced by a plethora of EU Directives and national government policies that have conflicting targets. Current river restoration tends to encounter obstacles as a result of societal demands, particularly through a select number of ecosystem services, such as provisioning and regulating services like flood protection, hydropower, navigation and agriculture. Recent developments have resulted in directives such as Floods Directive (FD (2007/60/EC) and Renewable Energy Directive (RED (2009/28/EC); these are directives and legislation that are potentially at conflict with the WFD, but are necessary to support river management from social and economic perspectives. As a consequence, managers are required to change the way European waters are conserved, especially as ecological classification under the WFD may change with climate-induced effects and therefore, cannot be considered as static (Bernasconia et al. 2005).

This deliverable (D5.3) will address the potential for restoring river ecosystems to optimise benefits accrued for biodiversity and ecosystem services, whilst considering climate change effects on the ability to deliver these outcomes. We aim to provide a framework and examples to guide river managers in the planning process of restoration actions that proceeds in a rational way, with specific emphasis on strategies for Programme of Measures (PoM) to support future RBMP cycles and the tuning of the WFD with other directives (HD, BD, FD, GWD, RED and STD). In this perspective, it is important to understand the context of how climate change and land use change affect the riverine environment so this is discussed below.

1.2 Objective of this study

Climate and land use change alter the boundary conditions that direct and constrain river restoration. Restoration practise should anticipate and be adaptive or be tuned with changing environmental conditions. Within this deliverable climate and land use change are taken into account for the choice and design of river restoration practises that promote wider ecosystem and societal benefits.

Information was consolidated to develop an integrated planning strategy to guide river managers, especially through adaptation to change by using nature-based restoration measures where possible. This will accommodate extreme events (floods & droughts) rather than seeking severe engineering solutions that impact on biodiversity or have compromised river ecosystem services in the past. Nevertheless, nature-based solutions are not always feasible so alternative options are developed.

In this context, the DPSIR approach is examined to identify pressures and measures for each interacting sector and a nested DPSIR approach is proposed to harmonise benefits to restoration producing 'win-win' synergistic actions between sectors and users of riverine systems.

The description of work (DoW: Box 1) highlights how this deliverable (D5.3) uses the outputs from previous deliverables in WP1, 2 & 4 and also how the outcomes of D5.3 will contribute to WP6. REFORM D1.2 *Effects of pressures on hydromorphology* (http://www.reformrivers.eu/deliverables/d1-2), reviews the effects of HYMO pressures (hydrological regime, river fragmentation, morphological alteration and physico-chemical pressures) on hydromorphological processes (water flow, sediment dynamics, bank dynamics, vegetation dynamics, large wood dynamics and aquifer dynamics) and variables resulting from both degradation and restoration. It distinguishes single river pressures and their most direct impacts on ecosystems. Consequently, D5.3 does not intend to duplicate information previously provided in D1.2, but to summarise and build on this existing material. The information will be used to identify the multiple pressures caused by each sector and how they affect HYMO processes and variables. Furthermore, D5.3 uses information collated in REFORM D1.3 *Review on ecological response to hydromorphology* (http://www.reformrivers.eu/deliverables/d1-3), to highlight available knowledge on biological responses (WFD BQEs: macrophytes, macroinvertebrates & fish) to hydromorphological degradation and restoration.

Box 1: WP5.3 Description of Work:

Review motives, drivers, pressures and measures (Links to WP1), with specific focus on soft engineering techniques for sectors to identify constraints and synergies for integrated river improvement practise.

In conjunction with stakeholders associated with the WP4 case studies, information from LIFE and Interreg projects and the case studies collected by the CIS–HYMO, identify and assess current approaches where climate and land use change are taken into account for the choice and design of river restoration practices that promote wider ecosystem and societal benefits.

Based on the models developed in WP2 and integration with generic habitat modelling tools such as PHABsim, analyse the potential effects of climate and land use changes on hydromorphological processes, river ecosystem functioning and restoration practices at the WP4 case study sites.

Using outputs from the above sub-task, use the DPSIR approach to assess the scope for adaptation strategies to mitigate climate change (especially floods and droughts) for its effects on river form and functioning and how these compromise or benefit meeting WFD objectives.

To consolidate information and develop a strategy for integrate planning for practical approaches on how climate and land use should be addressed in the cost effective design of restoration and mitigation measures to identify 'win-win' scenarios for flood mitigation and improvement of ecological status for input into WP6.

1.3 Land use change

Human influences have dominated geomorphological changes to the earth through 'land use' actions (Brown et al. 2013). 'Land use change' may be used where both land use and land cover are being considered. For land use change hydrogeomorphological analyses, both land use and land cover are important, but the differences between the two are crucial. This is because a particular land use may result in more than one land cover change, each, and in combination, having very different hydrogeomorphological characteristics. For instance, the land use of a "park" may be a football field or picnic area or woodland or a combination. The "land cover" will be different depending on which type of feature it is. Each of these land covers has different hydrological characteristics with different contributions of water flow and bed material flow to a receiving stream. Land cover changes affect the hydrogeomorphological responses of the landscape, through changes in the physical processes related to permeability and connectivity. Any land use change will lead to a land cover change and the degree of impact of this change on rivers may be positive, negative or neutral depending on its effects on the water flow and bed material flow rate regimes to rivers (Schumm 1969).

At present, land use change for European rivers come from two drivers, agriculture and urban development (Figure 1.1), including in the latter industrial, commercial and transport infrastructure. These drivers have caused up to 95% of European riverine floodplains to be lost and during the past century, approximately 50% of the world's wetlands have been destroyed. Floodplain and wetland land use changes are mainly associated with historical embankments and deforestation for agriculture because of their inherent high productivity, or urbanization and infrastructure, since approximately 50% of the European population inhabits former floodplains. An analysis of 164 rivers in Europe (including sub-catchments) revealed that only 28 are free-flowing and 60% of their catchments have been transformed to agricultural or urban land (Tockner et al. 2009). For example, the building of dykes in favour for agriculture in the Upper Rhine resulted in a river bed up to 12 km wide giving way to a channel between 200 and 250 m in width; the Rhine floodplains between Basel and Karlsruhe decreased by 87%. Overall, the natural floodplain area of the Upper Rhine was reduced by 60% or 130 km^2, which in turn entailed considerable expenditure for the associated increased risk of flooding in downstream areas. In addition, the conversion of 80% of the Lower Danube floodplain from wetlands to agriculture land by embankments caused an increase in peak flow water level of 0.6-0.8 m (Bondar 1996) and the fishery to collapse. Much of the remaining pristine wetland systems are found in the world's largest wetlands, and yet these areas have received surprisingly little scientific research or attention (Fraser et al. 2005). Wetland loss and degradation continues worldwide despite evidence from the scientific community of the significant services provided to humans.

In addition to agriculture and urban land use, sectors such as flood protection, inland navigation, hydropower and water resource management result in similar negative impacts and the foremost pressure types are channelization, continuum disruption, disconnecting channels from floodplains, impoundment, water abstraction and flow regulation. It is these pressures that cause many of the impacts present on European rivers (Figure 1.1), resulting in cumulative effects over time affecting a wide variety of different spatial scales along the whole river network. As a result, many rivers have highly simplified and uniform channels; up to 80% of the large rivers in Austria are moderately to heavily impacted and more than 95% of lowland river channels in south-east England and Denmark are altered. Urban land adjoining a channel, for example, may be associated with modified water quality, altered flow regime, structural changes to the channel (e.g. channelization, bank reinforcement) and disruption of processes such as sediment supply (Paul & Meyer 2001; Gurnell et al. 2007). Concomitant ecological changes in such situations (e.g. reduced taxonomic diversity or increased decomposition rates; Paul & Meyer 2001) could be a response to any or all of the changes associated with the land use.

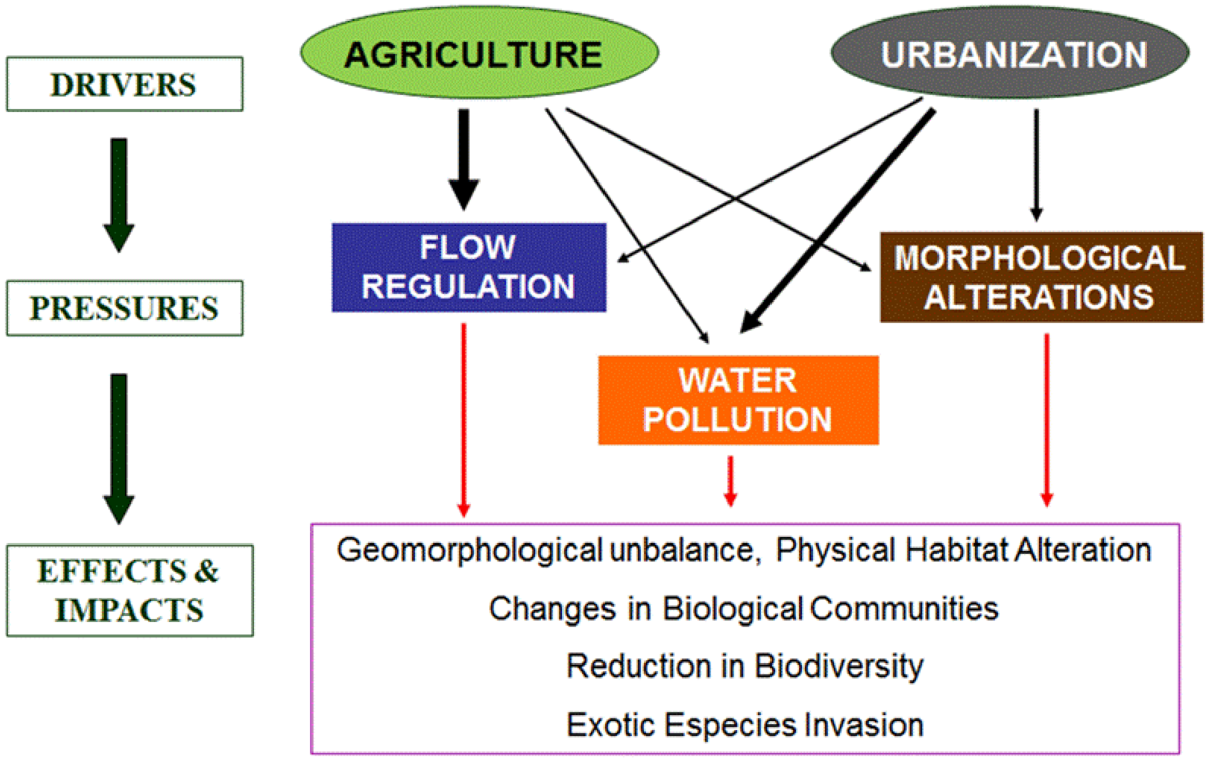

Figure 1.1. Main drivers (agriculture and urbanization) showing the pressures (flow regulation, water pollution and alteration of natural forms and fluvial processes) that they create, and the effects that occur in river ecosystems through generated impacts.

Economic needs have been the stimulus for land use change over time, resulting in numerous changes to hydrogeomorphological characteristics and consequently adding a higher level of complexity to the pressures that arise from land use change and mitigation measures applied. The Danube Delta provides a good example of how land use can change over time. At the end of the 19th Century, meanders were cut off to improve the navigability of the middle arm of the river in the Delta with no major impact on the other functions of the Delta. Between 1903-1960, in the so called 'capture fishery period', new channels were built or resized to enhance connectivity for fish production, followed by the 'reed period' between 1960-1970 by building polders for reed culture, the 'fish culture period' between 1971-1980 associated with new impoundments for aquaculture, and the 'agriculture period', by building large polders, mostly between 1983-1989. In addition, a new man-made canal altered the network of water courses and an area of 20% of the delta was been cut off from the Danube River system for agriculture use (Staras 2001). Since 1989 this has been partly reversed through several planned and realized restoration projects (Figure 1.2; Buijse et al. 2002).

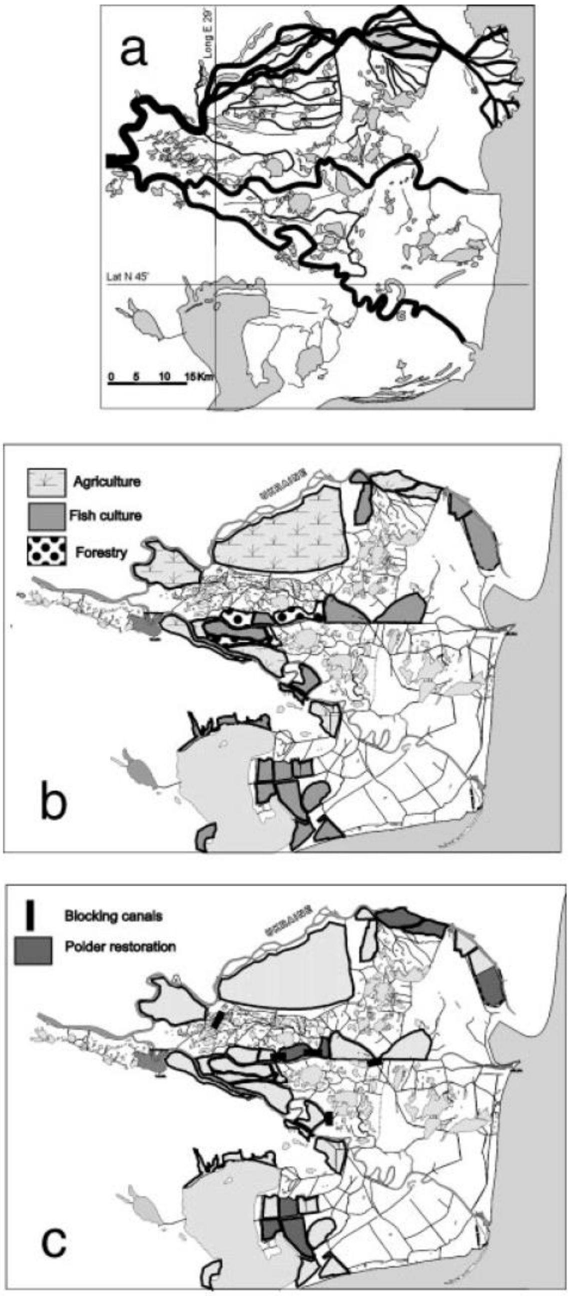

Figure 1.2 Danube delta in Romania. (a) Pristine situation around 1880, (b) Reclaimed land for agriculture, fish culture and forestry (1890–1989), and location of artificial canals. (c) Planned and realised restoration activities since 1994 including re-opening of polders and blocking of man-made canals (Source: Buijse et al. 2002).

River restoration and rehabilitation projects can also be considered land changes, albeit with an expected improvement in hydrogeomorphological responses. As such, these projects should be completely described in terms of land uses, land covers and land management practices. For example, a river restoration project example might include the following:

- old land-use: inaccessible, incised river channel, flooding, erosion, poor habitat;
- new land use: recreational green way along an accessible river channel with improved flood storage capacity and good fishing;
- land cover: native forest woody and herbaceous species, gravel trails;
- land management practices: maximize stream bank protection and stabilization and create a sustainable habitat corridor using a permeable trail surface with a wide and native vegetation riparian buffer on a reconstructed floodplain, initial operation and maintenance practices leading to a self-sustaining system.

However, river restoration projects are not the entire answer, even when land uses, land cover changes, and land management are all addressed. River corridors are only the recipients of the changes in the water flow and bed material flow regimes operating throughout the watershed. Land change anywhere in the watershed must undergo the same thorough analysis. Additionally, the history of land change must be studied because hydrogeomorphological responses may occur over a time period much greater than the duration of the land use. For example, legacy sediments may affect channel geometry and ecology long after the dam and the impoundment that trapped the sediments are gone (Slawson 2004).

If land planners, legislators, and engineers continue to conflate "land use" and "land cover" and ignore "land management", they will continue to make land change decisions that will negatively impact hydrogeomorphological responses to the continuing detriment of rivers and their ecology. River restoration and rehabilitation projects and the achievement of the "good ecological status" for rivers will also be negatively affected. The knowledge base to evaluate the ecological status and impacts due to these single HYMO pressures is not optimal nowadays. This is because most ecological literature relates aquatic biology to pressures without considering geomorphological process, while most geomorphological literature links processes with forms with little ecological understanding (Garcia de Jalón et al. 2013). The achievement of "good ecological status" will be more likely and less expensive if we work with the physical process forming the landscape, instead of fighting them, whilst considering ecological factors.

1.4 Climate change of freshwater systems

Global effects of climate change are becoming more evident (IPCC 2007) and considered to be a major threat to biodiversity and to the structure and functioning of ecosystems (Vitousek 1994; McCarthy et al*.* 2001; FSBI 2007). In freshwater ecosystems, climate change will influence precipitation and temperature (Figure 1.3), two variables that have a large impact on ecosystem functioning and diversity, especially those that are subject to anthropogenic stress through land use change, such as urban areas. An increasing trend in precipitation has been reported for Northern Europe over the 20th Century, but the tendency for Southern Europe and the Mediterranean area has been towards less precipitation (Bernasconia et al. 2005; Moren-Abat et al. 2006). Land precipitation within Europe and globally has increased by about 2% since the beginning of the 20th Century, but this trend is neither temporally nor spatially uniform (Bernasconia et al. 2005). Therefore, the average discharge, timing, duration and inter-annual variability of peak and low flows may all be affected by changes in precipitation and runoff. Especially as it is predicted that winter and spring precipitation will increase in Northern Europe and summer precipitation will decrease, although southern, central and Eastern Europe may experience reduced precipitation (Bernasconia et al. 2005).

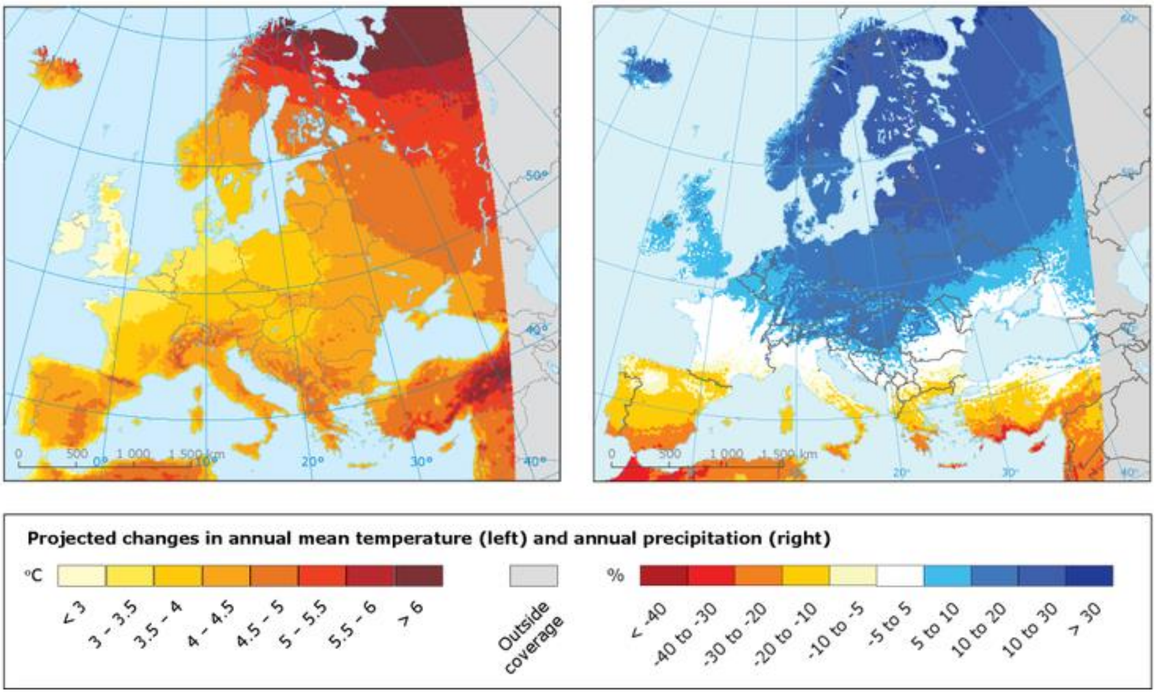

Figure 1.3. Projected changes are for 2071-2100, compared to 1971-2000, based on the average of a multi-model ensemble forced with the RCP8.5 high emissions scenario. All changes marked with a colour (i.e. not white) are statistically significant. Individual models from the EURO-CORDEX ensemble or high-resolution models for smaller regions may show different results (From EEA: www.eea.europa.eu/data-and-maps/figures/projected-change-in-annual-mean, accesses 15/5/2015).

Climate change can alter the physical and chemical conditions of an ecosystem and consequently, a change in the frequency and intensity of these disturbances will determine the rate at which plant and animal assemblages will change or adapt to the change (Wilson & Peter 1990; Webb & Bartlein 1992; Gates 1993; Vitousek 1994; Chaumot et al. 2006). Climate change is predicted to be the cause for the increased frequency of natural hazards (floods and droughts) (Bernasconia et al. 2005; Moren-Abat et al. 2006) and combined with human pressures, will have a great impact on water bodies (Alcamo et al. 2007). The capacity of an ecosystem to adapt to climate change depends not only on the diversity of species it currently supports, but the number of pressures acting on the system. Hydromorphological (HYMO) pressures (Appendix 1; e.g. channelisation, dams and weirs), especially in urban areas, result in spatial fragmentation and spatial heterogeneity that condition the population response to perturbations and is now recognised as a threat to future biodiversity (Hanski 1999; Willis et al. 2009), particularly influencing fish population dynamics in river networks (Morita & Yamamoto 2002; Charles et al. 2000; Chaumot et al. 2003; Ormerod 2003). Direct and indirect effects of climate change will influence water temperature, dissolved oxygen content, discharge and flow velocity, predator and prey abundance and interactions, chemical contaminants and disease (Johnson et al. 2009). Water temperature is one parameter that can determine the health of aquatic ecosystems, especially as most aquatic organisms (e.g. salmonid fish) have a specific range of temperatures they can tolerate, determining their spatial distribution (EC 2012b). Flow, whether increased or reduced, will influence river functioning and subsequently biota and ecological health or quality, demonstrated by a relationship between declining worldwide river flows and reductions in fish biodiversity (Xenopoulos et al. 2005). Consequently, climate change could lead to the extinction of some aquatic species or could change their distribution, if they are not prevented from doing so due to a lack and degradation of suitable habitats or obstacles along the water's course (EC 2012b).

The likely increase in the variability of extreme flood events, especially in urban areas, through increased precipitation are now widely recognized as a major challenge for flood risk management (Wheater 2006; Douglas et al. 2007) and as a consequence, pressures from flood protection activities are predicted to intensify in the future (Booth & Jackson 1997; Kemp & Spotila 1997; Schleiger 2000; Wang et al. 2000; Fitzpatrick et al. 2004; Blakely & Harding 2005; Brown et al. 2005; Europa 2006; Schwartz & Herricks 2007; European Commission 2009; Webb & King 2009; Nelson et al. 2009; Wenger et al. 2009). As climate change pressures become more frequent on river systems and flood protection becomes the preferred solution, it is important to reduce the negative impacts by balancing human needs with the ecological needs of rivers themselves. Climate change becomes an important driver for river rehabilitation, mitigation and adaptation strategies (Battarbee et al. 2008) because the rehabilitation increases ecological resilience through recovery of lost habitat form and function (Mainstone & Holmes 2010). Considerable uncertainty remains concerning the direction and extent of change on a regional basis, and this poses significant challenges for restoration and ecosystem management in general (Harris et al. 2006).

2. Review of main sectors

Increasing human population and advancing levels of social and economic development have led to a rapid increase in the demand for freshwater resources. Development sectors such as water resource management, flood protection, inland navigation and hydropower have led to the replacement of naturally occurring and functioning systems with highly modified and human-engineered systems, resulting in a number of pressures (Table 1). Water resources development results in the construction of dams and irrigation channels, the construction of river embankments to improve navigation, drainage of wetlands for flood control, and the establishment of inter-basin connections and water transfers, all of which regulate the natural hydrograph and simplify river processes to meet human needs.

Table 1. Linkages between drivers and pressures

	Sectors					
Pressures	Agriculture	Urban land use	Water resource management	Flood protection	Inland navigation	Hydropower
Water abstraction	x	x	x			x
Embankment, levees or dikes	x	x		x	x	x
Impoundment, artificial barriers		x	x		x	x
Riparian vegetation alteration	x	x		x	x	
Flow regulation, hydropeaking			x		x	x
River fragmentation	x	x	x	x	x	x
Alteration of instream habitat		x	x	x	x	
Sediment input	x					
Sand & gravel extractions, dredging		x		x	x	

Governance, economic incentives and legislation are indirect, but significant, drivers with respect to balancing competing demands for freshwater resources, especially as each tends to be biased towards its own requirements leading to significant environmental impacts on the natural functioning of inland water ecosystems. Adopting a ‘synergy and trade-off’ approach to river restoration with a specific focus on soft engineering techniques to co-benefit in relation to climate change, will enable planners to consider the links in integrated freshwater conservation planning and overcome constraints that might hinder other (or multiple) sectors. Consequently, the motives, pressures and restoration measures for the dominant sectors (drivers) are reviewed in this section to subsequently consider the effect of potential interactions between pressures and restoration measures (benefits and losses for different conservation features).

2.1 DPSIR assessment framework

The DPSIR (Driver - Pressures – State - Impact - Response) framework is a holistic approach that identifies key relationships between society and the environment (Figure 2.1). It supports managers in their decision making, especially to structure and communicate policy relevant rehabilitation projects (Atkins et al. 2011). **Drivers** are the key demands by society such as agricultural and urban land use, flood protection, inland navigation and hydropower, all of which are discussed in the following sections. These drivers are responsible for **pressures** that cause biological and abiotic **state** changes and further **impacts** within the river system (EEA 1999):

- ***Abiotic state*** – reflects the magnitude, frequency and concentration of the environment including;
    - ***Physical variables*** – climate variables (air and sea temperature, precipitation, storms & hurricanes, drought);
    - ***Chemical variables*** – contaminants, nutrients, pH, atmospheric CO2 levels, salinity. The abiotic environment determines the survival, growth, and distribution of living organisms in the Biological state;
- ***Biological state*** – includes the biological components of the ecosystem and their interactions;
- ***Living habitat*** – is generally defined by the ecosystem of interest.

Natural variability, invasive species and climate change are indirect pressures that can also cause for changes in river state and combined with pressures resulting from human activities can intensify impacts on the ecosystem. The DPSIR approach disentangles these knock on effects and identifies mitigation **response** to the impacts on ecosystem services and ecosystem function through the application of river restoration to prevent or improve state changes in the environment (United States Environmental Protection Agency). A feedback loop between human response (river restoration) and pressures identifies the need to assess the chosen restoration measure and the risk and uncertainty of being ecologically effective (this is discussed further in D5.4).

A DPSIR table can be created to help practitioners identify technically feasible and economically viable restoration measures at river basin and reach scale. The user should list all drivers present, the pressures they create, the resulting state changes, subsequent impacts and potential rehabilitation measures (Table 2). In this section the DPSIR method has been applied to overview the main sectors and a DPSIR tables for each sector can be found in Appendix 1. To reduce duplication in REFORM deliverables it is recommended that this section is read in conjunction with REFORM D1.2 (Garcia de Jalón et al. 2013) and REFORM D1.3 (Wolter et al. 2013) as they review effects of pressures on HYMO processes and ecological response to both HYMO degradation and restoration.

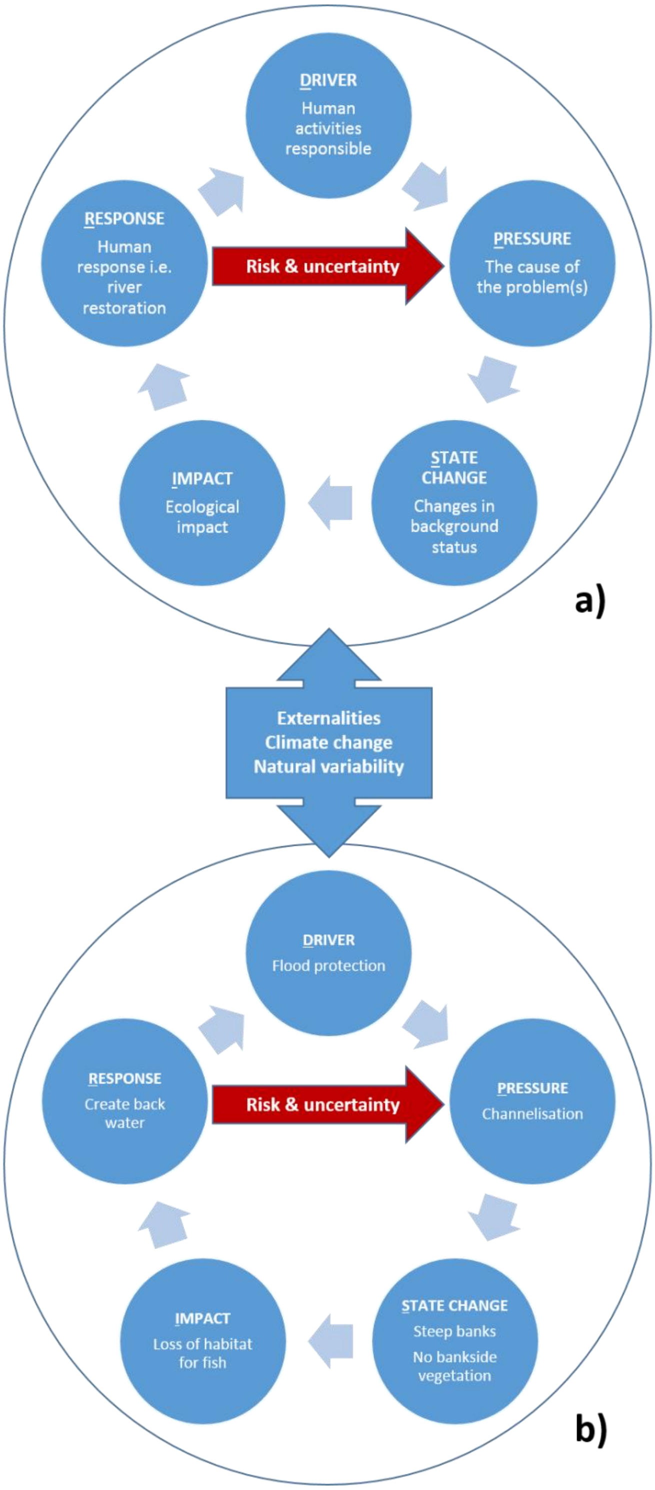

Figure 2.1. The DPSIR framework as a cyclic system, diagram a) explanation of the different stages. Diagram b) example of DPSIR framework for river restoration (adapted from Atkins et al. 2011).

Table 2. DPSIR table example to aid decision making in the planning stages for river restoration (description in text).

Driver	Pressure	State	Impact	Response
E.g. *Flood protection*	*Channelisation*	*Steep banks & simplification of the channel*	*Loss of lateral connectivity*	*Reconnect floodplain through disused gravel pits*

2.2 Agriculture land use

Agricultural practice results in a number of pressures such as water abstraction, embankments and ditches for efficient drainage, alteration of riparian vegetation and sediment runoff from the land (Table 1; Appendix 1). Agriculture is an activity that has a high demand for water, intensified in Southern European countries, and is generally supplied by reservoirs, rivers, groundwater and canal systems. Abstraction causes changes in HYMO processes such as water flow and sedimentation, as well as vegetation. The reduction of water flow can have negative impacts by altering the average flow, causing further changes to the channel width, depth and velocity (Appendix 1). Embankments due to levees and dikes for land drainage result in changes to HYMO processes - water flow, may increase flood water depth and shear stress, sediment entrainment and sediment transport will negatively impact on thalweg altitude and where armoring is applied, substrate size will increase (Appendix 1). According to the European Environment Agency (Feher et al. 2012) many landscapes in Northern Europe have been ditched and lakes drained to increase the surface area for agricultural land and in particular arable land. Many lowland rivers in Western Europe have been substantially modified to aid land drainage primarily for conversion from grassland to arable land use and, subsequently, to support the intensification of agriculture. Furthermore, agriculture is also a source for high concentration of nutrients in the water and addition of toxic substances such as pesticides. This can occur through sediment input because of channel erosion or run-off from land, intensified by a lack of riparian vegetation that would usually act as a buffer between agricultural land and the river (Figure 2.2).

Figure 2.2. Bankside erosion and sediment input to river resulting from cattle poaching and no bankside vegetation (source: Natalie Angelopoulos).

2.3 Urban land use

Urban rivers tend to make up a small section of a whole river catchment, but anthropogenic pressures that impact on freshwater systems can be magnified in contrast to non-urban rivers. This is due to the combined effect of multiple pressures, such as water abstraction, fragmentation, impoundment, channelization, alteration of riparian vegetation and instream habitat, embankments, increased impervious surfaces and sediment input, and loss of vertical connectivity (Table 1; Figure 2.3; Appendix 1) (Dynesius & Nilsson 1994; Forman & Alexander 1998; Paul & Meyer 2001; Aarts et al. 2004; Pyrce 2004; Reid 2004; Vinebrooke & Cottingham 2004; Vaughn et al. 2009; Schinegger et al. 2011). All of these have a notable impact on HYMO variables changing instream habitats and communities and can result in

Figure 2.3. Urban rivers and streams showing many of the main urban pressures such as increased impervious surfaces, channelization, fragmentation, artificial river bed, reduced instream and bankside vegetation (source: Natalie Angelopoulos).

reduced biotic richness, such as fish (Wang et al. 2000, 2001; Roy et al. 2006), invertebrates (Beavan et al. 2001; Chadwick et al. 2006) and macrophytes (Suren 2000). In many instances, urban river banks and beds are artificially modified to reduce erosion and substrate movement by the exchange of natural substratum to a more firm, man-made surface and in some cases a lining of the river bed can be installed through dense urban areas (Rocha et al. 2004). As a result, artificial channels increase overall drainage densities; in addition to an increased slope this contributes to an increase in-stream velocity and conveyance efficiency (Pizzuto et al. 2000; Meyer & Wallace 2001). The construction of culverts to cover streams occurs in many urban areas, for example there is an entire network of culverted rivers under central London (Barton 1992), of which many were once noted for their rich fisheries (Walton 1653; Everard & Moggridge 2012). Some of these culverted streams have also been converted into storm drainage systems (Rocha et al. 2004). In addition, natural land surfaces are replaced by artificial, impervious surfaces such as pavements, roads and roofs meaning vegetation is cleared and soil compacted. Efficient drainage systems, in addition to artificial surfaces in urban areas, will increase the volume and velocity of runoff that reaches the river and therefore, alters the hydrology of the river system and can lead to peak flow and flood risk downstream (Rocha et al. 2004). This reduces the availability of flow refugia, lowering the diversity and abundance of biota capable of tolerating or recovering from flooding (Negishi et al. 2002; Lake et al 2007). Urban land run off from impermeable surface, flash flooding and drainage contribute greatly to the poor water quality of urban river systems (Paul & Meyer 2001). Point source pollution from domestic and industrial (both past and present) sources results in the introduction of toxic substances (both of organic and inorganic origin (Omernik 1976; House et al. 1993; Meybeck 1998; USGS 1999; Winger & Duthie 2000; Wenger et al. 2009). Elevated suspended sediment levels are caused by anthropogenic actions such as mining, road-deposited sediments, industrial point sources and waste water (Walters et al. 2003; Grimm et al. 2005; Gurnell et al. 2007; Taylor & Owens 2009; Everard & Moggridge 2012), and have effects such as bed sediment changes, nutrient enrichment and turbidity, all of which contribute to reduced diversity of stream macrophytes. Degraded riparian buffer zones magnify these effects (Suren 2000).

A European Commission project on Natural Water Retention Measures identified the main urban measures to be buffer strips and swales, permeable surfaces and filter drains, infiltration devices and green roofs. Considerable success in reducing the discharge of pollutants into Europe's waters in recent decades shows that we are on the right track towards reducing pollution from urban and industrial wastewater and agricultural sources (EEA 2012). Continuing improvement in the level of pollutant removal from urban wastewater discharges is anticipated and driven by requirements under the Urban Waste Water Treatment (UWWT) Directive (91/271/EEC) and national legislation (EEA 2012). In addition, to improve water run-off and pollution pressures, habitats in urban rivers need to be restored with suitable refugia capable of enhancing the resistance and resilience of biotic communities to both natural and anthropogenic disturbances (Sedell et al. 1990; Lancaster & Hildrew 1993; Bond & Lake 2005).

2.4 *Water resource management*

Dynamics of flowing water are the most important hydromorphological process after water quality, and underline the necessity to rehabilitate a more natural flow regime to improve the hydromorphological status of the rivers and the related biological communities (Garcia de Jalón et al. 2013). The natural flow regime has five components: magnitude, frequency, duration, timing, and rate of change, which all might become limiting factors next to water quantity (Poff et al. 1997). Climate change may affect precipitation and run off, which in turn, may affect flow and cause changes to the average discharge, timing, duration, and inter-annual variability of peak and low flows. Here we overview flow regulation but more detail can be found in REFORM D1.2 (www.reformrivers.eu/system/files/1.2%20Pressure%20effects%20on%20HyMo_final.pdf) on the following sections:

- Morphological pressures & impacts;
- Hydrological pressures & impacts;
- Water quality pressures & impacts;
- Effects of flow regulation on vegetation;
- Biological and ecological effects of flow regulation.

Hydrological characterisation of rivers in support of their management is well established (Kennard et al. 2010; Belmar; Velasco & Martinez-Capel 2011), and is fundamental to the science of environmental flow assessment and implementation (Poff et al. 2010; Bobbi et al. 2014). Flow regulation in rivers enforces fundamental changes on water and sediment transfer, which are the principal controls on fluvial morphodynamics (Church 1995). There are many different types of flow regulation (Appendix 1), for example flow reduction by water abstraction and increased flow by inter-basin water transfers, irrigation flows (summer increased flows and winter reduced flows), discharge of water for supply, hydropeaking and flushing flows done by reservoir operations. Reductions in flow can also influence water temperature, both of which are important abiotic factors that change after the regulation of rivers (Ward & Stanford 1979; Petts 1984). When flows are reduced, such as in depleted stretches of river, temperatures can increase due to a reduction in wetted area and increase in shallower water, but also reduction in hyporheic flows, all of which may have consequences for the development and reproduction of aquatic organisms that are influenced by temperature (Floodmark et al. 2004).

Water abstractions may be taken directly from the flowing waters in the channel (surface water abstraction), or indirectly from wells by pumping water from aquifers that may be closely connected to rivers (groundwater abstraction). Furthermore, water abstraction from rivers can be achieved through inter-basin flow transfer schemes, whereby the donor river system has its flow reduced below its diversion. Groundwater over-abstraction can lead to decline in groundwater levels within aquifers and drying up or causing severe flow reduction in rivers. Surface seepage from aquifers supports groundwater-fed ecosystems such as wetlands and springs. Riparian vegetation affected by declining hyporheic levels rapidly shows signs of water stress, leading in extreme cases to widespread riparian plant death. Removal and downstream return of water from the river through a man-made diversion structure called a *bypass* often results in significant flow reduction in the intervening section of the river's course. This is a typical pressure that affects rivers used for hydropower, whereby flow is diverted from the river by a weir at higher altitude and discharged through a bypass channel into turbines that are located downstream at a lower altitude (Figure 2.4). A similar pressure occurs in association with irrigation of farmlands located in the floodplain and near the river margins, but in this case the return flows are greatly reduced by plant water consumption, evaporation and infiltration, and may also suffer from a reduction in water quality. Diversion also takes place to supply urban areas and industries with water, and in these cases the return flow is affected by significant reductions in both water quality and quantity. Flood diversion is a special case of flow diversion and return that is designed to alleviate flooding.

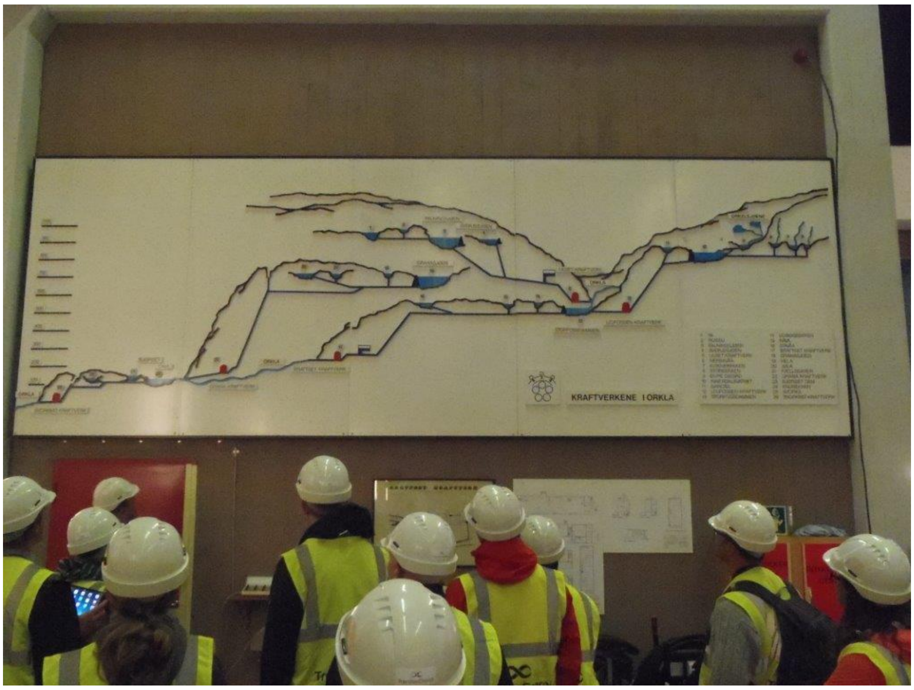

Figure 2.4. The by-pass scheme of a hydropower plant in Norway. The by-pass runs through the mountains (Photo: Tom Buijse).

To modify the natural flow regime markedly, a major artificial water store, in the form of a reservoir, or a major water transfer scheme from another watershed is usually needed, although groundwater resources are sometimes used to augment or regulate river flow regimes to match water demand (e.g. Cowx 2000). The hydrological changes produced by this type of regulation are strongly influenced by its purpose: flood control, hydropower, water supply and irrigation (Ward & Stanford 1979; Petts 1984). Each type of water use produces a different type of regulated flow regime that results in different ecological alterations, and often the same reservoir is operated for multiple purposes. For example, reservoirs for irrigation are operated to store water during rainy seasons and to release it during dry seasons, usually producing a regime of more seasonally constant flows. Reservoirs designed for irrigation, domestic or industrial water supply and hydropower generation all tend to attenuate and delay the seasonal regime of flows to the downstream water body. Vörösmarty et al. (1997) estimated that in the mid-1980s the maximum water storage of the 746 World’s largest dams was equivalent to 20% of global mean annual runoff and the median water residence time in these impoundments was 0.40 years.

The production of electricity by hydropower plants is often implemented to satisfy peaks in electricity demand (Robertson et al. 2004; Anderson et al. 2006; Murchie et al. 2008). For this reason these plants work intermittently, creating periodic and extremely rapid and short-term fluctuations in flow in the receiving water body. These fluctuations are called hydropeaking and usually show a marked daily rhythm.

Flushing flows are peaks of flow released from reservoirs to imitate elements of the natural flow regime downstream and purge reservoirs of accumulated sediment to aid recovery of their associated HYMO and ecological processes. Flushing flows maintain stream channel composition by removing accumulated fine sediment and organic debris, mobilizing and sorting bed material and restricting riparian vegetation encroachment. Common practice of reservoir flushing to get rid of accumulated fine sediments may have detrimental effects on the habitats and aquatic communities downstream of the dam. Elevated regulation flows are also produced in rainy years, for security reasons when storms occur at the end of the spring when the reservoirs are full.

Although water abstractions may have relatively minor impacts in temperate regions, in Mediterranean countries they can represent major alterations with the potential to turn perennial rivers into intermittent rivers and to severely degrade physico-chemical conditions, if base flow becomes limited in relation to emissions or discharge of effluents (Prat & Munne 2000; Mencio & Mas-Pla 2010).

2.5 *Flood protection*

Climate change predictions indicate a likely increase in flood risk to large parts of the European member states, emphasising the importance of effective flood protection. Floodplains have been converted to agricultural or urban land; technical structures such as levees and drains were built to protect these areas from flooding, by rapidly transporting the water to rivers, but flooding can be caused by excessive rainfall and inefficient drainage systems. Urbanisation accelerates the transport of water, pollutants and sediment into rivers and their typically constrained nature is inadequate to cope with the increased flow volumes (Leopold 1968; Finkenbine et al. 2000; Andjelkovic 2001; Paul & Meyer 2001; Walsh et al. 2001). A growing number of serious flood events across Europe has brought in the need for flood protection, and has had a major impact on water management in member states. There is growing concern as flood events in Europe still regularly occur. The flooding of the Elbe river basin May/June 2013 caused 25 casualties and 12 billion Euro of damage (http://www.bloomberg.com/news/2013-07-09/europe-flood-damage-to-top-15-5-billion-munich-re-says.html). In June 2007, The River Don, Sheffield UK, flooded after prolonged heavy rain in the Don catchment, where almost 100 mm fell in just 24 hours (EA 2007) and as a result approximately 1,200 homes and 1,000 businesses were flooded (EA 2011). As a consequence, flood protection schemes were put in place along several sections of the River Don, the most frequent method was to remove bankside vegetation and trees to increase the volume for flood water (Figure 2.5). The costs of maintaining flood defence barriers are cause for growing concern in Europe (Moss & Monstadt 2008) and it is predicted that the expected annual flood damage in EU27 will be € 14-21.5 billion by the end of the century (Feyen et al. 2012).

Figure 2.5. Removal of trees to reduce the risk of flooding on the River Don a) before and b) after flood defence works (source: Jon Harvey).

Increased flow, embankments, alteration to riparian vegetation, instream habitat alteration and sand and gravel extraction are all key flood defence pressures that act upon HYMO processes, many of which have negative impacts on HYMO variables. They reduce the heterogeneity within the channel by changing the river profile and also reduce lateral connectivity through embankments. Loss of vegetation results in loss of sediment trapping and island formation, which reduces habitat availability for invertebrates and fish. This in turn causes impacts such as increased stream power, change in substrate size and loss of available habitat for fish. Flood defence measures are put in place to reduce the societal problems that come with flooding. The application of natural flood defence strategies is encouraged to combine the objectives of the FD with the objectives of the WFD. Strategies to combine flood protection and ecological restoration like ECO-Flood have been developed (Blackwell & Maltby 2006) (see DPSIR table (Table 1; Appendix 1) which overviews the problems and possible solutions to flood defence).

2.6 Inland navigation

Inland navigation on European rivers dates back to Roman times about 63 BC - 200 AD (Eckoldt 1980; Kalfhues 1985) and starts again in the 7th/8th Century (Rohde 1986; Schich 1994; Elmshäuser 2002; Molkenthin 2006). For centuries, navigation became the most powerful and important mode of transport (Figure 2.6). Many canals and navigation locks were constructed between the 16th and 18th century to connect rivers and river sections (Phillips 1803, Brühöfner 2004, Brolsma 2011). In the last 150 years the global commercial inland navigation network has been enlarged more than 57 times from 8750 canal-km and 3125 river-km altered for navigation before 1900 to 671,868 km of inland waterways in 2012 (CIA 2013). The total network of inland waterways used, at least temporarily (at higher floods) for navigation of small commercial vessels and pleasure boats, sums up to 2,293,412 km world-wide (CIA 2013). The inland waterway network in the EU includes about 37,000 km of inland waterways in 20 Member States (in the EU 27 about 53,384 km in 2013 [CIA 2013]). On average around 140 billion tonne-kilometres of transport work is performed each year on these EU 20 waterways transporting around 500 million tonnes of cargo (EC 2012b). Inland waterway transport is still considered the most energy-efficient and climate friendly of all modes of transport (EC 2012b). However, inland navigation in the EU-27 only accounted for 0.42% of transported goods corresponding to 19.09 million tonnes CO_2 equivalents of all greenhouse gas emissions in 2011 (Hill et al. 2012). In the U.S. inland navigation emitted 27.8 million tonnes CO_2 equivalents in 2012 accounting for only 1.6% of the GHG emissions of the transport sector (EPA 2014). The global emission of CO_2 equivalents of the domestic waterborne transport was 84.5 million tonnes in 2010, representing 1.91% of the total GHG emissions of the transport sector (IPCC 2013). Effects of inland navigation comprise construction and maintenance related pressures and impacts as well as operation related disturbances (Table 1; Appendix 1).

Figure 2.6. Inland navigation (source: Tom Buijse).

2.6.1 Construction and maintenance related pressures and impacts

In the second half of the 19th Century the paradigm for improving inland navigation shifted to an adaptation of rivers and waterways to larger vessels with higher draughts, width and engine power. This management persists until today and any likely increase of traffic on waterways will be accompanied by increased power of towboats, size of barges, and number of barges transported together (Hüsig et al. 2000). The 57-fold increase in maintained waterways in the last 150 years has also resulted in a wide homogenisation of rivers and riverine habitats as well as dramatic losses of habitat structures, habitat complexity and of freshwater biodiversity. For example, all larger European rivers have lost on average one fifth of their total length due to modifications and meander cut-offs (van Urk & Smit 1989; Kausch 1996, Konold & Schütz 1996; Nachtnebel 1996; Tittizer & Krebs 1996; Uhlemann & Eckoldt 1998; Herget et al. 2005; IKSE 2005, Biss & Vobis 2006; Kremer 2010); single rivers like the German River Weser have reduced in length by more than one third (Busch et al. 1984). In the substantially shorter river channels both flow velocity and depth erosion have increased (Table 3); for example, modifications of the upper River Rhine have resulted in a channel incision of 7 m (Biss & Vobis 2006). Braided sections have been widely modified to single thread channels through channelization (Petts et al. 1989; Roux et al. 1989) and reduction in the historical number of islands by 85% (Gurnell & Petts 2002), often more than 90% (Micha & Borlee 1989, Roux et al. 1989, van Urk & Smit 1989) and in the upper River Rhine more than 97% (50 islands out of 2218, Schwarzmann 1964). Inland navigation significantly reduces the variability in depth and width of rivers (Ockhardt 1816; Rommel 2000) and tremendous amounts of natural shore line and shallow littoral habitats have been lost (Rommel 2000). Many rivers are regulated by groynes to increase the waterway depth and width during mean flow to allow for greater traffic of larger barges, e.g. in the River Oder 5432 groynes and about 263.6 km of embankments were constructed between 1819 and 1844 (Herrmann 1930) and in the River Elbe 4298 groynes, 27.8 km of parallel dikes, and 113.4 km of embankments were built prior to 1858 (Rohde 1998). Furthermore, the banks of these single thread European waterways have been steepened and embanked, mostly with rip-rap, but also sheet piling, along approximately 60% of their length and often much more (Schuchardt et al. 1984; Micha & Borlee 1989; Gerken 1995; Tittizer & Krebs 1996; Wolter & Vilcinskas 1997; Wolter 2001). For navigation ways such as canals, fragmentation is common due the numerous locks that raise and lower boats between stretches of water at different levels.

2.6.2 Operation-related pressures and impacts

Moving and manoeuvring ships induces a variety of hydro-dynamic changes and physical forces having different impacts on banks, flow and sediments, and accordingly, different ecological impacts based on significance, affected species groups, prevention and mitigation. Sailing watercraft penetrate the water body and displace the water towards the sides, downwards and backwards. This causes a primary flow field around the ship's hull which is strongly curved at the bow (displacement flow) and stern (Söhngen et al. 2008), and combined with propulsion effects will lead to peak values of near bed velocities and shear (Maynard 2000; Rodriguez 2002). The backwards component of the displaced water is called the return current. It is more or less constantly distributed along the middle section of the vessel and also across the width in small canals. Displacement flows and return current velocities have to be added to the vessel speed to get the hydrodynamic relevant local velocity relative to the ship's hull. This velocity increases the velocity head of the flow field around the ship and causes a decrease in pressure head, which in turn decreases the water level on both sides of the sailing watercraft, called the primary wave field. One part is the drawdown. The drawdown forms, together with the displacement flow, propulsion induced flows and the secondary waves in the stern area, the transversal stern wave. If it breaks, especially in narrow channels and in the vicinity of berms and the banks, it causes the slope supply flow, filling the drawdown trough from behind with water, producing strong hydraulic loads on the river banks. Söhngen et al. (2008) provided typical peak values for vessel-induced forces close to the banks of return currents (0.4-1.0 m s^{-1}), drawdown (0.2-0.4 m) or wave heights (0.2-0.5 m) (Table 3).

Table 3. Typical peak values of selected impacts in large rivers, caused by typically sized modern motor vessels and large, multi-lane push tow units, passenger ships and recreational boats (from Söhngen et al. 2008).

impacted zone		return current and displacement flow velocity		drawdown		stern wave height		secondary waves			near bed propeller jet velocities				near bed wake velocity behind stern (downstream drive)
									passenger ships and recreational boats		large motor vessels and push tow units		Recreational boats		
		large motor vessels	push tow units	large motor vessels	push tow units	large motor vessels	push tow units	large motor vessels and push tow units	average fast speed	planing speed	manoeuvring	driving	manoeuvring	driving	
		[m/s]	[m/s]	[m]	[m]	[m]	[m]	[m]	[m]	[m]	[m/s]	[m/s]	[m/s]	[m/s]	[m/s]
channel bed		1.5	1.0 1.8 1.2	0.5	0.4 1.2	-	-	-	-	-	3 (4) 2.0	2.0 1.5	1.5 0 0	1.0 0 0	2.5 1.5 0
bank slopes	centric ship path	0.8 0.5	0.7 1.0 0.4	0.4 (0.5) 0.2	0.3 (0.4) 0.4	0.4 (0.5)	0.3 (0.4) 0.5 0.25	0.2 (0.3) 0.2 0.2	0.3	0.6 0.1 0.1	-	- 0 0	- 0 0	- 0 0	-
	vessel 50 m to banks	0.8 0.4	0.7 0.4	0.4 (0.5)	0.4 (0.5) 0.1	0.7 (1.0)	0.6 (0.8)	0.3 (0.4) 0.2	0.5 0.3	0.9 0.2 0.2	3	- 0 0	1.5 0 0	- 0 0	-

Operation-related environmental impacts of inland navigation vary between waterways according to their size, depth, cross-section, hydrodynamics, flow velocity and species assemblages present, and the conditions they are more adapted to, whether riverine or lacustrine-like habitat conditions. In wide- and depth-restricted waterways, the dynamic changes of the flow field around a moving vessel are the most significant impacts comprising return currents (Figure 2.7), drawdown, transversal stern waves (Figure 2.8), and slope supply flow. The magnitude of the hydraulic forces generated depends, among others, on the flow velocity of the waterway. The environmental impacts of the flow field changes are inversely correlated to the flow velocity of the waterway, and most significant in narrow stagnant canals. The likely increase of traffic on waterways will be accompanied by increased power of towboats, size of barges, and number of barges transported together (Hüsig et al.

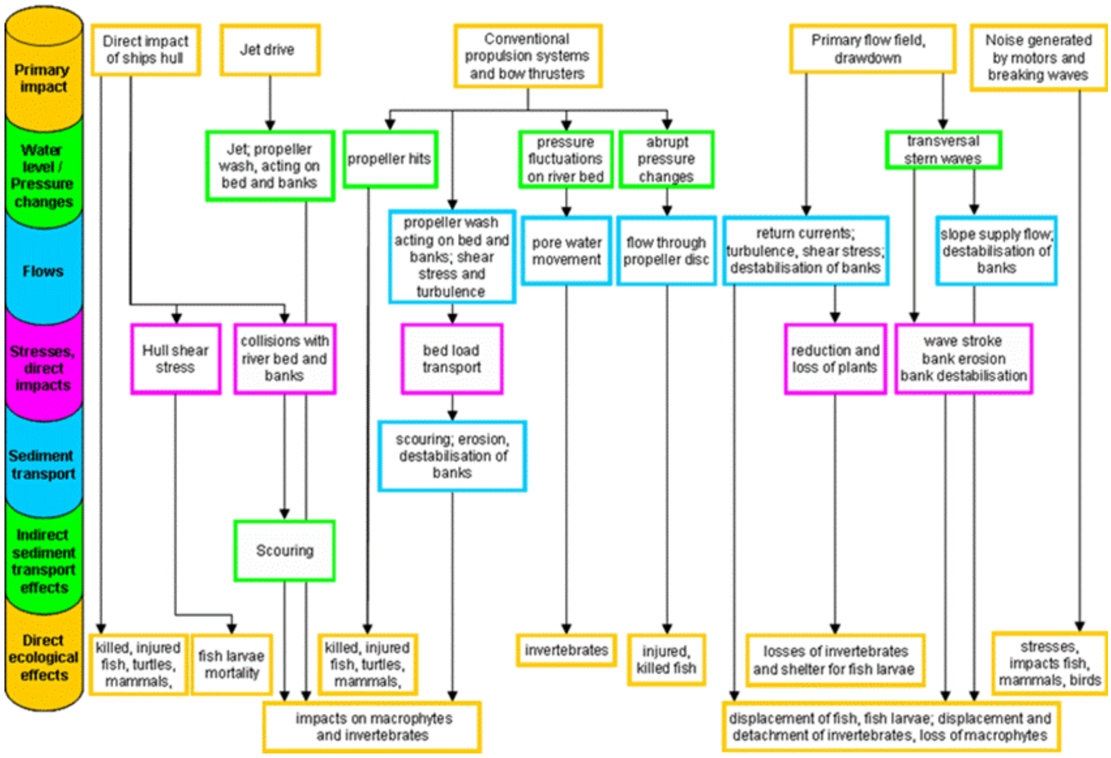

Figure 2.7. Impact cascade of currents induced by moving vessels (from Söhngen et al. 2008)

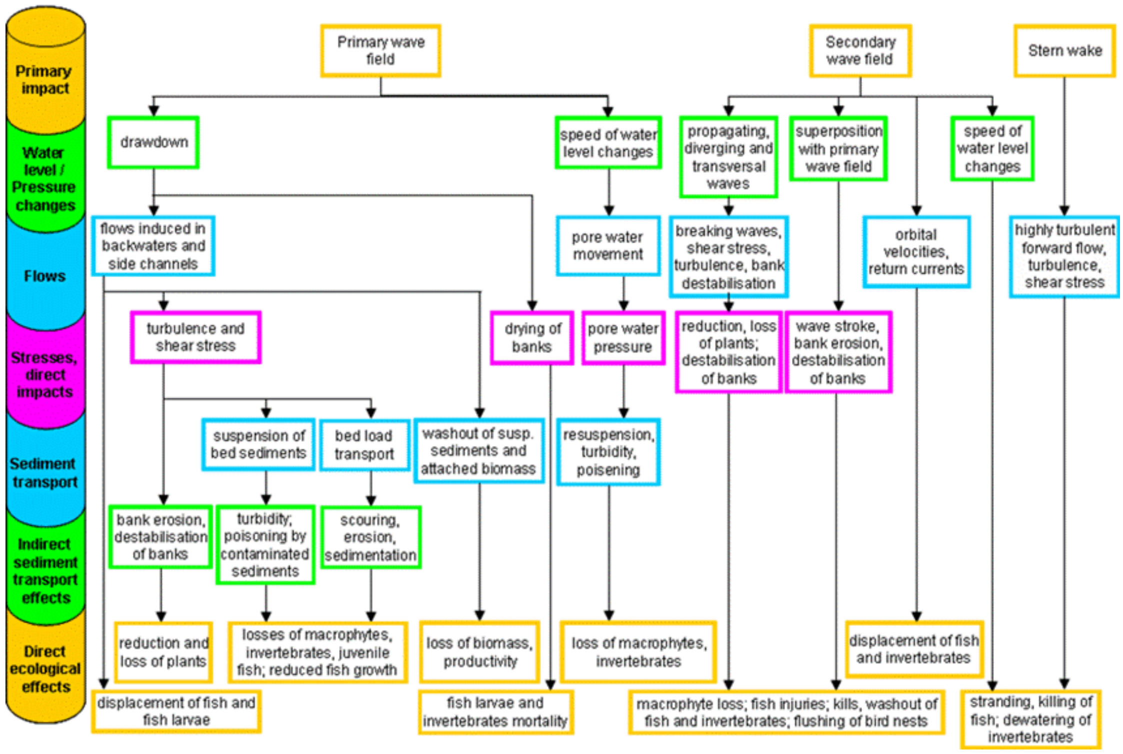

Figure 2.8. Impact cascade of waves induced by moving vessels (from Söhngen et al. 2008)

2000). Increasing economic pressures which forced ship owners to reduce the specific freight costs (per transported tonne), especially those related to personnel and fuel consumption, led to a successive enlargement of vessel sizes in length, frame height and maximum draught, together with an accordingly increased engine power. These increases have in turn resulted in increased impacts on riverine habitats and channel morphology, especially river banks and littoral zones.

2.7 Hydropower

The basic principle of hydropower schemes is to use the gravitational movement of water to produce electricity. Essentially, this is achieved by passing water over turbines to convert kinetic or potential energy into electrical energy. The largest hydropower schemes invariably use a dam to store a reservoir of water for electricity generation. By contrast, run-of-river schemes simply divert a proportion of the river flow through turbines and return the water downstream. In Scotland, data suggest that a total of 102 (67%) hydro developments are storage schemes with potential installed capacity of 2148.42 MW and the remaining 32% are run-of-river (usually small scale) schemes, with an approximate installed capacity of 62.35 MW (Bean & Thin 2008).

Although the harnessing of energy from water discharge and conversion to electrical power did not begin until the mid-19th Century (Poff & Hart 2002), it is now considered the most important renewable electricity source worldwide (Bratrich et al. 2004), accounting for 19% of the world's electricity (Paish 2002). Furthermore, the International Energy Agency (IEA) predicts that hydropower output worldwide will increase from 2809 TWh in 2004 to 4749 TWh by 2030. Hydropower is often presented as a clean (Rosenberg et al. 1995) and renewable energy source that is environmentally preferable to fossil fuels or nuclear power (Renofault et al. 2010), although with major economic, social and environmental limitations (Demirbas 2007). As there is no carbon dioxide, sulphur dioxide, nitrous oxides or any other gaseous emissions and no solid or liquid wastes (Ramos & Almeida 1999), hydropower is often portrayed to have no negative impacts on the environment, but this description has been challenged by numerous authors, including Ausubel (2007) and Butterworth (2009, 2010), who consider the impacts on fisheries and biota as significant.

2.7.1 Hydropower pressures & measures

The main pressures from hydropower (Figure 2.9) are water diversion, hydropeaking, river fragmentation (Arnekleiv & Ronning 2004; Tomsic et al. 2007), impoundment, channelization and impacts during construction phase, causing many changes to hydromorphological processes and habitat characteristics (Table 1; Appendix 1). In large schemes requiring the creation of a dam and a reservoir, a pre-determined volume of water produces a more reliable power supply (Jansson 2002) than small-scale schemes without an impoundment that are dependent on ambient river flows. The larger schemes are also able to provide a much more stable power output as the release of water can be controlled to match demand

Figure 2.9. An example of how opportunities arise between hydropower scheme and the restoration of longitudinal connectivity to improve fish passage along an existing barrier. Hydropower on the left and a Larinier fish pass to the right (source: Jamie Dodd).

(Hogan 2005). This is known as hydro-peaking, and causes rapid, large and frequent fluctuations, often over 24-hour period, in water flow downstream of hydropower outfalls (Floodmark et al. 2004). Such schemes are well documented to have numerous ecological and environmental impacts, affecting the quantity and quality of river habitat (Angilletta et al. 2008). Dams can interfere with the transport of sediment and nutrients along a water course, reduce or alter natural fluctuations in discharge levels, prevent inundation of floodplains and create wider or shallower rivers (de Leaniz 2006). It should be noted, that hydropower schemes, regardless as to whether they are run-of-river or storage schemes, are characterised by the same structural elements (impounding structure [potential barrier to migration, water diversion, water intake and outfall) and thus may elicit the same impacts; it is the scale of the operation and thus potential impacts that vary.

The majority of new schemes are small-scale run-of-river, which have no significant storage of water. These small-scale hydropower schemes, defined as having an installed hydropower capacity of up to 10 MW, are considered the backbone of electricity production in many EU countries (Bruno et al. 2008). Small-scale run-of-river hydropower schemes can be split into two main types: high-head and low-head. Essentially the main difference is the head of water available for power generation. The head of water relates to the difference in altitude from the intake at the top of the scheme and the floor level of the turbine at the bottom of the scheme, i.e. the outfall (McKenzie 2007). Low-head hydropower schemes generally have a head of water of <5 m, while high-head schemes generally have a head of >50 m. Usually it is considered that the higher the head available, the greater the power output (Hogan 2005), but in reality power output is a function of discharge volume against head height, and this is particularly relevant to low-head schemes. Low-head schemes are generally constructed on lowland reaches of rivers, with gentle gradients, while high-head schemes are sited in upper reaches of rivers with steep gradients (Egre & Milewski 2002).

Run-of-river schemes can only operate when there is sufficient flow in the river. However, the amount of water available for power generation is not only determined by the discharge of the river (Larinier 2008), but is dependent upon the abstraction regime of individual schemes, which relates to the discharge. Consequently, run-of-river schemes are thought to cause lower disturbance and impact to stream ecology (Batrich et al. 2004). Additionally, impacts are considered to be less damaging as they do not lead to fragmentation of riverine habitat, with the condition that in-stream flows remain sufficient (Habit et al. 2007) to protect river characteristics and ecology. Nevertheless, run-of-river schemes generally require an impounding structure, and many are re-developments of existing sites, such as old mills, are located on existing structures or require construction of small weirs, the impacts of which on fish communities are poorly understood (Benstead et al. 1999; Kingsford 2000; Aarestrup & Koed 2003; de Leaniz 2006; Poulet 2007).

2.7.2 Longitudinal connectivity

Fragmentation of the continuity of the river system is a key impact of dam and weir construction (Arnekleiv & Ronning 2004; Tomsic et al. 2007). Weirs and dams result in modification of the physical processes within the channel effecting flow velocity, depth and substrate distribution (Bernacsek 2001; Tomsic et al. 2007). Upstream, water depth is often increased and flow velocity reduced causing a ponding effect; sediment becomes finer or covered with silt (Cowx et al. 1993; Poff & Hart 2002; Ashley et al. 2006; de Leaniz 2008) as reduced velocity and presence of the obstruction interferes with or stops sediment transport along the longitudinal channel thus disrupting the river’s natural processes (Stanley & Doyle 2003; Ligon et al. 1995; de Leaniz 2008). These changes in geomorphological processes can lead to altered nutrient and energy fluxes (Poff & Hart 2002), alteration of the thermal regime (Poff & Hart 2002), storage of contaminants in trapped sediments (Bernacsek 2001; Ashley et al. 2006), separation of the channel from the floodplain (Bernacsek 2001; de Leaniz 2008) and habitat alteration at a range of spatial scales (Poff & Hart 2002). Downstream of the weir, higher flow velocities expose clean gravel substrates with a rejuvenated erosion zone produced for some distance downstream (Welcomme 1994). Natural gravel recruitment can be limited (Larinier 2001; de Leaniz 2008). Turbines from the hydropower cause mechanical damage to biota passing through them directly impacting on the survival of fish and sustainability of populations, especially of migratory species.

2.7.3 Altered flow regime

Flow maintains the structure, species, communities, processes and functions that provide ecosystems with specific characters (Acreman & Ferguson 2010). Reductions in river flow can cause substantial ecological impacts and are frequently associated with large impoundment hydropower schemes (Armstrong et al. 1998; Saltveit et al. 2001). However, run-of-river schemes, which generally have small impoundment weirs, can also cause ecological impacts, as the reaches between water diversion and release have a reduced flow. This may impact on the ecology of the depleted flow reaches (Copestake 2006), including an altered availability of habitat features (Whiting 2002), a reduction of fish biomass (Baran et al. 1995), loss of river continuity and impediment to fish movements (Butterworth 2010), risks of fish entrapment at intakes, build-up of sediment at outfalls and sudden releases at turbine houses.

2.7.4 Changes in habitat characteristics

Flow reductions affect the physical habitat characteristics of rivers, such as water velocity, sediment transport, turbidity, bed and bank stability (Growns 2008), wetted width, water depth and water temperature. Much of the changes experienced will depend on the channel morphology but flow modifications have the potential to alter the quantity and quality of available aquatic habitat (Lake 2003), which subsequently influences stream biota (Anderson et al. 2006). Reductions in flow can result in shallow areas and side channels drying out, thus reducing the amount of potential spawning and/or nursery habitat.

The initial construction of hydropower schemes can cause an array of environmental impacts such as increased sedimentation. The construction of both intakes and outfalls are not without risks and there are many potential impacts as a consequence of the change they have upon sediment transport, river flow and substrate composition. The first concern relates to their construction, causing direct loss of bank side habitat which is primarily riparian. Overhanging trees and shrubs can also be lost, which provide cover and shelter for many juvenile fish, riparian habitat is also a prime source of food for an array of aquatic species. Increased sedimentation is also a risk as mentioned previously; increased sedimentation can result from the mechanical and engineering work, but additionally a build-up of sediment in front of the intake is a potential impact In addition, reduced flow will hinder sediment transport to downstream reaches and potentially affect the deposition of sediment in upstream reaches.

Physical damage to the environment may include ground clearing leading to the removal of vegetation cover and/or trees if located in forested area, trenching to bury pipelines, blasting and grading. Pedestrian traffic, noise and visual pollution may not be a cause for concern regarding high head schemes due to their location but could be problematic for low head schemes. During the construction of new access roads and pipelines, top soil/vegetation is removed, which has potential ecological consequences including reduction of plant diversity and wildlife habitat. Sediment disturbance and run off can ultimately lead to weathering of newly exposed soils that could potentially cause leaching and oxidation; the release of new chemicals into the rivers.

2.8 *Effects of HYMO degradation and restoration on biota*

It is important to understand biological responses to HYMO degradation of rivers and their restoration, in particular the response of WFD BQE, viz. macrophytes, macroinvertebrates and fish. In the previous sections the impacts of the primary pressures (channelization, continuum disruption, disconnecting channels from floodplains, impoundment, water abstraction, flow regulation) on HYMO processes and HYMO variables have been discussed, here we summarise how these changes can influence the three BQEs (more detail can be found in D1.3 *Review on ecological response to hydromorphology,* Wolter et al. 2013 http://www.reformrivers.eu/deliverables/d1-3).

Hydromorphological changes or impacts may set physical thresholds for macrophyte, macroinvertebrates and fish habitat maintenance or utilisation by exceeding suitable physical habitat characteristics, velocities, stream power or depth (Wolter et al. 2013). For fish, limiting thresholds are commonly mediated by swimming performance and accordingly, affect especially weaker performing functional species or age groups like larvae and juveniles (Wolter & Arlinghaus 2003, 2004; Wolter et al. 2004). Sensitive species are the first to be lost from a local species pool leading to the conclusion that efficient river rehabilitation should target the key mechanisms or key bottlenecks for specialist species responding to specific habitat structures, whilst benefiting a broader range of species (Wolter et al. 2013).

Aquatic macrophytes benefit their surroundings in a number of ways, e.g. by stabilising the sediment (Hickin 1984; James et al. 2004), altering the flow velocity regime (Marshall & Westlake 1990; Cotton et al. 2006), increasing water depth (Hearne & Armitage 1993), providing substrate and habitat (Flynn et al. 2002; Weber et al. 2012), trapping sediment (Sharpe & James 2006; Wharton et al. 2006), or increasing habitat complexity (Champion & Tanner 2000). Changes in flow regimes vary in response to climate change (precipitation & temperature) and catchment controls on runoff as topography, geology & land cover vary (Poff & Zimmerman 2010). High flow velocities may prevent plant establishment by forming bars of coarse and nutrient-poor sediments, while in contrast, low flow velocities support sedimentation of fine materials resulting in sediments too loose and unstable for anchoring (Madsen et al. 1993). Preventing plant establishment will have further ramifications such as water quality problems, especially in agricultural areas where high concentrations of nutrients enter the water if there is a lack of riparian vegetation that would usually act as a buffer between agricultural land and the river. This also occurs in urban areas where run off from impermeable surfaces such as roads, roof tops and pavements is one of the main sources of contaminants entering the river and could be reduced by a vegetative buffer strip. Preventing plant establishment can also increase sediment levels entering the water course through erosion or run off from land, intensified by a reducing the physical link between water and air for many invertebrates that are food for fish and have aquatic larval stages, reducing refugia for zooplankton, invertebrates and fish, and reducing spawning areas for many cyprinid fish, e.g. tench, roach, rudd, perch. Instream vegetation should therefore been seen as a vital biological variable within the conservation of rivers.

Benthic invertebrates are the organisms most widely used in freshwater biomonitoring of human impacts (Bonada et al. 2006). Numerous habitat requirements of benthic invertebrates have been compiled within European funded projects like STAR and WISER and went into assessment schemes like ASTERISCS with modules on hydromorphology, general degradation and river zonation. Fishes are comparably long-living, mobile organisms with various habitat requirements, habitat shifts during ontogeny, and functional differences between age groups. Thus, fish also provide a well suited environmental indicator integrating over large spatial and temporal scales (e.g. Karr 1981; Fausch et al. 1990; Dußling et al. 2004; De Leeuw et al. 2007; Schmutz et al. 2007). This integration over space and time, however, causes major variation in local habitat utilization and accordingly in environmental assessments at the reach scale, where most of the river rehabilitation works are applied (e.g. Roni et al. 2002; 2005, 2008; Kail et al. 2007; Palmer et al. 2010; Feld et al. 2011).

Flow refuges are important habitats for benthic invertebrates as they provide shelter from exposure to harsh adverse hydraulic stress conditions (Rempel et al. 1999, Winter-bottom et al. 1997). Refuges provide stable substrate structures and low hydraulic stress conditions in times of increased discharge that have been shown to severely impact benthic invertebrate communities (Lancaster & Hildrew 1993). Milner & Gilvear (2012) observed step-pool reaches providing more flow refuges for benthic invertebrates during high flow events than bedrock, plane-bed, or pool-riffle reaches. One key feature of a suitable hydromorphological environment is the provision of a diverse mosaic landscape offering a wide range of complexity (Garcia et al. 2012).

Unfortunately, flow alterations to meet human demands can result in pressures such as the removal of water through abstractions or increased flow velocity from run-off and efficient drainage systems, or hydropower, all of which cause changes to the HYMO processes such as sedimentation, vegetation encroachment, physico-chemical variables and therefore change channel width, depth and velocity. Furthermore, increased flow will reduce the availability of flow refugia, lowering the diversity and abundance of biota capable of recovering from flooding (Negishi et al. 2002; Lake et al 2007). Consequently, the re-development of habitat complexity addressed by various restoration approaches should always consider flow (Ward & Tockner 2001). Enhancing physical and hydraulic habitat complexity and heterogeneity (the latter often results from the former) by river restoration is commonly sought to improve in-stream biodiversity (e.g. Milner & Gilvear 2012; Palmer et al. 2010). Flow is a key variable that affects fish survival particularly because it influences spawning migrations, habitat shifts, dispersal and habitat maintenance in hydro-dynamically determined environments that are of profound ecological importance and depend substantially on the individuals' capacity for locomotion (e.g. Kolok 1999; Plaut 2001). Knowledge of fishes' swimming performance is prerequisite to assess impacts from inland navigation or hydro-peaking on fish and further serves in designing proper migration facilities for fish. In addition, absolute swimming performance was considered as ecologically most relevant, because the hydrodynamic characters of the habitat represent physical thresholds determining minimum swimming requirements for habitat use to avoid displacement (Wolter & Arlinghaus 2003, 2004).

Larvae and juveniles of freshwater fish essentially depend on the availability of shallow, low flowing shore line refugees for feeding and shelter, and with them the successful natural recruitment of most of the freshwater fishes. In lowland rivers, structural complexity and low flowing nursery areas for fish larvae and juveniles are, in particular, provided in the inner bends of meanders and side waters as well by instream structures like dead wood, roots of the riparian vegetation and aquatic plants (e.g. Grenouillet et al. 2000, 2002, 2004; Duncan et al. 2001; Grenouillet & Pont 2001; Sindilariu et al. 2006). By contrast, in lower mountain and higher altitude rivers aquatic vegetation is commonly absent and pools and large stones are the most important instream structures providing shelter from flow. Here, multiple channels in braided river sections and the formation of islands provide recirculation flows and the necessary low flowing shallow refuges for juvenile fish. For adult fish a decrease of structural habitat complexity has been principally reported detrimental to fish species diversity and composition (e.g. Zauner & Schiemer 1992, 1994; Wolter & Vilcinskas 1997, 2000; Penczak & Kruk 2000; Raat 2001; Wolter 2001, 2008; Rhoads et al. 2003; Vasileva 2003; Aarts et al. 2004; Weber et al. 2011), while its increase has shown increases as well as decreases or no measurable changes of fish assemblages (Smokorowski & Pratt 2007). The latter has been suggested to result from a threshold response of fish to environmental changes (e.g. Harding et al. 1998), respectively, from insufficient spatial scales of measures and/or temporal scales of evaluations (Smokorowski & Pratt 2007). Large fish use deep pools and large wood accumulations as shelter, feeding places, for hiding, resting, and overwintering (Fette et al. 2007, Schwartz & Herricks 2008). River rehabilitation has to consider especially the provision of wake wash protected, low flowing, shallow littoral habitats for juvenile fish recruitment as this is a common bottleneck in regulated multiple use river systems (e.g. Wolter et al. 2004).

Sediment structure and calibre are strongly interlinked with flow velocity. There is a general relationship between the flow velocity and the gravel diameter mediated by stream power, with higher flow velocities able to erode and transport coarser substrate. Thus, sediment transport and sediment size distribution fluctuate with the hydrograph: higher flows support a higher transport rate of coarser material and lower flows support a lower transport rate of finer material. In conclusion, a broad variety of flow velocity patterns within a river stretch supports a mosaic of different substrates, textures and sediment calibres (Wolter et al. 2013). Substrate composition influences benthic invertebrate communities and certain species show substrate preferences or avoidances (Angradi 1999; Buss et al. 2004; Waters 1995). Sediment beds with greater particle sizes can create high quality habitat environments for benthic invertebrates in contrast to sand sediment beds of smaller particle sizes (Duan et al. 2009). The quality and quantity of organic matter in the sediment and the stability of the substrate can alter benthic invertebrate communities (Buss et al. 2004; Jowett 2003), but also the chemical composition of fine sediment (Von Bertrab et al. 2013). Thereby, water flow is the primary driver that determines substrate particle size and subsequently the presence of flow refuges or food sources in interstitial spaces. Substrate composition is also important for gravel spawning fish; their requirement is well oxygenated, permeable gravel beds. Gravel spawning is commonly considered as adaptation of fish to faster flowing environmental conditions by protecting eggs and hatchling from becoming washed away. Lithophilic fish bury their eggs in or lay them on coarse gravel and the larvae live in the interstitial spaces between substrate materials (Balon 1975, 1981). Eggs and larvae of lithophilic fish develop in the gravel layer (Wolter et al. 2013).

Wood and woody debris provide not only important food resources for grazers and shredders by the retention of organic matter (Wondzell & Bisson 2003), they also act as a food source itself for many facultative and obligate xylophagous benthic species, as well as providing a physical habitat (reviewed by Hoffmann & Hering 2000). The local changes in sediment grain size and organic matter content caused by wood assemblages therefore offer a huge variety of meso- and microhabitats for benthic invertebrates. Benthic invertebrates particularly profit from complex habitat structures such as wood in areas where other structures are not available (Strayer & Findlay 2010) and community composition is driven by substrate composition (Entrekin et al. 2009). Submerged macrophytes increase the habitat complexity for benthic invertebrates similar to large wood (Armitage et al. 1995; Kovalenko et al. 2012). This macrophyte-based increase in complexity yields benthic invertebrates assemblages within macrophyte stands which substantially differ from those of silt, sand or gravel substrates (e.g. Armitage et al.

1995). In addition, the increase in habitat complexity due to different macrophyte structures and growth forms can lead to higher species richness.

The heterogeneity of a channel and its flow structure, particularly the presence of low-transit zones and backwaters, controls the downstream displacement of fish and determines the availability of shelter and nursing habitats (Sukhodolov et al. 2009). As a result, a complex mosaic of flow-protected habitats, gravel bars, large wood deposits, diverse sediment structures, and scour pools, is pivotal for maintaining diverse, self-recruiting, and native fish assemblages in rivers (Pearsons et al. 1992; Jungwirth et al. 2000; Bardonnet 2001; Schiemer et al. 2003; Armstrong & Nislow 2006). In many instances, urban river banks and beds are artificially modified to reduce erosion and substrate movement by the exchange of natural substrate to a more firm, man-made substance and in some cases a lining of the river bed will be completed through a dense urban area (Rocha et al. 2004). This is also the case for navigable water ways and results in homogenisation of rivers and riverine habitats as well as dramatic losses of habitat structures, habitat complexity and of freshwater biota, such as fish and invertebrates. Wetlands and floodplains are associated with the lateral dimension of a river system (riverine-riparian-floodplain) (Ward & Stanford 1989), but many have been disconnected through channelisation, embankments and similar physical modifications. to support urbanisation, navigation and flood protection (Junk et al. 1989; Diester 1994; Tockner et al. 1998; Toth et al. 1998; Junk 1999; Tockner et al. 1999; Tockner et al. 2000; Buijse et al. 2002; Schneider 2002; Tockner et al. 2009). Common consequences are disruption of lateral and longitudinal connectivity, loss and changes of habitats, disturbance to flora and fauna, increased peak discharge, frequency of floods, and fishery depletion. Abandoned channels and riparian wetlands that are not permanently connected to the main river channel may suffer from interrupted species drift (Pan et al. 2012). Therefore, hydrological connectivity with the main channel needs to be maintained where possible, to enable constant species turnover and high benthic invertebrate diversity. Pan et al. (2012) proposed that abandoned sections need to be connected, e.g. by flooding, at least once within three years when other anthropogenic impacts are low, otherwise more frequently, e.g. once every year. Preserving and protecting river floodplain and wetlands can offer a degree of protection by buffering of climate change impacts and is often more effective and costs less than a system of traditional dikes and levees.

2.9 *Scope for synergies between cross-sectoral river services and ecological requirements*

Multiple benefits can be achieved by integrating management across social, environmental and economic dimensions. Incorporating synergies into river restoration involves optimisation of delivery of ecosystem services from all sectors (delivery of the primary societal and economic services whilst improving aesthetics and saving money) while improving ecological features and enhancing habitat. For example, fencing of the riparian zone to prevent access to cattle can benefit riparian vegetation and associated terrestrial fauna – but also benefit aquatic systems by intercepting sediments and nutrient flow from the land (Naiman & Decamps 1997; Pusey & Arthington 2003). Moreover, fencing can generate financial benefits to private business (e.g. preventing cattle from straying Ross et al. 2011), which in turn can improve social acceptability (and cost effectiveness) or conservation actions that benefit both terrestrial and freshwater ecosystems (Adams et al. 2014).

Synergistic interactions between sectors to benefit river restoration is limited at present because of both weak governance and technical capabilities. Technical barriers to integrated cross-sectoral planning are substantial, related partly to limited data and poor understanding of drivers of each sector and thus cross-sectoral threats as well as indirect effects of actions, and partly to the inadequacies of decision support tools (Adams et al. 2014). Harmonising synergies for 'win-win' benefits for river restoration between sector/human needs while improving ecological features and enhancing habitat does not come without trade-offs, especially when climate change is considered. Synergies in river restoration occur when benefits can be found for both ecosystem services and the environment, whereas a trade-off occurs when one changes at the expense of another (Bennett et al. 2009). For example, managers of freshwater ecosystems face decisions that result in conflicts about abstraction from rivers and lakes for drinking, irrigation or industry that can conflict with services that depend upon stream flow or depth, such as fisheries maintenance (Rodriguez et al. 2006). Land use decisions are often based on immediate societal needs, without fully weighing up the potential ecosystem consequences and can result in unintended ecosystem services trade-offs (Palmer & Filoso 2009; DeFries et al. 2004). Trade-offs among services are not always explicit, they can occur unintentionally and without our knowledge (Tilman et al. 2002; Ricketts et al. 2004; Rodriguez et al. 2006), especially as ecosystem services can be linked, but may respond in different or similar ways to changes in environmental pressures (Mitchell et al. 2013; Raudsepp-Hearne et al. 2010).

Identification of the drivers, synergies and trade-offs allows policymakers to better understand the hidden consequences of preferring one ecosystem service to another, including ecological implications (Haase et al. 2012). Understanding the links between ecosystem services and ecological implications (WP1.3) will enable successful integrated planning to produce multiple benefits. Failure to plan across the full array of ecological and socioeconomic co-benefits can have undesirable and unanticipated consequences (Adams et al 2014). Making changes to a river in one area might detract from actions in another, for example, the construction of artificial wetlands that likely benefit freshwater species while altering the composition of terrestrial communities (Ernst & Broks 2003), or the use of herbicides for terrestrial weed control that have detrimental impacts on aquatic fauna (Rybicki et al. 2012).

Integrated, win-win, approaches are now emerging in river restoration and cross-sectoral interactions, and are supported by various policy documents, for example, synergies between flood-risk and river water management or between hydropower development and restoration of longitudinal connectivity for fisheries. Flood-risk management is probably the policy with the best potentialities for synergies with other aspects of water management, provided that adequate strategies are implemented (CIS 2007). In some cases, traditional engineering solutions (dams, channelisation or dykes) did not delivered the expected results. The occurrence of floods cannot be reduced completely and the consequences of future floods are likely to have an increasing social and economic impact. Moreover, the prioritisation for locating flood defences to protect particular sites or land uses is being reviewed. Thus, integrated flood-risk management is now focussed on prevention, protection and preparedness (including forecasting). In this framework, making space for river and coastal flooding in the areas where the human and economic stakes are relatively low, represents a more sustainable way of dealing with floods. The conservation and the restoration of the natural functions of wetlands and floodplains, with their ability to retain flood waters and reduce the flood pulse, i.e. working with natural processes, are a key feature of this strategy, thus allowing important opportunities for synergies with WFD implementation gains. Similarly, considerable opportunities arise between restoration of longitudinal connectivity and hydropower development, especially to improve fish passage across existing barriers created by a legacy of agricultural and industrial development. As part of the licensing of run-of river hydropower schemes, the developers should seek options to first maintain and second improve fish passage easement past the obstruction, especially if it is a partial or total barrier to movement. Such actions will open up areas of catchments to migratory fish that, in some cases, may have been excluded for many years as a result of historical developments. Such approaches can be seen as opportunistic but they meet the WFD requirement of addressing barriers to longitudinal connectivity and improving ecological status of fisheries in the upstream affected reaches. As part of such actions, it is essential that sufficient flows are allocated to the fish passage facility to allow all-year-round migration and there is no depleted reach associated with the scheme. Additional attention will also be required to ensure upstream migrating fish are not attracted to the turbine discharge or downstream migrating fish do not pass through the turbines where they are prone to high mortality.

3. Nature based restoration solutions

3.1 *Natural flood defence measures*

Nature based restoration means working with natural processes, including managing flood risk by restoring and emulating the natural regulating function of catchments, rivers and floodplains (Figure 3.1). There is concern over the growing number of major flood events of rivers across Europe and because it is expected that the flood damage will increase during this century, there is an increasing societal demand for flood protection. Over the past years, two EU Directives have been introduced that are relevant for ecological rehabilitation and flood protection, respectively, the WFD and EU FD. Both directives have major implications for management of rivers and because of this, there is a requirement that measures for flood reduction and ecological rehabilitation are combined.

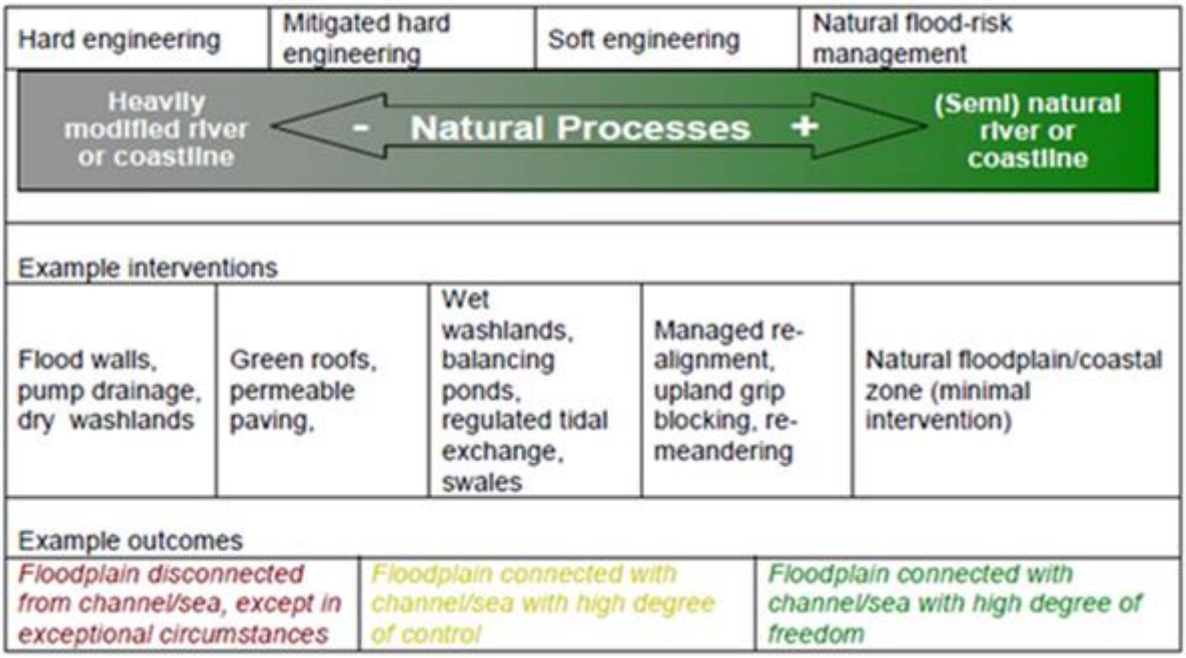

Figure 3.1. A conceptual model of "working with natural processes" (Environment Agency 2010).

The introduction of the WFD in 2000 has had a major impact on the water management practices in member states. The importance of a healthy river system was acknowledged and ecological objectives were set. All surface waters in Europe should have a good ecological status or maximum ecological potential by the year 2015, with a maximum delay to 2027 (2000/60/EG, Water Framework Directive). To reach this good ecological status, many rivers and streams need to be rehabilitated to a more natural state to recover habitats for native aquatic species.

Similarly, the Flood Directive (2007/60/EG, Flood Directive) has a large impact on the management of rivers. For the future, it is expected that flood damages will increase due to changes in climate as well as growth in numbers people and wealth in flood-prone areas. This is a growing concern because severe flood events still regularly occur in

Europe. Depending on the climate scenario, the expected annual flood damage in the EU27 is projected to be €14-21.5 billion by the end of the century (Feyen et al. 2012). The Flood Directive requires member states to make flood risk maps for all flood prone areas with possible solutions to prevent or mitigate flood damages. The aim of this directive is to reduce and manage the flood risk on human health, the environment, properties and infrastructure.

Over the past decade, it has been increasingly recognized that attempts to control rivers through hard engineering activities may be counter-productive in the long term, and that more natural flood defence/protection measures may offer the best return in terms of societal benefits from flood control, water quality and sustainable economics. In this context, the terms "natural flood defence" or "natural flood management" are often used when a specific set of measures reduces flood risk and improves natural floodplain functioning at the same time (Blackwell & Maltby 2006; WWF a, b. without year). The measures are preventative flood reduction measures that aim to both reduce the flooding probability and minimise the potential damage. In 2006, the "Ecoflood guidelines" were published, which promote the use of floodplains as natural flood defence measures, while at the same time optimising other compatible functions and values through conservation and restoration (Blackwell & Maltby 2006). In general, natural flood risk reduction measures aim to increase the retention capacity of upland areas storage capacity of floodplains or discharge capacity of river channels.

A variety of natural flood defence measures have been applied in projects across Europe (see case study examples in D5.3 Part 2) and specific techniques are described in Table 4. For example, natural measures using land to temporarily store flood water away from high risk areas, reconnecting rivers to their floodplains, restoring degraded peat bogs or blocking artificial drainage channels, lengthening watercourses to a more natural alignment and reforesting floodplains will also help to slow run-off and increase infiltration (Table 4; Environment Agency 2010).

The possibilities and effectiveness of these categories of natural flood defense measures will vary for different river types. Approaches should complement and extend the life of traditional defences, whilst working with natural processes to provide a wider range of other benefits, from creating new habitats and enhancing biodiversity, to providing large expanses of green space for recreation and amenity. In urban areas green roofs, permeable paving, surface water attenuation ponds, opening up and realigning watercourses, and establishing blue corridors are equivalent examples (Table 4; Environment Agency 2010). Natural flood risk reduction measures are non-technical measures that contribute to the restoration of the characteristic hydrological and geomorphological dynamics of rivers and floodplains and ecological restoration. Changes in land use are often needed for the implementation of these measures. Therefore, spatial planning and stakeholder involvement are of vital importance when implementing a natural flood defence scheme.

Table 4. Description of techniques for working with natural processes to manage flood risk (Adapted from Environment Agency 2010).

Technique name	Catchment location	Techniques description	Aim
Land and soil management activities to retain / delay surface flows	Upper / middle	Field scale activities include; tree planting, reduced stocking densities, moving gates and water troughs, planting cover crops, contour ploughing, maintaining soil quality.	Retain
Moorland grip blocking to slow run-off rate	Upper	Blocking previously dug drainage ditches ("grips") to allow peat bogs to re-wet.	Retain
Woody debris dams on streams and tributaries	Upper / middle	Naturally occurring or induced in-channel dams of woody debris and vegetation.	Store
Field drain blocking, ditch blocking	Middle / lower	Deliberate blocking or impeding the flow of water along field drains and field ditches to raise water levels and increase field storage / detention potential. (cf moorland grip blocking).	Retain
Land use changes – arable reversion	Upper / middle / lower	Reversion of arable fields (or part fields (buffer strips)) to pasture to improve soil infiltration rates and reduce surface run-off.	Retain
Flood plain woodland, re-forestation	Upper / middle / lower	Creating or re-instating floodplain woodland to intercept out of channel flows and encourage infiltration.	Retain
Creation or re-instatement of a ditch network to promote infiltration (swales, interception ditches)	Middle / lower / urban	Maintained road and track-side ditches to intercept overland flow and detain field and road drainage.	Retain
(Cessation of) in-channel vegetation management	Middle / lower	Alteration of channel vegetation maintenance regime to selectively promote in-channel vegetation growth.	Store
Floodplain reconnection	Middle / lower	Removed or lowered river embankments or new spillways to reconnect river channel to floodplain.	Store and discharge
Selective bed raising / riffle creation	Middle	Technique used to repair damage from over dredging. Mimics a natural process to the extent that it aligns with the rivers natural sedimentation cycle.	Discharge
Washlands	Middle / lower	An area of floodplain that is allowed to flood or deliberately flooded for flood management purposes. (cf. Flood storage areas and wetlands)	Store and discharge
Wetland creation	Middle / lower	Permanently wet areas where water levels are managed to allow some additional flood storage and high flow detention.	Store

Technique name	Catchment location	Techniques description	Aim
On-line flood storage areas	Middle / lower	Engineered flood storage typically involving use of a flood storage embankment and flow control structure to detain out of channel flows and control downstream flow volumes.	Store and discharge
Off-line flood storage areas	Middle / lower	Pond, backwater or off-line bypass channel providing a below surface level flood storage connected to the river by a low bund or overflow pipe allowing the storage to fill during times of high flow and empty through evaporation or seepage or designed drainage back to the main river. Design can allow for a minimum retained water level within the storage area.	Store
Two-stage channels	Lower	Techniques to build additional high flow capacity into a river channel. May involve the creation of wet berms and measures to maintain a narrow low flow channel.	Store and discharge
Flood bypasses	Lower	Divert floodwaters from main channel and reduce discharge	Store and discharge
Re-meandering straightened rivers	Middle / lower	Reintroduction or reconnection of river meanders to delay downstream time to peak.	Retain and store
Permeable surfacing	Urban	Increased areas of impermeable surfacing affect both the volume and rate of (urban) surface water run-off. Permeable paving reduces run-off rates and increases infiltration. See also green roofs / green walls.	Retain
Green roofs / green walls	Urban	Provision of vegetated surface covering (roofs, walls) on impermeable building surfaces in order to intercept rainfall and reduce or slow surface water run-off.	Retain and store
Surface water attenuation ponds	Urban	Engineered water storage areas designed to detain surface water run-off from roads, housing estates etc. Design may involve a retained water level and will include some control on discharge to an adjacent watercourse.	Store
Removal of in-channel constrictions	Rural / Urban	Deliberate removal of artificial constrictions to flow and natural hydromorphology. Could include de-culverting, removal of redundant bridge supports, weirs, or service pipework.	Store and discharge

Important aspects are the presence of floodplains along the main channel (e.g. 'confined' versus 'unconfined' rivers), and the energy and size of the river. In upland areas which receive a large proportion of their water budget from surrounding hill slopes, emphasize on measures that reduce run off (retain) will be especially effective (see Table 5). In the middle section of rivers, the high energy flood flows emerge from the uplands and flow into the lowlands. Without significant buffering of these flood flows there would be extensive damage to the floodplain with erosion caused by the power and turbulence of the water, followed by deposition of the sediments over the floodplain and widespread flood inundation. In this river section, a combination of measures that increase storage and regulate release will be effective. In more downstream reaches, emphasis will be on measures that increase river discharge, in addition to measures that increase storage (Table 5).

Approaches should complement and extend the life of traditional defences, whilst working with natural processes to provide a wider range of other benefits, from creating new habitats and enhancing biodiversity, to providing large expanses of green space for recreation and amenity. In urban areas green roofs, permeable paving, surface water attenuation ponds, opening up and realigning watercourses, and establishing blue corridors are equivalent examples (Table 4) (Environment Agency 2010). Natural flood risk reduction measures are non-technical measures that contribute to the restoration of the characteristic hydrological and geomorphological dynamics of rivers and floodplains and ecological restoration. Changes in land use are often needed for the implementation of these measures. Therefore, spatial planning and stakeholder involvement are of vital importance when implementing a natural flood defence scheme.

Important aspects are the presence of floodplains along the main channel (e.g. ‘confined’ versus ‘unconfined’ rivers), and the energy and size of the river. In upland areas which receive a large proportion of their water budget from surrounding hill slopes, emphasize on measures that reduce run off (retain) will be especially effective (see Table 5). In the middle section of rivers, the high energy flood flows emerge from the uplands and flow into the lowlands. Without significant buffering of these flood flows there would be extensive damage to the floodplain with erosion caused by the power and turbulence of the water, followed by deposition of the sediments over the floodplain and widespread flood inundation. In this river section, a combination of measures that increase storage and regulate release will be effective. In more downstream reaches, emphasis will be on measures that increase river discharge, in addition to measures that increase storage.

The approach to working with natural processes is gradually being reflected in legislation. For example, Box 2 below describes how the concept of ‘natural flood management’ is written into Scottish legislation (Environment Agency 2010). The EU Floods Directive is beginning to take account of floodplains as natural retention areas and the need for flood risk management plans to address non-structural initiatives and the promotion of sustainable land.

Table 5. Suitability of natural flood defence measures in rivers with different types of floodplains.

	Confined		Braided	Lateral migration			Anabranching (low energy)
	Coarse textured	Vertical accretion	Braided	Scrolled	Counterpoint	Backswamp	Organic rich
1. Measures that retain water							
Reforestation	++	++	+				
Restoring upland wetlands	++	++	+				
Managing different types of drains	++	++	+				
Deflection of water current	++	++	+				
Re-meander of river course	++	++	+	+	+	+	
2. Measures that temporary store water							
Setting-back of embankments			++	++	++	++	++
Floodplain excavations			++	++	++	++	++
Flood detention polders			++	++	++	++	++
Flood retention polders			++	++	++	++	++
3. Measures that increase discharge capacity							
Flood bypasses			+	++	++	++	++
Reconstruction of flowing side channels			++	++	++	++	++
Removal of vegetation with high roughness			+	++	++	++	++

3.1.1 Measures that retain water

The principle behind measures that retain water is to increase the capacity to absorb water that infiltrates the soil, and to decrease the amount of water that runs off directly into rivers. As a result, the water levels during peak flows will be reduced, thereby reducing flood risk and the need for structures such as dams. Additionally, water levels will rise during low flow conditions, because the aquifer will release its groundwater at a much slower rate to the river.

Box 2. Natural Flood Management in the Flood Risk Management (Scotland) Act 2009

An aim of the Scottish Government is to create a more successful country, with opportunities for all of Scotland to flourish, through increasing sustainable economic growth. Sustainable flood risk management contributes to this by taking the most sustainable way to reduce impacts to human health, the environment and economic activity both today and in the future. Natural flood management (NFM) is an important part of the sustainable flood management process. NFM is defined as: "*working with or restoring natural flooding processes with the aim of reducing flood risk and delivering other benefits*"

Competent flood authorities have a duty to promote sustainable flood risk management (Section 1(2) (c) (ii) Flood Risk Management (Scotland) Act 2009). In particular, SEPA must assess whether altering (including enhancing) or restoration of natural features and characteristics of a river basin or coastal area could contribute to the management of flood risk. Natural features and characteristics include such things which could assist in the retention of flood water (permanently or otherwise, such as flood plains, woodlands and wetlands) or in slowing the flow of water (such as woodlands and other vegetation), those which contribute to the transporting and depositing of sediment, and the shape of rivers and coastal areas (Section 20(1) & (2) Flood Risk Management (Scotland) Act 2009).

When looking at structural measures to manage flood risk and setting flood risk management plan objectives, competent authorities must consider measures that seek to reduce, slow or otherwise manage flood water by altering (including enhancing) or restoring natural features and characteristics (Section 28(3) Flood Risk Management (Scotland) Act 2009).

3.3.1.1 Upland reforestation

Operative processes

In many countries, most of the uplands have been cleared of their natural forest cover because of historical demands for fuel, building materials and to expand the land available for grazing and agriculture (WWF a,b, without year). As a consequence, only remnants of the native woodlands remain and most of these are in a degraded condition. Native woodlands have a significant effect on reducing storm water run-off and snow melt. Trees intercept both rain and snow but they also absorb moisture from the ground enabling the soil to hold more water during heavy rains. However, in many countries the uplands have been cleared of woodland cover to make way for agricultural use, creating slippery slopes that speed run-off.

Upland woodlands can be described as either hill slope woodlands or gully woodlands. The upland woodlands grow extensively over the hill slopes providing a buffer between intense rainfall and the soils, while gull woodlands provide a buffer between run-off from the hill slopes and the river network (WWF a,b, undated).

Upland woodlands

Upland woodlands create a robust buffer between heavy rainfall and the ground surface. The upland areas of a catchment usually have the highest and most intense rainfall totals and the steepest slopes so are key areas where floods are generated (WWF a,b, without year). Trees provide a deep ground cover which intercepts large proportions of the rain and snow and for broadleaved trees particularly in summer when the leaves are still on the trees. The intercepted rain can be evaporated back into the atmosphere or, more likely in storm conditions, drips off the foliage or runs down the branches and trunks. This creates a buffer for intense rainfall by providing a temporary storage of the rain water. In addition, significant amounts of snowfall can be held on the tree canopies, again providing storage before melt occurs.

The trees also take water out of the soils and release water back into the atmosphere by transpiration. In humid climates, this process results in the soils below the trees having lower water contents than soils with vegetation cover such as grasses. Lower water content results in more rainfall and snow melt being able to infiltrate into the soils during rainy conditions and be held in storage rather than flowing rapidly into the rivers. The trees also help to stabilise soils, provide debris onto the forest flood to reduce overland flow rates and provide shading for the snow which falls off the canopy reducing melt rates.

Without upland woodlands the hill slopes are very vulnerable to intense or prolonged rainfall and rapid rates of snowmelt. Rainfall will rapidly run off the steep slopes with little storage and protection in the short grasses, heathers and tree debris covering the ground. More rapid run-off will concentrate storm waters into main rivers and also increase erosion and landslides, which reduces soil depths and further increases run-off rates (WWF a,b, undated).

Gully woodlands
Gullies are found in most catchments varying from shallow gently sloping features to steep gorge features (WWF a,b, undated). The gullies concentrate water runoff and become the main route for water to flow rapidly off the hills and into the lower valley. They develop where overland flow from heavy rainfall forms a series of small rivulets. When they combine down steeper slopes they erode into the soils to form gullies. Within the gullies there will be a range of active hill slope processes all reacting to the concentrated flows. The channels will be eroding down into the soils exposing rocks and boulders, which in turn form steps and pools along the channel. The side slopes erode to maintain stable gradients as the gully is deepened and the rivulets transport material down the gully.

Through the process of gully formation, flow rates will increase as the gullies grow and collect more surface water drainage from the upper slopes. Bedrock and boulders within the channel will form buffers to break up the energetic flow but they are only successful in the upper gully areas before the rivulets have formed into a single watercourse. Lower down flows in the gullies is highly energetic and turbulent with capabilities of moving large boulders and causing further erosion. This may result in landslides, especially when forest is absent. In this situation, the gully is highly unstable with the potential to discharge the high energy water into the main rivers where there are no robust defences for this type of flood (WWF a,b, undated).

Flood flow down the gullies can be buffered and slowed down if there is mature and dense gully woodland. In this way, gully woodlands function as a buffer between surface run-off and natural water courses in uplands. Gullies, sheltered from the harsh upland weather, are suitable for woodlands to develop. Woodlands filter the rain and provide a series of dams over steep ground, slowing the rush downstream. Woody debris builds up creating pools to slow flood water and trap sediment. Instead, in many places, decades of overgrazing have prevented woodland regenerating round the headwaters; unstable waters wash downstream, deepening the gullies and speeding rapid run-off.

Measures
The first step is to secure a stock fence, which stimulates natural regeneration of trees until they are mature if large herbivores (cattle, deer) are excluded. This may be an effective measure, especially in gullies, as conditions are less extreme at these sites. When rapid regeneration of mature forest is desirable or conditions are too harsh, tree planting with species native to the area and suited to ground conditions is preferable. Within the gullies the trees should be planted more densely to form an interlocking canopy. As a result, woody debris is encouraged to build up and restore natural ponds and dams, which slows down the water flow to the river.

Case study
Glendey demonstration site: further information can be found in D5.3 Part 2 Section 2.1.

3.3.1.2 Restoring upland wetlands

Operative processes
Wetlands are natural sponges that hold immense amounts of water and play a vital role in natural flood management. In upland situations wetlands can be either in-line with the surface water drainage features, i.e. natural water courses either rise in them or flow through the wetlands, or they can be off-line, i.e. separated from surface water courses. In many upland areas natural hollows exist where water accumulates and creates a wetland. Upland wetlands are usually relatively small in size compared to lowland wetlands, but there are many more of them. They are naturally dynamic features filling up with water during intense rainfall but then slowly releasing the water over a period of days after the event. They are a crucial part of the hydrology of an upland catchment acting as buffers to flood flows and providing water reserves during low flow conditions.

In the past, in many upland wetland open drains were dug lo lower the water table and regular maintenance was carried out to keep the drains free-flowing. This has reduced the flood storage capacity of the area, which has resulted in an increased run-off in upland areas with a cumulative effect as the numerous former small wetlands now discharge rapidly into the water course.

Measures
Blocking drains and planting trees can slow the water flow in selected areas. The drain blocking should be carried out by building a series of small leaky dams down the length of the drain forming small reservoirs to trap silt which gradually fills in each section of the drain. The dam should be built from natural materials, either tree debris anchored across

the drain or straw bales anchored by fence posts and woven willow walls. These structures provide temporary dams until trees and bushes have grown substantial enough to replace the artificial leaky dams.

Case study
Glendey demonstration site: further information can be found in D5.3 Part 2 Section 2.1.

3.3.1.3 Managing different types of drains

Operative processes
In uplands, many different forms of drainage may be present, e.g. old forest drains, in agricultural land and along roads. Old forest drains are exposed by forestry clear felling. Often, there are no guidelines on how forest managers should cope with the drains, which soon become active once tree cover is gone, thereby accelerating a greater flow of water into the river. Other types of drainage may also speed the flow towards the river.

Measures
Blocking different types of drains will result in a reduced run-off, restoration of wetlands and increase the sponge function of uplands.

Case study
Glendey demonstration site: further information can be found in D5.3 Part 2 Section 2.1).

3.3.1.4 Deflection of water current

Operative processes
Deflecting the current as a design approach is derived from engineering of navigable rivers. The current is diverted away from the riverbanks into the center by groynes or embankments that extend out into the river channel (Prominski et al. 2012). This serves both to protect the banks and to keep the shipping channel in the middle open. In the context of natural flood defense strategies, this principle is used for the process-oriented revitalization of the watercourse. Using elements that disturb and divert the current creates variation in water flow and thus initiates morphological sediment shifting processes. Pushing the current away from the riverbanks means that hard construction measures such as reinforcing them with stones is unnecessary. The elements that disrupt and guide the current can be installed directly on the banks or in the middle of the river, and purposeful arrangements of several elements can create diversified current patterns; by staggering them, sinuous flow paths can emerge, while two groynes opposite each other create a straight, accelerated currents in the center of the water course. The angle of the groynes, pointing upstream or downstream, is decisive for the direction in which the current will be guided and the creation of aggradation zones or scour holes. It is also crucial whether the groynes are always covered with water or higher than the mean water level: if the river flows over them the path of the water is diverted at right angles to the groyne and a depression is scooped out behind it. If the water flows around the groyne, vortices are created at its end, along with a calm area behind it where sediment deposition can occur. Completely submerged groynes hardly impede discharge during high

water periods, and so if high water levels are already a problem, submerged groynes are preferable (Prominski et al. 2012).

Measures
There are diverse variants of current-deflecting elements such as groynes, large boulders and stepping stones, or dead wood fixed in the river (Prominski et al. 2012); the way they are employed has a bearing on the open space design and ecological added value. Such elements can blend into their surroundings or deliberately contrast with them to accentuate the intervention through the choice of form and material

<u>Dead wood</u> (or large woody debris) occurs naturally in watercourses in the form of entire trees, branches, trunks and root wads, and are of vital importance for many macroinvertebrate and fish species. Over the past century, all tree debris was usually removed from rivers so that the material would not block culverts, bridges and hence cause flooding and damage to infrastructure. This has resulted in increased flow rates, increased sediment movement, incision of the channel bed, homogenization of in-stream habitats and reduced the abundance and diversity of macroinvertebrates and fish.

Tree trunks with or without branches can be installed as current-deflecting elements in a water course. The dead wood is fixed in position, either by embedding it partially in the riverbank or anchoring it in the riverbed with steel cables and stakes. The alignment of the trunk can be at right angles to the current or angled downstream. As a special case, it is possible to fix a trunk at just one end so that it can swing freely in the current.

Case study
Avon Hale and Avon Seven Hatches: further information can be found in D5.3 Part 2 Section 2.5.

<u>Large single rocks:</u> Current diverters in the form of stones are placed in the riverbed either singly or in small groups. Their shapes and the choice of material can easily be suited to the river and its surroundings, for instance by choosing locally occurring types of stone. The rocks must be of sufficient size and weight to withstand the strongest expected current and remain in position. The small-scale flow variations and substrate differentiation allow riparian habitats for aquatic organisms (e.g. macro-invertebrates) to develop.

<u>Groynes:</u> A groyne made of loosely piled-up stones, preferably of various sizes, is relatively easy to construct in forms varying from very narrow spurs that hardly extend out into the water at all to triangular groynes with a broad baseline along the bank that jut out a long way into the river. Groynes can also be made of living woven willow, fascines or diagonally-laid willow branches. Because willows will spread their roots through the construction and keep growing, these natural groynes offer a valuable habitat and refuge for various organisms. The willow functions as a pioneer species; other shrubs follow and establish themselves to further stabilize the groyne which, as a green lining to the riverbank, is hardly recognizable as a technical construction. Combinations of stone or other ‘hard’ materials with living vegetation offer a wide range of design opportunities, although for relatively large groynes there are limits on the use of living materials, as strong currents can only be withstood by solid built constructions.

Submerged groynes or piled stones that are not joined to the riverbank and over which the water flows are very useful for shaping the currents of medium-sized and even large rivers; their angle to the main flow determines the current patterns that emerge and water processes such as flow eddies, aggradation and scour holes.

Riverbed sills
Measures to secure the riverbed and prevent the watercourse from cutting deeper into the substrate can also be used to shape the current. Sills across the river bed, usually made of large stones, can be set at an angle to the main flow and thus deflect and shape it. The flow is always diverted at right angles to a cross-river bar. These sills should be varied in height to create deeper areas with strong currents and shallower, calmer areas in the river. A series of several sills can be staggered on both river banks, so that the alternately angled sills divert the current from one riverbank to the other. At low and medium water levels, the current 'swings' downstream, and the flow distance is longer because the current meanders. These new riverbed sills are of varying heights and thus passable for water organisms, as opposed to engineered ground sills.

3.3.1.5 Remeandering of river course

Operative processes
Many river channels have been historically straightened to increase conveyance, improve navigability or accommodate floodplain development. As a result, the length of such rivers has decreased, resulting in reduced storage capacity, in addition to a stronger slope of the river, which results in an increased river discharge with higher peak flows. When a river is allowed to re-meander again, the length of the river is increased, which decreases flow conveyance, and increases the storage capacity of water in the river channel. Re-meandering can therefore decrease flood risk to sites further downstream, by reducing hydrological response times during periods of high flows. This measure is applicable to river systems that would naturally be expected to have a meandering planform that has been modified (Kondolf and Railsback 2001, Kondolf 2006). Therefore, it is crucial to assess the channel planform and dimensions adequately in relation to catchment characteristics (e.g. grain size, discharge, sediment load, bank material and riparian vegetation).

Measures
In general, three approaches can be used to re-meander a straightened river, viz. (1) creating a new channel and initiating lateral channel migration, (2) allow/increase lateral channel migration or river mobility, and (3) an intermediate method, which combines elements of both these approaches.

Case study

1) Avon Hale and Avon Seven Hatches: further information can be found in D5.3 Part 2 Section 2.5.
2) Skjern: Re-meandering of the river course, further information can be found in D5.3 Part 2 Section 2.2.

3.3.1.6 Creating a new channel and initiating lateral migration

One of the more common techniques for rehabilitating rivers and reconnecting them to their floodplains is to construct a new meandering channel (Cowx & Welcomme 1998; Pess et al. 2005) (see Figure 3.2). This technique is particularly common in Denmark and northern Europe where most rivers are low gradient, highly channelized, and unlikely to return to their historical sinuous channel type without intervention (Brookes 1992; Hansen 1996). Restoring the sinuosity of a stream is done by: 1) pulling back levees and constructing a new meandering channel (rather than allowing the stream to naturally form its own channel as with a levee set back or removal project); 2) constructing a meandering channel adjacent to the straightened channel and then diverting the river into the new channel; 3) if remnants of the original meandering channel exist adjacent to the straightened channel, diverting the

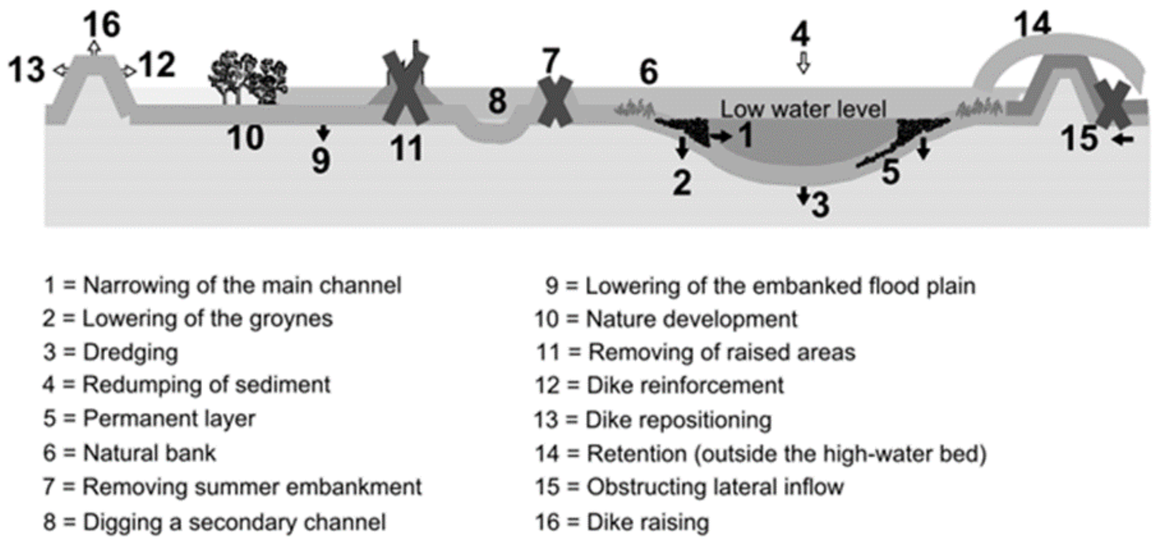

Figure 3.2. Possible natural flood defence measures along regulated lowland rivers to facilitate navigation, flood protection and ecological processes (after Buijse et al. 2002).

straightened channel into its old channel; 4) some variation of these three approaches. Many smaller channels have been straightened and piped, and "daylighting" or exposing these concealed watercourses and then restoring the natural re-meandering pattern is an increasing common technique in urban and agricultural landscapes (Nielsen 1996; Riley 1998). Sometimes in highly incised channels it may not be feasible to aggrade the channel and reconnect it with the historical floodplain; in this case a new floodplain is created by excavating the banks and widening the channels (Cowx & Welcomme 1998). This is often coupled with a two-stage channel design, which incorporates a low flow channel and a new high-flow channel or new floodplain above the low flow channel but below the historic floodplain (Iversen et al. 1993). All these methods seek to reconnect the river with its floodplain, increase the diversity of habitats (mixture of slow and fast water habitats), and lengthen the stream channel (reduce the gradient) (http://www.fao.org/docrep/008/a0039e/a0039e06.htm).

Allow/increase lateral channel migration or river mobility

Instead of creating a new channel using heavy machinery, lateral channel dynamics and migration can be initiated by the river itself (“let the river do the work”). The increase of lateral channel dynamics can substantially enhance habitat diversity even if a meandering planform is not reached. However, this “passive restoration” of rivers potentially causes high sediment loads in the beginning (which may have negative effects downstream like filling pools) and it may take several decades until a meandering planform is reached, especially in streams with cohesive banks or banks reinforced by reeds and dense vegetation.

Intermediate approach

Given the problems and constraints of the two approaches mentioned above, a third, intermediate approach would be to create a new channel with a width, depth and sinuosity well below the values assessed based on the catchment characteristics. Since the capacity of the channel is lower than in its dynamic equilibrium state, the resulting high flows will most probably result in bank erosion and reshaping of the cross-sections. However, sediment output from the restored reach will be considerably less than with the passive restoration approach and a meandering planform can be reached in an engineering time scale. Furthermore, attention should be paid to the importance of riparian forests. Several studies indicate that planting and developing riparian forests may be crucial for the success of re-meandering projects: Flow velocity and depth are typically lower in re-meandered streams, which can significantly increase water temperature if riparian trees and shade are missing (Buckaveckas 2007). Moreover, riparian vegetation would increase bank stability and appeared to be the key to long-term improvements of fish habitat (Klein et al. 2007).

Case study

1) Water retention: Grote Noordwaard, further information can be found in D5.3 Part 2 Section 2.4.
2) Creation of side channels along the Rhine, further information can be found in D5.3 Part 2 Section 2.6.
3) Floodplain excavation: Grensmaas (Border Maas), further information can be found in D5.3 Part 2 Section 2.7.
4) Lower Danube and Danube Delta, further information can be found in D5.3 Part 2 Section 2.8.

3.3.1.7 Measures that temporarily store water

The principle behind measures that temporarily store water is to decrease the amount of water that runs off directly into rivers. As a result, the water levels during peak flows will be decreased, thereby reducing the risk for flooding. For some measures (e.g. flood retention polders), the water can be released during low flow conditions, which will result in a rise in water level during periods with moderate to low flow conditions. The following measures can be applied for the temporary storage of water.

Setting-back of embankments

This measure is only feasible at those river stretches where sufficient space is available, and is impossible where urban development, industrial areas or natural hills border the embanked floodplain. Setting back of embankments enlarges the storage capacity of a floodplain and leads to enlargement and restoration prospects for a floodplain. Although expensive, this measure is a very effective way of resolving bottlenecks for water flow in river systems. The enlarged floodplains can be converted into nature reserve areas, thereby increasing biodiversity of river systems. Set-back embankments are also less prone to erosion of the riverward face due to high velocity flow, but may be more prone to wave damage, because of the increased fetch length.

Flood retention polders

A retention basin is used to manage runoff of storm water to prevent flooding and downstream erosion, and improve water quality in adjacent rivers and streams. Along rivers, wetland areas can be used as flood retention polders. Often, these polders have been cut off from the active floodplain by the construction of main embankments. By incidental flooding these areas during peak flows, the connectivity of the river can, to some extent, be restored. In addition, these wetlands can be used for water quality improvement and groundwater recharge. However, care should be taken for existing nature values, as mesotrophic conditions have often developed in these areas. These habitats are often highly sensitive for river flooding, especially when the river water is loaded with high concentrations of nutrients, silt or toxic contaminants.

Flood detention polders

A detention basin or retarding basin is an excavated area installed on, or adjacent to, tributaries of rivers, streams, lakes or bays to protect against flooding and, in some cases, downstream erosion by storing water for a limited period of a time. These basins are also called "dry ponds", "holding ponds" or "dry detention basins" if no permanent pool of water exists. Some detention ponds are also "wet ponds" in that they are designed to retain some volume of water permanently.

The potential for ecological rehabilitation of specific riverine habitats strongly depends on land use of the area. Often, these areas are used for intensive agriculture, and – hence – possibilities for nature development are limited.

Case study

1) Water retention: Grote Noordwaard, further information can be found in D5.3 Part 2 Section 2.4.
2) Water retention: Polder Altenheim, further information can be found in D5.3 Part 2 Section 2.3.
3) Creation of side channels along the Rhine, further information can be found in D5.3 Part 2 Section 2.6.
4) Floodplain excavation: Grensmaas (Border Maas), further information can be found in D5.3 Part 2 Section 2.7.
5) Lower Danube and Danube Delta, further information can be found in D5.3 Part 2 Section 2.8.

3.3.1.8 Floodplain excavation

Operating processes

Along many regulated rivers, the main channel is not allowed to meander. As a result, the position of the main channel is fixed and erosion as a result of lateral migration of the main channel does not occur. As a result, floodplain height gradually increases due to continuous sedimentation during river floods. In the long-term, this may result in a significant increase of floodplain height, e.g. for floodplains along the River Waal in The Netherlands, it is estimated that the height has increased by 1.7 – 3.8 m over the past two centuries (Middelkoop 1997). Meanwhile, also river incision has taken place, which has reduced the average river water level by 1 – 1.5 m.

Both sedimentation and river incision have negative consequences for river discharge capacity, as well as ecological functioning of floodplains. As a consequence of the increasing height of floodplains, the conveyance capacity of the river is reduced, as well as the volume of water that can be stored during river flooding. Furthermore, floodplains are less frequently flooded with 'minor' floods, which has a negative impact on ecological functioning, e.g. due to decreased possibilities for spawning of riverine fishes in floodplains. Additionally, both river incision and sedimentation have supported a large decline in the ground water table in floodplains, which has resulted in a strong decrease of the area of marshes and floodplain lakes along regulated rivers.

Measures

Excavation of floodplains can increase both the conveyance capacity of the river during floods and the potential for the ecological rehabilitation of riverine systems. With these excavations, minor embankments can also be lowered or removed. This measure will result in a reduced hydrological resistance of the floodplain, and can be combined with the creation of secondary channels and stagnant water bodies. Excavated areas give the potential to develop pioneer vegetation, which has strongly decreased due to the reduction of river dynamics. Additionally, the excavated floodplains will be flooded more often, giving fish species the potential to spawn in these areas. Furthermore, the ground water table in floodplains will be shallower, giving the potential to develop wetland areas, especially when shallow lakes and oxbows are created.

3.1.2 Measures that increase river discharge

The purpose behind measures that increase river discharge is to increase the discharge capacity of the river during peak flow, which will result in lower water levels in river stretches upstream of the location where the measure have been carried out. Care should be taken that this measure does not result in a higher chance for severe floods in downstream areas.

Flood bypasses

Flood bypasses divert floodwaters away from flood-sensitive areas and into less developed lands. A flood bypass is a region of land or a large man-made structure that is designed to convey excess flood waters from a river or stream to reduce the risk of flooding on the natural river or stream near a key point of interest, such as an urban area. Flood bypasses, sometimes called *floodways*, often have man-made diversion works, such as diversion weirs and spillways, at their head or point of origin. The main body of a flood bypass is often a natural floodplain. Many flood bypasses are designed to carry sufficient water such that combined flows down the original river or stream and flood bypass will not exceed the expected maximum flood flow of the river or stream.

Flood bypasses are typically used only during major floods and act in a similar nature to a detention basin. Since the area of a flood bypass is significantly larger than the cross-sectional area of the original river or stream channel from which water is diverted, the velocity of water in a flood bypass will be significantly lower than the velocity of the flood water in the original system. These low velocities often cause increased sediment deposition in the flood bypass, thus it is important to incorporate a maintenance programme for the entire flood bypass system when it is not being actively used during a flood operation.

Similar to flood detention polders, the potential for ecological rehabilitation of flood bypasses strongly depends on land use of the area. Often, these areas are used for intensive agriculture, and – hence – possibilities for nature development are limited. The land is often owned by a public authority and then rented to farmers or ranchers, who in turn plant crops or herd livestock that feed off the floodplain.

Removing vegetation with high roughness
Because dense riparian vegetation slows downstream flow, the water level is higher and the area of inundation during floods is greater for the same discharge, increasing flood hazards upstream while decreasing flood hazards downstream. Therefore, the removal of vegetation at sites with high vegetation roughness may be an effective measure to reduce the risk for flooding upstream of these sides. In addition, attention should be paid that removal of riparian vegetation could result in large changes in channel form (widening, deepening and straightening), especially in 'high energy' rivers with steep gradients. For the Cann River in Australia, clearing of riparian vegetation resulted in a 700% increase in channel discharge capacity and 150-fold increase in the rate of lateral channel migration (Brooks et al. 1999a, b, 2003). Therefore, removal of riparian vegetation with high roughness may be especially useful in low energy, downstream reaches of rivers.

Reconstruction of flowing side channels
Secondary channel networks were once common features on the floodplain of large, gravel-bed rivers (e.g. Rhone River, Rhine River). From an ecological perspective, they are the interface between the river and its floodplain and serve an important function in nutrient exchange, primary production and riparian habitat development. They are also widely used by fish for spawning and rearing, and provide refuge for fish and other animals during floods. From the perspective of flood protection, a well-developed secondary channel network serves to attenuate flood flows in the main channel.

Case study

1) Creation of side channels along the Rhine, further information can be found in D5.3 Part 2 Section 2.6.
2) Floodplain excavation: Grensmaas (Border Maas), further information can be found in D5.3 Part 2 Section 2.7.

3.1.3 Floodplain retention

In recent years, a strategy has been developed that combines measures for flood protection with ecological rehabilitation of rivers (Duel et al. 2002; Geerling et al. 2013). To ensure safe levels for flooding, a strategy that includes cyclic lowering of the floodplains, (re)construction of the secondary channels and setting back vegetation succession (e.g. cutting of vegetation with high roughness, such as floodplain forests) into juvenile vegetation stages may be a solution. These measures may also mimic natural dynamics of unregulated rivers, creating pioneer habitats which have declined strongly because of river regulation. This strategy is called Cyclic Floodplain Rejuvenation (Duel et al. 2002; Geerling et al. 2013).

In a natural river system "room for the river" is created by its own dynamics from time to time. The ecological succession is occasionally set back into juvenile stages due to river dynamics. In these river systems, the main stream rejuvenates the adjacent floodplains by shifting into these floodplains and creating pioneer stages at the opposite side of the main channel. Along regulated rivers, these resetting mechanisms do not occur anymore, because the river is fixed into one channel. This results in a decrease or disappearance of (pioneer) habitats with a young to intermediate 'age' (e.g. Figure 3.3c). By taking measures that rejuvenate the landscape, the landscape composition of these habitats may be partly restored to reference conditions (e.g. Figure 3.3a). This will both enhance the floodplain diversity (creating new pioneer stages) and increase the discharge capacity. Along regulated rivers, secondary channels can be shifted in dynamic parts of the floodplain. When hydraulic resistance is too high, a new side channel is created alongside (parallel to the streamlines). This has two effects. Firstly, the hydraulic resistance on the spot of the new channel has decreased, and secondly, new pioneer stages are created where the old channel was situated.

The scale and frequency of these measures is related to the succession rate and the required decrease of the water levels for both flood protection and ecological development. For the rejuvenation frequency of vegetation, it is important to take into account the development time of vegetation to reach the mature phase. Therefore, the ecological reference condition should also include the different stages of succession (initial/juvenile, mature, degradation/ transition phase). For example, it takes 30-50 years at least for softwood floodplain forests to establish and to develop into its climax stage. After that, the softwood floodplain forests will be in degeneration or transition phase. Consequently, softwood floodplain forests can be rejuvenated after 30-50 years. However, it is recommended to remove not all the softwood floodplain forests after 30-50 years of development time, because softwood floodplain forests in degradation or transition phase provide characteristic habitats for a high diversity of faunal species. Nevertheless, it can be decided that softwood floodplain forests will be removed for safety reasons, because increased vegetation roughness impedes river discharge.

Note that the conceptual graphs (Figure 3.3) are based on a meandering channel form as the reference process/condition. However, the pattern and rate of hydromorphological processes and the resulting landscape composition vary across rivers, and especially depend on river type (e.g. braiding or meandering). Therefore, the shape of the conceptual graphs in Figure 3.3 (viz. the areas of different habitats) needs to be determined separately for each river (stretch). For each river stretch, ideally occurring surface areas or at least minimum surface areas of each element should be defined. The rejuvenation frequency of (parts of) the floodplains depends on the sedimentation rate. When the sedimentation rate is high, the rejuvenation frequency should be high as well. In the floodplain areas where low stream velocities exist during high discharges, increasing the hydraulic roughness due to vegetation succession may have a relatively small effect on the water levels. These areas are suitable for development of vegetation types that need decades to centuries to reach the mature stage of succession, such as hardwood floodplain forests. In parts of a floodplain with high flow velocities during the high discharges, the rejuvenation frequency needs to be higher because of safety. This would occur in natural rivers as well.

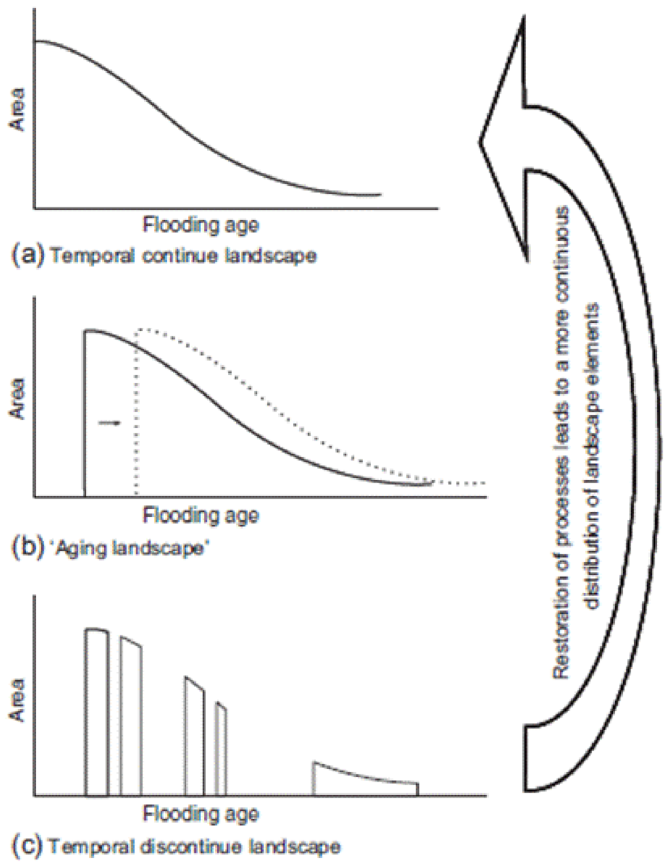

Figure 3.3. Hypothetical area versus age distributions of riverine landscapes. (a) Conceptual graph of hypothetical area versus age distribution along unregulated, meandering rivers; (b) conceptual graph of hypothetical area versus age distribution of natural ecotopes in a regulated river. Existing ecotopes continue their succession, while pioneer ecotopes disappear; and (c) conceptual graph of a hypothetical area versus age distribution of natural ecotopes in a regulated river floodplain without rejuvenation and with natural ecotopes converted to agriculture or other land uses. To restore the landscape diversity, processes must be activated that rejuvenate the landscape and reinstate the continuity of succession stages (viz. change type (c) landscapes to type (a) landscapes).

For Cyclic Floodplain Rejuvenation, measures related to vegetation development of floodplains can be divided in three categories:

- relatively high parts, irregularly flooded, low flow velocities during high discharges;
- relatively low parts, regularly flooded, but the flow velocity is low;
- relatively low parts, regularly flooded often with fast flowing water.

The first category would is most suitable for floodplain lowering and the latter category would be most appropriate for rejuvenation of vegetation where these areas are covered by forest.

3.2 *Inland navigation & options for restoration*

An integrated approach towards Inland Waterway Transport (IWT) and environmental protection is becoming increasing popular. Ecologically-orientated river engineering started on a local scale in the 1980s but is now common practice on many rivers, notably in Austria, Belgium, Netherlands, France, Denmark and Germany (EC 2012). Inland waterway infrastructure planners that have an understanding of the complexities of riverine ecosystems will be better able to develop integrated plans or projects for their sector, which accounts for ecological and other river user's requirements at the start of the design process to search for win-win solutions wherever possible (EC 2012b). Primarily, stakeholders need to reach agreement on both environment and navigation solutions for improvements within the planning stages. The type of restoration measures implemented will depend on local circumstance, such as condition of the river, the type of navigation required in addition to other externalities. Within the '*Guidance document on inland water way transport and Natura 2000'* (EC 2012b), they recommend the following criteria should be applied during the design phase of navigation projects:

- Use a case-by-case approach that considers both the ecological requirements for river sections and the basin-wide scale, and the strategic requirements of IWT at the basin-wide scale when deciding on adequate fairway width and depth;
- "Working with nature" wherever possible through implementation of measures according to given natural river-morphological processes following the principle of minimum or temporary engineering intervention;
- Integrated design of regulation structures, equally regarding hydraulic, morphological and ecological criteria;
- Implementation of measures in an adaptive form (e.g. river bed stabilisation by granulometric bed improvement, low water regulation by groynes);
- Optimal use of the potential for river restoration (e.g. river banks restoration) and side channel reconnection;
- Ensuring that flood water levels are not exacerbated and, ideally, are reduced.

The EU PLATINA project prepared a '*Manual on Good Practices in Sustainable Waterway Planning'* to provide guidance to apply integrated planning principles for IWT planners across Europe (ICPDR 2010). The manual identifies four essential criteria for integrated planning:

- Defining integrated project objectives combining IWT aims, environmental needs and the objectives of other uses of the river reach such as nature protection, flood management and fisheries;

- Integrating relevant stakeholders right from the initial phase of the project;
- Carrying out an integrated planning process to translate the IWT and environmental objectives into concrete project measures, securing win-win results wherever possible;
- Conducting comprehensive environmental monitoring before, during and after the project works to enable an adaptive implementation approach if necessary.

Integrated approaches for inland navigation are especially prevalent in connection with the Danube River and through the Worldwide Association for Waterborne Transport Infrastructure (PIANC). In 2007, the International Commission for the Protection of the Danube River (ICPDR), the Danube Commission and the International Sava River Basin Commission joined forces to initiate an intense, cross-sectoral discussion with stakeholders from different countries, sectors and interests on how to ensure sustainable IWT activities along the two rivers. This led to the adoption of a "Joint Statement on Guiding Principles on the Development of Inland Navigation and Environmental Protection in the Danube River Basin" in 2008 (EC 2012b). The "Joint Statement" is now being used by all range states as a recommendation for:

- Development of the "programme of measures" required by the EU Water Framework Directive;
- Maintenance of the current inland navigation;
- Planning investments in future infrastructure and environmental protection projects.

Integrated approaches to inland navigable waterways should be designed to incorporate restoration for natural key functions such as:

- Morphological processes (erosion, sediment transport and sedimentation);
- Maintenance of the hydrological balance (e.g. flood pulse);
- Provision of habitat (ecological continuum);
- Maintenance of biological and chemical processes (nutrient cycles).

Navigable water ways require suitable depth, clearance, width and velocity, but to minimize impact, measures should be put in place to support the key functions mentioned above. Such measures include:

- Removal of obsolete infrastructures or the modernisation of these infrastructures in a way that helps to improve the river’s ecology;
- Restoration or removal of hard reinforcement structures along riverbanks and the use of more natural embankment techniques;
- Use of alternative groyne types leading to higher dynamics along the river bank;
- Re-connection of side arms, floodplains and ox-bows to restore riverine habitats;
- Creation of a bypasses or floodways to improve structural diversity of the river ecosystems and encourage the passage of fish;
- Use of ecologically orientated maintenance dredging and sediment management techniques;
- Recreation of typical riverine habitats such as floodplain islands or the creation of soft side channels to increase the range of natural habitats available for local wildlife.

It is essential that each project is planned on an individual basis and goals are developed to the rivers specific condition, ecological processes and navigation needs. Conversely, common ground cannot always be found between societal and environmental interests, the importance of some maybe ranked higher than others, depending on site specific interests.

Case studies

1) The River Waal, The Netherlands, further information can be found in D5.3 Part 2 Section 2.2.1.
2) The Danube, East Vienna, further information can be found in D5.3 Part 2 Section 2.2.2.
3) Germanys, River Moselle, further information can be found in D5.3 Part 2 Section 2.2.3.
4) Germany, River Main, further information can be found in D5.3 Part 2 Section 2.2.4.
5) Flood-spillway Rees, Germany, further information can be found in D5.3 Part 2 Section 2.2.5.
6) Modification of groynes at Elbe riverbanks (DE), further information can be found in D5.3 Part 2 Section 2.2.6.
7) River Spree, Berlin, further information can be found in D5.3 Part 2 Section 2.2.7.
8) Canal Oder-Havel-Kanal, Eberswalde, further information can be found in D5.3 Part 2 Section 2.2.8.

3.3 *Concluding remarks*

River restoration projects in Europe are widespread and diverse. The assessment of case studies (D5.3 Part 2) has given new insights into practical approaches to improve ecological restoration when modifying rivers for flood protection or navigation motives. Overall, the following conclusions can be made:

- A wide variety of natural flood defences are available, which successfully combine flood protection and ecological rehabilitation of rivers;
- The effectiveness of these measures strongly depends on the river type, position along the river (upstream, middle reach, downstream) and width of the floodplains along the rivers.
- The project structure of both ecological restoration and flood protection/navigation projects miss specific objectives and success criteria for ecological restoration and flood protection. Specific objectives with measurable success criteria are important to evaluate the success of the ecological restoration measures. Without these elements, the objectives of projects are too generic and their ecological and flood protection targets are not according to the SMART criteria.
- Flood protection projects can benefit from ecological restoration in the project area, but do not incorporate all elements necessary for ecological restoration projects. The assessed flood protection projects showed that ecology is given more room in the retention areas or discharge zones of the floodplain. However, vegetation development is often restricted by strict roughness criteria to maintain the design discharge capacity. Ecological restoration projects rarely involve flood protection in the project structure, but execution of physical reconstruction measures and subsequent nature development cannot compromise flood protection. In the Avon Seven Hatches case study in the UK, lowering the sluices

for fish migration was cancelled due to concerns on effects on the flood protection level of a town downstream.

- The River Waal as part of the 'Room for the River' project is a multi-benefit project that incorporate opportunities for natural flooding, whilst keeping the channel navigable and improving bankside and floodplain habitats.

4. Non-natured based restoration options

Working with natural processes is a best practise approach to river restoration, but when balancing societal and ecological needs, it is not always practical or feasible. For example, reconnecting a floodplain to reduce the impact of flood water in an urban area is not a realistic option and traditional hard defences may be needed. Furthermore, hard engineered solutions are still required in many areas of synergistic river restoration. For example, fish passes incorporated in to hydropower design and construction will improve fish migration pathways over barriers, whilst society still gains from hydropower production. This leads to a 'win-win' scenario and the cost of the restoration measure can often be subsidised by the sector, in this case the hydropower sector. Current practise has shown that waterway development to meet societal needs can be done in such a way to mitigate potential negative effects whilst actively improving the ecology and natural functioning of the river in a way that benefits both the river and its users. D5.3 Part 2 overviews a number of non-nature based restoration case study examples that include synergistic approaches between societal and ecological needs.

4.1 Hydropower and options for restoration

Hydropower involves two of the most pressing global environmental challenges of modern society – accelerated by biodiversity loss and climate change (Rudberg et al. 2015). The EU and national policies on renewable energy production means hydropower is becoming a significant driver of hydromorphological alterations and loss of river longitudinal connectivity. A synergistic approach is needed between the production of hydropower plants for renewable energy and WFD mitigation measures to restore the ecological form and functioning of rivers. It is therefore important to reduce the impact of existing hydropower plants and carefully plan the sustainability of new ones by incorporating suitable restoration measures. The best mitigation options are:

- Reduce the alteration of natural discharge and change the timing of power generation to more closely mimic natural flow and not be limited to minimum flow conditions;
- Correct protocols for the mobilisation of fine sediments accumulated in the associated reservoir
- Installation of screens and fish friendly turbines to reduce mortality of downstream migrating fish
- Re-establish longitudinal connectivity, e.g. removal of structure (not often possible, especially where impounding structures have heritage value), construction of fish passes or bypass channel.

Restoration options for hydropower tend to be hard engineering solutions such as fish passes, turbine design and screens, with the exception of flow management. These measures should be incorporated into hydropower design or maintenance to produce win-win results. Many of these mitigation measures have been applied with good results, for example, in northern Michigan, Consumer Power worked with government agencies and citizen groups to restore more natural flows to a local river. Fish populations increased, bringing more than $590,000 a year from fisheries into neighbouring communities. A 2004 agreement on Oregon Pelton-Round Butte Project – now jointly owned by Portland

General Electric and Confederated Tribes of the Warm Springs resulted in salmon and steelhead returning to the upper reaches of the Deschutes River for the first time in decades while continuing to supply more than 366 MW of power to customers. A moveable hydroelectric power plant in the Kinzig River provided ecological river improvement and re-established fish migration (further information is provided in section 3.1.1 of REFORM D5.3 Part 2 Case Studies). These integrated approaches are becoming innovative solutions to contribute towards environmentally sustainable hydropower for existing and new schemes whilst remediating much of the damage done by their presence and operation.

4.1.1 Fishpasses/ fishways

The ability of fish to negotiate weir structures will depend not only on the topography of the barrier but also the flow regime and how it has been modified by the hydropower (or other flow regulation) development. Some obstructions may only be passable during periods of high flow or at a particular range of flows. If the flow over the obstruction is reduced either by diverting water through a different channel or through a turbine on the impoundment, fish passage may be delayed or even prevented. Without mitigation, this could potentially threaten the long term survival of natural salmonid and other migratory fish populations (Lundqvist et al 2008), leading to failure to achieve the WFD objectives. Therefore, there is a need to enhance fish passage where migration pathways are impaired. In the UK, this is accommodated under the Salmon and Freshwater Fisheries Act and the Water Environment (Controlled Activities) (Scotland) Regulations 2005. Where it is considered that any reduction in fish passage may cause deterioration in ecological class status or that the absence of one is preventing achievement of good ecological status under the EU Water Framework Directive, and more recently must be actively promoted to enable recovery of eel under the EU Eel Regulation. It should be noted that as part of the *GreenHydro* certification, the provision of fish passage facilities at new, or re-licensed, hydropower schemes is insisted in many countries, including France and Germany. According to the Environment Agency's Good Practice Guidelines (EA 2009), a fish pass is required under the Salmon and Freshwater Fisheries Act, in waters frequented by salmon and sea trout if:

- a new impoundment is constructed, or;
- an impoundment is rebuilt or reinstated over half its length, or;
- an existing impoundment is altered physically, or;
- as a result of flow reduction to create an increased obstruction.

Where an existing impounding structure is partially passable, removing flow from it to a hydropower scheme will in most circumstances reduce passage for fish. It may prevent passage altogether, or more likely reduce the window of opportunity for fish to pass. Thus, as a condition of an abstraction license, impoundment license or flood defence/ land drainage consent, a fish pass should be required if the species of fish present will experience increased difficulty completing their life cycles as a result of the hydropower installation, especially if this will lead to a deterioration in ecological status.

4.1.2 Flow management

For any hydropower operation, there is a maximum abstraction limit for power generation, basically to ensure flow variability is maintained in valuable stretches of rivers, for example, to preserve salmonid spawning areas that need essential high winter flows to clean gravels for reproductive success. In addition there is a requirement for flows in downstream reaches to ensure free access of migratory fish, but often this reach has depleted flows because of demand to maximise power generation, which compromises fish recruitment. The flows along each river system must be sufficient to ensure no net deterioration of ecological status under the terms of the WFD. A key approach to integrate freshwater management with ecological sustainability is the provision of 'environmental flows' (Arthington *et al.* 2010; EC 2015). All elements of a flow regime are important, including floods, medium and low flows. Thus setting environmental flows should relate to the quantity, timing, duration, frequency and quality of water flows required to sustain freshwater and estuarine ecosystems and human livelihoods (Brisbane Declaration 2007; Acreman & Ferguson 2010). Hydropower and dam development in general give the opportunity to benefit ecosystem restoration through the provision of suitable flows to enhance the recovery of ecosystem form and function. It requires the magnitude and frequency of short-duration higher flows to be sufficient to maintain channel morphology and river habitats or support restoration measures designed to recover habitat bottlenecks. By working with the dam and hydropower operators there is the opportunity to optimise flow characteristics that support the ecology (often fisheries) without reducing the power production significantly. It requires open dialogue between the hydropower developers and the river planners and managers to understand the operations and motives of both sectors. Methods such as the building bock approach (Figure 4.1) or DRIFT can be applied to establish the flow regimes required to support ecosystem functioning whilst optimising use of water for power production or supply for domestic or agricultural use.
Within the context of hydropower operation, the following good ecological potential flow components, or flow building blocks, should be considered (after UKTAG 2013):

- **Annual low flow:** A flow that is the absolute minimum required to support incubation and development of egg and larval life stages, fry emergence, juvenile salmon and trout survival and non-salmonid species, and also growth which is itself dependent on the ecosystem. This flow should also, where possible, mimic the timing and magnitude of natural low flow periods, e.g. summer dry episodes, which maintain the balance between competitive and stress-tolerant species.
- **Early autumn flood flow:** Important for channel maintenance to refresh channel habitats by redistributing bed surface and sub-surface gravels and cobbles, in particular those used for fish spawning and as juvenile fish habitat and the downstream transportation of accumulations of fine sediment or old macrophyte growth. Also important for inundating wetlands and marginal areas that act as refuge and nursery habitat, although note this function may be degraded in heavily modified lowland rivers where the channel is constrained by levees to mitigate flood risk.

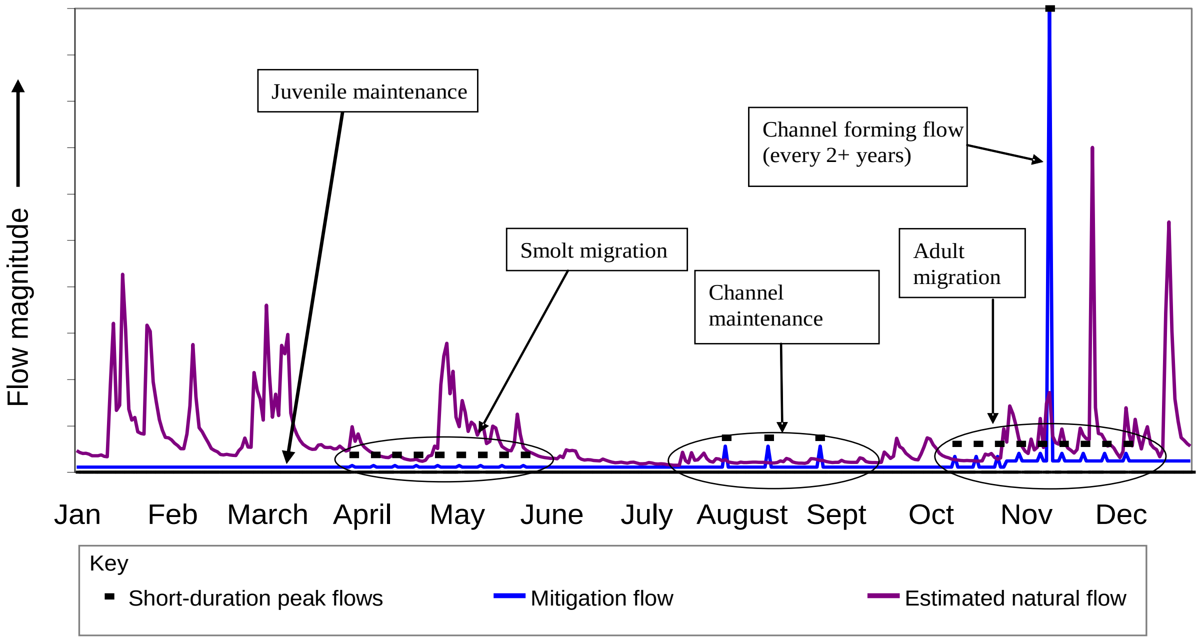

Figure 4.1. Example of a mitigation flow regime for salmonid population conservation based on recommended building blocks compared with the corresponding natural flow regime expected if the water body was not heavily modified.

- **Early autumn flow elevations:** Designed to remove any build up of fine sediment and/or plant debris lying on the channel bed or at the river margins. These flows should refresh gravels ready for optimising spawning conditions.
- **Autumn & winter flow elevations:** Designed to support the migration of adult salmon, trout and river lamprey into rivers and then onwards to their spawning grounds, as well as to support dispersal of juvenile non-salmonid species.
- **Spring flow elevations:** Designed to support downstream migration to sea of salmon and sea trout smolts and support migration of non-salmonid species, including shad and sea lamprey, to spawning areas, and in particular to facilitate migration past natural and man-made obstacles.
- **Out of bank flow:** Designed to allow fish species access to optimal floodplain habitat for spawning and reconnection of floodplain water bodies were appropriate.

Most of the blocks tend to designed to support the different freshwater lifecycle stages of fish, including for migration, spawning and juvenile growth, especially those of conservation importance. However, it should be recognised that each of the building blocks also supports ecosystem functions not specific to fish, such as providing the variability in flow to ensure a balance between competitive and stress-tolerant species.

4.1.3 Turbine design

Turbine design, such as the type of head, number of blades, and rotation speed, is an important factor with respect to survival of fish going through hydropower and pumping station turbines. Horizontal axis, adjustable (bulb) turbines cause the lowest mortality, followed by horizontal axis adjustable (Kaplan) turbines. Vertical axis, fixed (Francis) turbines and impulse turbines (Pelton) have the lowest survival ratios. Consequently, one area of actions is to improve the design of turbines to minimise injury and mortality of fish passing through the units. The Aulden turbine, although not yet commercially adopted, is a promising design.

Ultimately, for most turbines, the only effective way to improve survival is to direct the fish away from the intakes using screens or louvers and then, in both low and high head schemes, through systems which bypass the turbines. Directing more of the flow across spillways or through downstream bypass facilities may also help reduce mortality. These measures may, however, reduce the generating capacity of the plant, particularly in times of low flow. For high head schemes, screening is the only possible solution, although there is usually no need to consider bypass facilities where the intake structures are be above an impassable barrier and fish species tend to be isolated and resident.

4.1.4 Intake and outfall design

Potential impacts associated with erosion, scour and sediment deposition can arise as a result of the intake and outfall locations and design. The design of each feature will vary depending on the surrounding environment and criteria of the scheme, including abstraction properties, site conditions and type of discharge. The location and design of the intakes and outfalls can go a long way to minimising problems with fish entrainment into turbines or disruption of upstream migration of fish, there will usually remain a need to prevent any further likelihood of fish being entrained or diverted away from the optimal migration route, and appropriate screening should also be installed.

4.1.5 Screening

There are two areas where screening may be needed: 1) if mortality of fish during passage through turbines is high, then a bypass or protection system is needed (Godinho & Kynard 2009); and 2) where discharge at the tailrace of the turbine attracts upstream migrants. Damage to fish passing through turbines is a major cause for concern of newly proposed and existing hydropower schemes. To mitigate this problem, a number of solutions are available (e.g. see EA Good Practice Guidelines 2009 and SEPA Good Practice Guidelines 2010). These include intake screens and other bypass systems, including surface collectors and barges, which steer or transport fish away from the intakes. The most common and effective measure to protect fish from entrainment is screening of the turbine water intake, especially in circumstances where a downstream fish pass is not provided or perhaps not necessary (Clay 1995; Kynard 2004). There is also a need to prevent fish that may be attracted to a discharge flow from entering the turbine discharge or being distracted away from the main natural flow (Vovk-Korze *et al.* 2008).

4.1.6 Provision for sediment transport

Hydropower and water resource schemes have the potential to cause accumulation of sediment upstream of the impounding structure, thus disrupting sediment supply to river reaches downstream. Where this is the case, measures should be taken to re-supply those reaches with sediment that occurs upstream of the intake structure. It is recommended that natural sediments are reintroduced to a suitable location downstream that is as close as possible to the intake structure. The accumulations can be returned by:

- designing the intake structure such that high flows move sediments over the impounding structure and into the river downstream;
- operating scour values (although this is not considered realistic at the impoundments associated with small-scale schemes; or
- excavating, transporting and reintroducing the sediments.

SEPA (2010) also recommend that sediment is returned during periods of high flow (to aid redistribution of the sediments), at locations that will not impede the free passage of migratory fishes and during periods that will not interfere with spawning or between spawning and the emergence of juvenile fishes.

4.2 Concluding remarks

A review of measures and assessment of case studies for both nature and non-nature based solutions gives practical insight into synergies that can be evolved when considering socio-economic and ecological needs of rivers. Working with natural processes is becoming a desirable approach to river restoration, especially as they aim to reduce flood risk and maximise benefits and therefore, sequentially reduce the effects of climate change and other anthropogenic activities. Nature-based solutions should be applied and prioritised where possible, nevertheless it is important to understand that this is not always a pragmatic proposal. Soft engineering, and in many instances hard engineering, solutions for restoration will almost certainly still be applied in the future. To conclude, nature-based solutions for sustainable river restoration should be the primary approach where possible, but it is imperative to acknowledge the need for hard engineered solutions in many instances.

5. Tools and models to analyse the potential effects of climate and land use changes on river processes

5.1 *Introduction*

Freshwater rivers are highly complex ecosystems with interrelated processes between physical, chemical and biological components. To stop restoration projects falling short of their objectives, there is a need to demonstrate, quantify and predict the effects of human activities on these components spatially and temporally. This sections overviews a number of tools and models that can be used to analyse the potential effects of degradation, restoration, climate and land use change on river processes to further identify and prioritize suitable restoration measures. It reflects the evolving concepts of restoration that have moved from focus on protection of species towards working with natural processes and ecosystem functioning and ultimately to optimize ecosystem services benefits from restoration practices (Figure 5.1). It is advised that any restoration measures taken are integrated fully into the planning of river restoration (REFORM WP 5.1 - Cowx et al. 2013), to assist project managers with decision making, problem solving and planning strategies for the WFDs PoMs to meet specific environmental and socio-economic objectives in RBMPs.

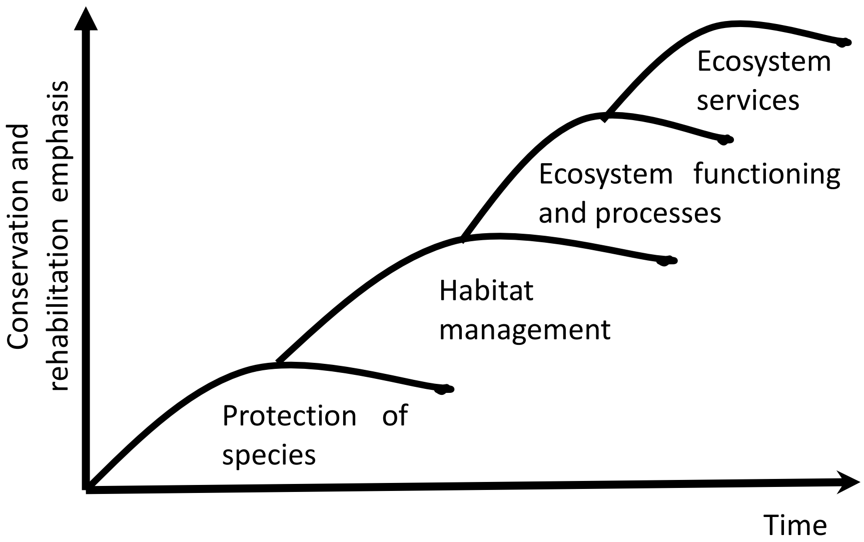

Figure 5.1. Evolution of restoration practices from protection of species to working with natural processes and ecosystem functioning and ultimately to optimize ecosystem services benefits from restoration practices.

5.2 Hydro-economic modelling as a tool to support integrated river basin management

5.2.1 Hydro-economic modelling

This section provides an introduction to the concept of hydro-economic modelling and its potential use as a tool to support integrated river basin management. Hydro-economic models represent regional scale hydrological, engineering, environmental and economic aspects of water resources systems within a single framework (Figure 5.2). Traditional hydrological models dealing with water quantity and flow regimes are extended and/or combined with economic models of water as a scarce resource, and water quality models where hydrology is linked with physicochemical, hydromorphological and ecological conditions. The complexity of interactions between water and the economy can be captured through formal, mathematical models linking relevant hydrological and biogeochemical processes to economic 'laws' of supply and demand underlying the provision of scarce water services (Brouwer & Hofkes 2008).

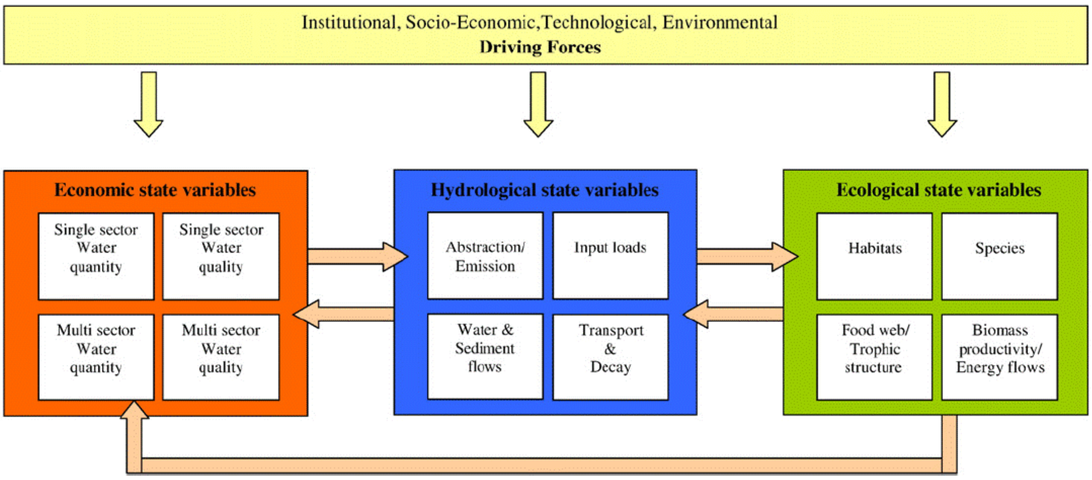

Figure 5.2. Disciplinary dimensions underlying integrated hydro-economic modelling (from Brouwer & Hofkes 2008).

Key methodological aspects of hydro-economic modelling, including model components, choices of model formulation and design, and software implementation are discussed in Harou et al. (2009); a summary of possible approaches including their advantages and limitations is provided in Table 6. Integrated hydro-economic models can suggest least-cost combinations of actions to attain specified goals and examine how alternative choices will affect different interests (Heinz et al. 2007).

Table 6. Some design choices, options, and implications for building a hydroeconomic model. (from Harou et al. 2009).

Options	Summary	Advantages	Limitations
Simulation/optimization			
Simulation	Time-marching, rule-based algorithms; Answers question: "what if?"	Conceptually simple; existing simulation models can be used, reproduces complexity and rules of real systems	Model only investigates simulated scenarios, requires trial and error to search for the best solution over wide feasibility region
Optimization	Maximizes/minimizes an objective subject to constraints*; answers question: "what is best?"	Optimal solutions can recommend system improvements; reveals what areas of decision space promising for detailed simulation	Economic objectives require economic valuation of water uses; ideal solutions often assume perfect knowledge, central planning or complete institutional flexibility
Representing time			
Deterministic time series	Model inputs and decision variables are time series, historical or synthetically generated	Conceptually simple: easy to compare with time series of historical data or simulated results	Inputs may not represent future conditions; limited representation of hydrologic uncertainty (system performance obtained just for a single sequence of events)
Stochastic and multi-stage stochastic	Probability distributions of model parameters or inputs; use of multiple input sequences ('Monte-Carlo' when equiprobable sequences, or 'ensemble approach' if weighted	Accounts for stochasticity inherent in real systems	Probability distributions must be estimated, synthetic time series generated; presentation of results more difficult; difficulties reproducing persistence (Hurst phenomenon) and non-stationarity of time series
Dynamic optimization	Inter-temporal substitution represented	Considers the time varying aspect of value; helps address sustainability issues	Requires optimal control or dynamic programming
Submodel integration			
Modular	Components of final model developed and run separately	Easier to develop, calibrate and solve individual models	Each model must be updated and run separately; difficult to connect models with different scales
Holistic	All components housed in a single model	Easier to represent causal relationships and interdependencies and perform scenario analyses	Must solve all models at once; increased complexity of holistic model requires simpler model components

Harou et al. (2009) provided an overview of published scientific studies applying hydro-economic modelling; the large majority of applications deal with water quality issues, including in-stream and off-stream inter-sectoral water allocation and use (17 studies); water supply, engineering infrastructure and capacity expansion (10 studies); conjunctive use of groundwater and surface water (17 studies); institutions, water markets and pricing (13 studies); conflict resolution, trans boundary management and sustainability (9 studies); managing for climate change and drought (6 studies). Water quality related applications are more scarce (4 studies).

5.2.2 Linking hydro-economic models with water quality and ecological status

From the previous overview, the strong points of hydro-economic modelling are they address water quantity issues and related problems (water scarcity, water allocation for different uses, floods). Because it is possible to link water quantity models with models of nutrients and chemical pollutants it is relatively straightforward to extend application to chemical water quality, addressing problems like eutrophication. For application in river basin management for the EU Water Framework Directive it is necessary to make the link with ecological status, since this is the principle environmental objective that has to be reached. The major pressures responsible for the deterioration of ecological status are physicochemical and hydromorphological derived.

- Pressure-impact relationships have been established for nutrients and in some cases also for chemical pollutants, and can be included in the modelling framework; however, a caveat is that such relationships are type-specific, and it is necessary to differentiate between different river and lake types.
- Water quantity requirements for environmental objectives (e-flows) can be taken on board, but at present this can be done only using extremely simplified

approaches (e.g. assuming that e-flows equate a specific flow percentile – see de Roo et al. 2012 for an example). Full application requires that ecological status is translated in a specific flood regime requiring a type specific approach, which is still a major challenge requiring a type-specific approach. However, when this challenge is addressed in a satisfactory way, including e-flows in the hydro-economic modelling framework will not be difficult.

- For morphological alterations it is difficult to use approaches based on hydrological modelling. Links between ecological status and hydromorphology need to be explicitly clarified before they can be included in hydro-economic modelling in a meaningful way.

In summary it can be argued that hydro-economic modelling is especially suitable to address water quantity issues, but that it is much more difficult to make the link with WFD environmental objectives that are ecological in nature. The main bottleneck in full application of hydro-economic modelling is to integrate type-specific pressure-impact relationships where hydrological regime is linked with ecological status.

5.3 Cross-impact Balance Analysis: Connecting land use, land management, and land cover with river hydrogeomorphology and services provision.

The cross-impact balance analysis (CIB) is a method for analysing impact networks. The method uses qualitative insights into the relations between the factors of an impact network in order to construct consistent images of the network behaviour (http://www.cross-impact.de/english/CIB_e.htm). As part of REFORM Work Package 5.3 "Restoration practices, climate and land use change and flood protection", a Cross-Impact Balance (CIB) analysis hypermatrix was developed, in Scenario Wizard 4.1 (Weimer-Jehle 2013), for land use planners and stream restoration stakeholders to use as a tool to anticipate the potential impacts of possible hydrological changes (reduced permeability and upland storage, increased runoff connectivity) on stream channel morphology, ecological function, and services provision (Slawson 2014).

To understand the procedure, a hypothetical example is described. A hyper matrix (Table 7) was created in Scenario Wizard 4.11, with 14 descriptors, nine of which are primary descriptors and five are intermediate linking descriptors, each having between four and nine possible states. The descriptors and their states were chosen to:

- link Land Use (LU) through Land Management (LM) to Land Cover (LC) to minimize effective impervious surface area (ISA);
- link the impacts of Land Cover changes on stream ecological quality;
- link Land Cover changes to changes in flow and sediment regimes and resulting changes in channel morphology; and
- link the changes in stream ecological quality, regime changes, and channel morphology to the provision of stream channel services.

Table 7. Nine primary descriptors and their states and the basis for determination. Where: Qw = water flow rate, Qsbed = bed material flow rate, + = increase,++ = significant increase, - = decrease, -- = significant decrease, 0 = either or none.

Descriptors:	States:		How determined:
Land Use	urban commerce/industry transportation residential, high density residential, low density	agriculture, row agriculture, perennial /pasture open space, managed undisturbed	Initial state or proposed state
Total impervious area % (LM)	100 80-100 60-80 40-60 20-40	10-20 5-10 1-5 0, vegetated	Measured or selected range based on expert judgment
	100 % connected (=ISA) Highly connected (=0.4ISA^1.2) average (= 0.1ISA^1.5) somewhat disconnected (= 0.04IA^1.7) mostly disconnected (= 0.01ISA^2)	agriculture with no soil conservation practices agriculture with soil conservation practices natural runoff regime, vegetated	Using expert judgment, calculated from urban runoff equations (Sutherland 2000) based on existing connectivity or proposed design, or selected based on agricultural practices
Effective impervious area/Total impervious area % (LC)	0 1-5 5-10 10-20	20-25 25-60 60-70 70-100	Schueler impervious surface area percent ranges (Schueler 2009)
Stream ecological condition	Sensitive (high, good) Impacted (moderate)	non-supporting (poor) urban drainage (bad)	Schueler classifications (Schueler 2009) (with approximate WFD equivalents)
Flow and bed sediment regime changes	Qw++Qsbed+ Qw+Qsbed+ Qw+Qsbed++ Qw+Qsbed0 Qw++Qsbed- Qw+Qsbed- Qw+Qsbed— Qw--Qsbed- Qw-Qsbed- Qw-Qsbed— QwQsbed0 QwQsbed+	Qw-Qsbed+ Qw-Qsbed++ Qw0Qsbed++ Qw0Qsbed+ Qw0Qsbed0 Qw0Qsbed- Qw0Qsbed- Qw++Qsbed— Qw--Qsbed++ Qw++Qsbed0 Qw--Qsbed0	Expert judgment
Channel cross-section	width +-0 depth +-0	width/depth ratio +-0	Schumm channel metamorphosis equations and expert judgment (Schumm 1969)

Descriptors:	States:		How determined:
Channel longitudinal profile	meander wavelength +-0 sinuosity +-0	slope +-0	Schumm channel metamorphosis equations and expert judgment (Schumm 1969)
Channel services	flood control on floodplain storm sewer/channel connectivity water quality biological communities	ecological status reservoir/water stocking navigation energy production	Expert judgment

The directional relationships between the descriptors are then mapped (Figure 5.3) to determine the scale and extent of interactions. In this example, the CIB analysis is simple and most descriptors have low passive and active sums, i.e. the scale and direction of interaction. Land Use is the only completely active descriptor and Channel Services is the only completely passive descriptor.

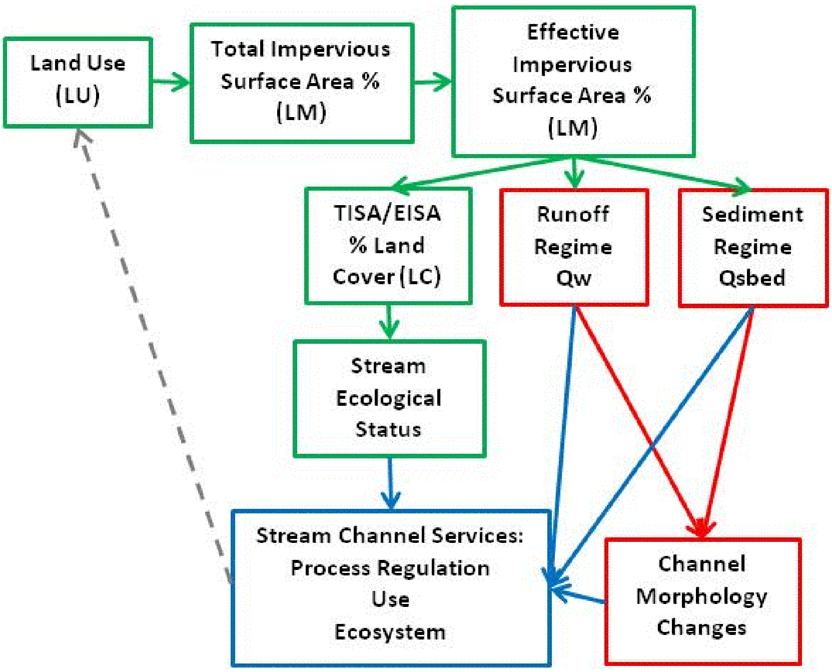

Figure 5.3. Map of CIB analysis descriptor interactions. The dashed grey line is not part of CIB analysis, but rather indicates the possibility of resetting the scenario to achieve different results.

The hypermatrix (linkages) was tested with three scenarios (Box 2) in ScenarioWizard 4.11. The spatial scale is that of the drainage area to the point of interest (POI) in the stream channel. The area is broken into discrete parcels. In the case of a defined parcel only, the CIB analysis is only relevant to the outfall point or reach directly and exclusively affected by that parcel's hydrology. Ideally, the initial state of the drainage basin should be analysed first and then the changes to the parcel may be analysed. In this example, the parcel area equals the entire drainage area to the POI.

Box 2: Example Scenarios

Initial Land Use scenario: perennial agricultural

Parcel area: 15 ha
Total ISA area: 0.75 ha (5%)
Choose agricultural practice: soil conservation agricultural practices
Calculate effective ISA: 0.006 ha
Calculate percent of parcel effective ISA: 0.04%

Planned Land Use Scenario A: traditional high density residential

Parcel area: 15 ha
Total ISA area: 11.5 ha (77%)
Choose effective ISA equation : totally connected EIA = ISA (Sutherland 2000)
Calculate effective ISA: 11.5 ha
Calculate percent of parcel effective ISA: 77%

Planned Land Use Scenario B: high density residential with stormwater best management practices (BMPs)

Parcel area: 15 ha
Total ISA area: 11.5 ha (77%)
Choose effective IA equation : somewhat connected EIA = 0.04 $ISA^{\wedge 1.7}$ (Sutherland 2000)
Calculate EIA: 2.54 ha
Calculate percent of parcel EIA: 17%

The states selected for each land use are given in Table 8. Note that the state selection of "somewhat disconnected (= $0.04ISA^{\wedge 1.7}$)" for the descriptor "Effective impervious area % (LM)" produces an inconsistency in the CIB Analysis of the "Proposed Scenario B: High Density Residential with Stormwater BMPs". Normally for a high density residential land use with traditional stormwater runoff management, "100%" or "high" connectivity states would apply. The "somewhat disconnected" state will only be possible if non-traditional, stormwater best management practices are implemented. The CIB analysis highlights this inconsistency to draw attention to the need for special design, engineering, permitting, construction, and maintenance efforts if this scenario is to be implemented successfully.

Table 8. States selected for the initial agricultural land use and for two variants of the high density residential land use scenario.

Descriptors:	States: Initial Use: Perennial Agriculture with Equilibrium Channel	States: Proposed Scenario A: High Density Residential Traditional Stormwater Runoff Management	States: Proposed Scenario B: High Density Residential Stormwater BMPs
Land Use	agriculture, perennial/pasture	residential, high density	residential, high density
Total impervious area % (LM)	1-5	60-80	60-80
Effective impervious area % (LM)	agriculture with soil conservation practices	100 % connected (=ISA)	somewhat disconnected (= 0.04IA^1.7) INCONSISTENCY
Effective impervious area/Total impervious area % (LC)	1-5	70-100	10-20
Stream ecological condition	sensitive (high, good)	urban drainage (bad)	impacted (moderate)
Flow and bed sediment regime changes	Qw0Qsbed0	Qw++Qsbed—	Qw+Qsbed+
Channel cross-section	width/depth ratio 0	depth+, width/depth ratio -	width+
Channel longitudinal profile	slope 0	slope-	sinuosity-

The CIB Analysis produces impact scores for the effects of hydrogeomorphology and stream quality changes on the provision of stream channel services. Eight services were selected for this analysis. The services were grouped as follows:

Process Regulation Group:

- flood control: use of channel and floodplain for stormwater storage. Requires good lateral connectivity with floodplain for floods occurring several times per year.
- storm sewer connectivity: use of channel as part of the urban drainage system/storm sewers. Requires constant discharge capacity over time.

Ecology Group:

- water quality: pollutant concentrations, including sediments. Requires consistent quality (DO, temperature, pH).
- biology: all biology in flowing water. Requires habitat diversity and function.
- ecological status: all regulatory requirements, including WFD ecological status. Requires constant ecological status.

Human Use Group:

- reservoir capacity: all impoundments to store water (water supply, irrigation, power, recreation). Requires constant water volume and quality.
- navigability: use of channel for free flowing navigation. Requires minimum flow for function.

- Hydro-energy capacity: use of fall of water (head) to produce energy. Requires constant head and minimum flow rate.

Table 9 presents the CIB analysis impact scores for two, proposed, high density residential Land Uses with different Land Management approaches on a parcel with an initial use of perennial agriculture using soil conservation practices. Implementation of the initial scenario in the CIB analysis hypermatrix results in a neutral outcome, with a score of 0 for all services, indicating no change. Ecological status was assumed to be good under this initial Land Use scenario

In Scenario A, ecological status will deteriorate (Table 9). Urban pollutants will be carried directly to the stream. Increased energy will lead to erosion of bed habitats and spawning sites. The loss of floodplain connectivity will result in lower habitat and biological diversity. Downstream bed sedimentation may also decrease biodiversity. The loss for the three ecological services is revealed in the CIB analysis with scores of -2 and -4. The reduction in score from zero to -1 for the two process regulation services indicates that these services are now needed. Impacts on use services vary. For one use service, reservoir, the score will be lowered, but for two others, navigation and energy, the score rises.

Scenario B proposes the same Land Use with a very different Land Management approach and, as a result, a different Land Cover and hydrology. The process regulation uses in scenario B have a score of zero, indicating that there may be no loss of floodplain connectivity or no need for an increase in stream channel flow capacity. The ecosystem services have degraded somewhat and the degree of impact on the WFD classification will depend partly on the pre-existing WFD status. If scenario A had been the initial scenario and scenario B were proposed as a retrofit, the ecosystem scores would represent an improvement. The importance of the degradation of use service scores will depend, in part, on the presence of uses. For reservoirs and navigation, there may be some loss of functionality that may require operation maintenance or may preclude the future possibility of this use. However, if the use is not present, then there is no loss.

Table 9. CIB analysis impact scores for two, proposed, high density residential Land Uses with different Land Management approaches on a parcel with an initial use of perennial agriculture using soil conservation practices.

Stream Channel Services	Initial Impact Score: Perennial Agriculture with Equilibrium Channel (Qw0,Qsbed0)	Proposed Scenario A Impact Score: High Density Residential Traditional (Qw++, Qsbed--, d+, w/d-, S-)	Proposed Scenario B Impact Score: High Density Residential Stormwater BMPs (Qw+, Qsbed+ , w+, w/d+, su-)
Flood control	0 Not needed.	-1 Flood control is now needed due to increased flow.	0 May not be needed. Runoff retained in upper watershed.
Storm sewer connectivity	0 Not needed.	-1 Stream channels will now act as stormwater conveyances. Channel incision will reduce floodplain connectivity.	0 May not be needed. No direct storm sewer outfalls.
Water quality	0 Good. No excess sediment.	-2 Degradation due to increased runoff pollutant concentrations.	-1 Possible degradation due to increased runoff pollutants and sediment (turbidity).
Biology	0 Sensitive. Good water quality.	-4 Urban drainage. No biosystem due to poor water quality and increased flow energy. Base flow probably reduced.	-1 Impacted. Some loss of biodiversity due to decrease in WQ (increased temperature) and to loss of bed habitat diversity with increase in w/d.
Ecological status	0 Sensitive; Intolerant species supported.	-4 Urban drainage. Bad.	-1 Impacted. Possible status degradation.
Reservoir capacity	0 If use present, no change.	-1 If use present, decrease in WQ. Elevation control infrastructure possibly at risk.	-1 If use present, decrease in WQ and possible sedimentation.
Navigability	0 If use present, no change.	2 If use is not present, it may become possible with increase in flow and decrease in sediment.	-1 If use present, decrease in flow depth.
Hydro-energy capacity	0 If use present, no change.	2 If use is not present, it may become possible with increase in flow.	1 If use is not present, it may become possible with increase in flow.

CIB Analysis and DPSIR:

The descriptors used in the CIB Analysis example given here are presented in Table 10 in light of the Driver-Pressure-State-Impact-Response (DPSIR) scheme (Gabrielsen 2003) – but see further description of the DPSIR scheme in the next section. The response may be designed to explore synergies between the mitigation of negatively impacted DPSIR elements and new opportunities. For example, floodplain protection or restoration can be designed with parklands and stormwater management and stormwater management retrofits can be designed with passive water recreation and water purification in mind.

Table 10. The CIB Analysis example is put into the DPSIR scheme with some possible synergies identified in the Responses column.

CIB Descriptor	CIB Initial Use State Changes to Proposed Use State	DPSIR Concepts	DPSIR Responses : synergies
Land Use	perennial agriculture to high density residential	**Drivers**	Relocate use, change use; floodplains reserved for recreation
Land Management	soil conservation practices to totally connected ISA (storm sewers)	**Pressures 1, 2** reduced permeability, increased connectivity	Stormwater BMPs coupled with water features with functioning ecosystems (wetlands)
Land Cover	1-5% effective impervious area to 70-100% effective impervious area	**State 1** hydrological cycle completely disrupted	Reduce ISA footprint, retain or plant natural vegetation, riparian buffers with greenways
Stream Ecological Quality	sensitive to urban drainage	**Impact 1** no biosystem	Upland stormwater management retrofits, combined with parklands, water features
Runoff and Sediment Regime Changes	Qw0Qsbed0 to Qw++Qsbed--	**State 2, 3** drastic increase in peak flow and reduction in sediment delivery	*Traditional Responses:* harden channels, construct flood dams and levees *Ecological Responses:* manage most runoff in the uplands, floodplains not to be built upon, permit dynamic channel
Cross-section Morphology Changes	none to width+, width/depth-	**Impact 2** channel incision with water table lowering	Stream channel geomorphology restoration with blue and greenways, room for the river
Long Profile Morphology Changes	none to eventual slope decrease	**Impact 2** Property loss, infrastructure damage	Stream channel geomorphology restoration with blue and greenways, room for the river
Services Effected	**Unchanged** to **Positively:** none **Negatively:** water quality biology, ecological status **New services needed:** flood control, storm sewer	**Impact 3** loss of services, need for new services	Find alternate service sources, construct new service infrastructure, change Land Use and Management policies.

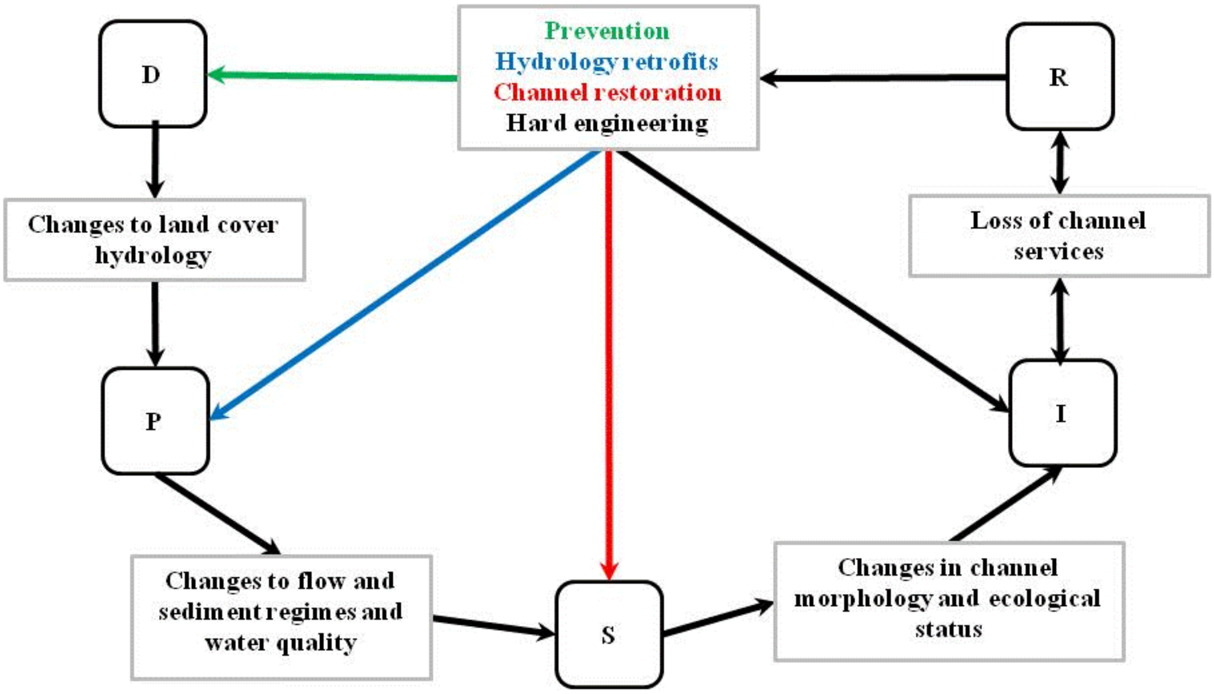

Figure 5.4. The relationships used in the CIB hypermatrix are integrated into the framework to show the dynamic links between the DPSIR elements. Four responses are color-coded to the element each addresses. D = Driver, P = Pressure, S = State, I = Impact, and R = Response. (after Gabrielsen, 2003)

The CIB Analysis hypermatrix can be structured to show the relationships between the DPSIR elements (Gabrielsen 2003). The CIB hypermatrix is designed to help land use planners implement the "prevention" response by directly addressing the Land Use, Land Management, and Land Cover Drivers (Figure 5.4). Planners can also address Land Management and Land Cover pressures with hydrological retrofits in the uplands. Use of the CIB hypermatrix allows stream restoration decision-makers to enter into the framework at the state level. Because channel geomorphological restoration corrects the channel dysfunction state without addressing the causes of the dysfunction, restoration projects should always be designed with the potential future states and impacts resulting from unaddressed drivers and pressures in mind. Hard engineering (or service abandonment) is the traditional Response to Impacts on services and may preserve process regulation and use services, but cannot preserve ecological services and may actually destroy them. Unless potential drivers and pressures are considered before implementing a Land Use change, altered states and undesirable impacts will need to be corrected and the corrections will require on-going maintenance. This is costly and unsustainable. Successful and sustainable stream restoration and long-term Land Use and Land Management planning must go hand in hand.

In summary, CIB balance analysis is a helpful approach that can give a number of options for plausible future scenarios. It is based on a qualitative judgement scale and relies on expert judgement across a number of disciples, the benefit here is that CIB is not data dependant, however, expert judgement can result in bias and strongly influence any outcome.

5.4 *Nested DPSIR*

The DPSIR (Drivers, Pressures, State, Impact and Response) and nested DPSIR frameworks are conceptual tools that can be applied in the project planning cycle at both a catchment and project scale (Figure 2.1 & Figure 5.6). They should be used within the project identification phase of the planning framework (Cowx et al. 2014) to reconcile conflicting interests between societal and the ecological needs of rivers, in addition to land uses change. The nested DPSIR concept map (Figure 5.5) captures key relationships between society and the environment and encourages the decision-maker to think about the challenges at a larger scale, across multiple sectors. As a result it will produce an outcome that can identify multi-benefits by linking the ecosystem approach, ecosystem services and societal benefits that come from these services. At a catchment scale it should be used to identify restoration potential and aid decisions for PoM objectives. At a project scale it will allow appropriate rehabilitation measures to be identified, whilst still considering a river basin scale.

In the first instance, a DPSIR map of concepts (Figure 5.5) is developed that visually aids the decision maker to see complex interactions between all stages in the DPSIR framework, i.e. the interactions between different sectors. It demonstrates how actions cannot be dealt with in isolation by identifying which activities interact with, or impact upon, other activities.

Microsoft PowerPoint or Cmap tools (http://cmap.ihmc.us/) can be used to generate flow charts showing linking concepts.

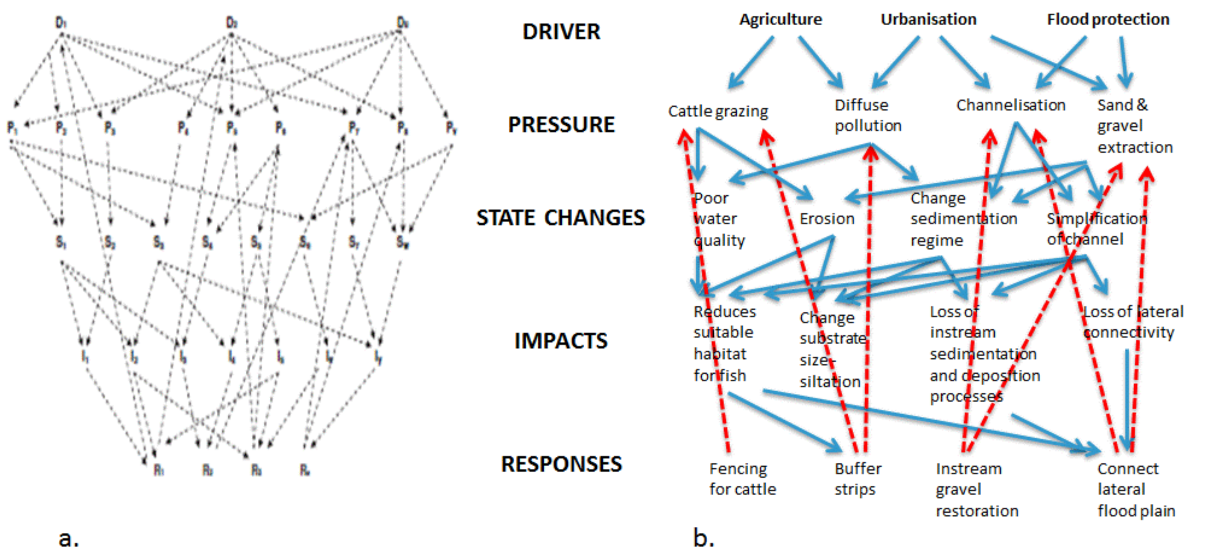

Figure 5.5. The multiple interactions, forward linkages and feedback loops within the nested DPSIR framework (a.). Figure b. demonstrates how it applies to rivers.

The term 'concept' is the sequence of interactions within the DPSIR and can span single or multiple sectors. The generic DPSIR concept map is intended to serve as a starting point from which users may remove or add components relating to their system and chosen restoration. Components can be removed or added to create different concepts to see specific problems in the system and how they can be overcome with little impact and to produce multiple benefits. A DPSIR concept map has several uses within river restoration projects and the decisions process (adapted from US Environment Protection Agency):

- Characterising major pressures, interactions, and trade-offs related to a decision
- Brainstorming or characterising alternative decision options
- Developing measurable endpoints
- Characterising where data, monitoring and research are needed
- Visualising obstacles and options
- Understanding interactions and needs for development of predictive mathematical models
- Concepts can be annotated with notes, documents, maps and other information
- Recording and documenting the decision process
- Enhancing communication with scientists, decision-makers, or the public

The nested DPSIR framework (Figure 5.6) is a development of the original DPSIR (Figure 2.1) and is an integrated approach that can assist decision makers when capturing key relationships between society and the environment. It nests many single DPSIR cycles for multiple Drivers (e.g. flood defence and agriculture) considering two factors (adapted from Atkins et al. 2011):

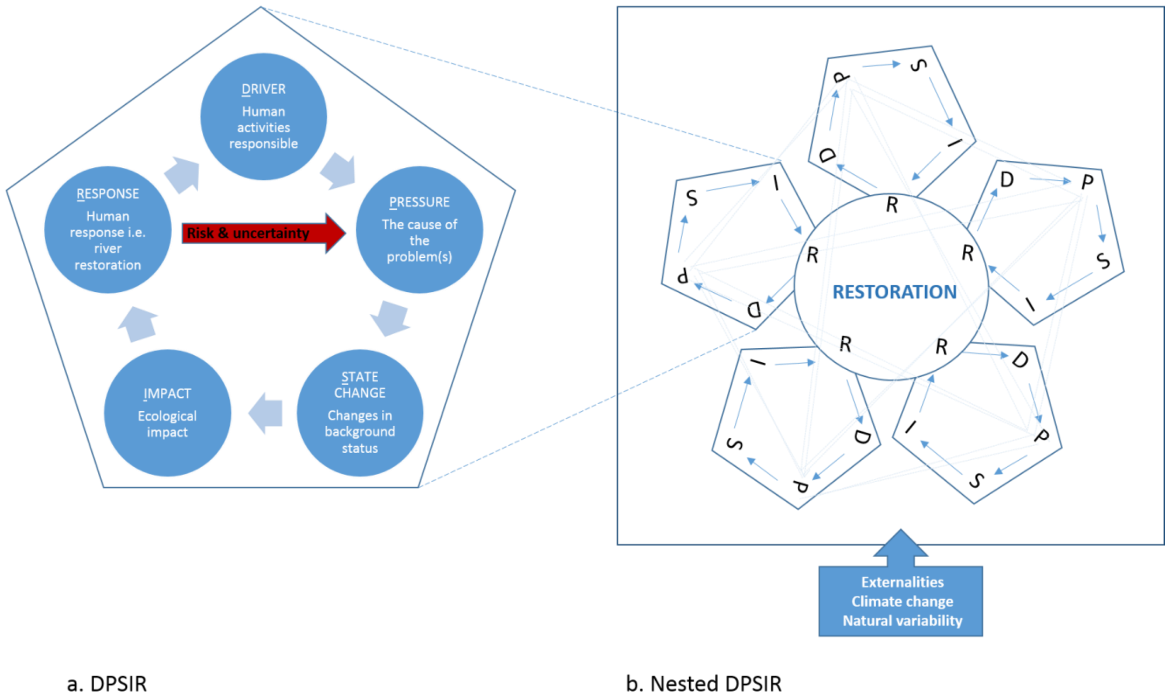

Figure 5.6. A nested-DPSIR framework for the management of fresh water rehabilitation (adapted from Atkins et al. 2011).

- One activity will impact on others, for example protecting cities from flooding by opening upstream flood plain areas will affect the agricultural sector, and the freshwater ecosystem is composed of many sectors each interacting and demanding a share of available resource.
- The framework allows complex interactions between pressures, impacts and responses to be visualised for multiple drivers. Integrating these interactions

allows users to explore relationships and identify measures that can produce win-win scenarios (Atkins et al. 2011).

The development of a nested DPSIR allows decision makers, scientists and stakeholders to characterise major pressures, interactions, benefits and trade-offs related to decision, and to brainstorm alternative decision options. Concepts can be removed or added to see specific problems in the system and how they can be overcome with little impact and to produce multiple benefits, whilst always considering the seven tenets for environmental management, suggested by Elliott (2010). Valuation methods seek to quantify the value of ecosystem services, such that their value can be incorporated into decision analyses or for comparison trade-offs under alternative scenarios. Monetary valuation methods, including willingness to pay, economic markets and non-monetary valuation methods, including multi-criteria attribute theory that are used to quantify stakeholder preferences.

For a win-win scenario the restoration measure should reduce sector pressure(s) without reducing the sectors effectiveness. We take the German River Moselle as an example (D5.3 Part 2 - Case studies Section 2.2.3) to show how different scenarios will produce different outcomes and not all of them will create win-wins. Inland navigation (**D**) requires channelisation (**P**) reducing the heterogeneity (**S**) of the system, in turn, reducing available habitat for fish refuge (**I**). Here an instream wall has been selected as a suitable restoration measure (**R**). For the River Moselle this restoration measure created a 'win-win' scenario because it reduced the impact of wave erosion on the bank, enabling vegetation to grow and creating a sheltered backwater for fish whilst maintaining the rivers navigability. However, for rivers smaller in width, this restoration measure will reduce the efficiency of the navigable channel and other restoration measures need to be considered. Creating a backwater (**R**) could be a restoration option, it would not obstruct the navigable way (**D**), but it would add diversity to the system (reducing **P** & improve **S**), creating cover and habitat for fish (reducing **I**).

In actuality, most scenarios would be influenced by multiple sectors, such as agriculture or urbanisation, and would restrict the possibility of measures. In addition, externalities such as climate change, or other pressures outside of the restoration locations can influence restoration success. It is here we see the complexities arise and a nested DPSIR can be applied to overcome these difficulties. Suitable restoration measure identified at a watershed scale by the nested DPSIR can then be prioritised using the cost-benefit analysis methods in the section below.

In summary, nested-DPSIR is a useful conceptual tool that river managers can use to identify and structure complex relationships between society and the environment. It is easy to use and encourages decision-makers to think about challenges at a larger scale, across multiple sectors. However, in some instances it can be seen as an over simplistic representation of relationship between pressures and state changes (Smith et al. 2014):

- only indicating that pressure leads to state change (which may not necessarily be the case);
- it takes no account of the processes (and hence where to target management), which may lead to state change or of the interaction between different activities and their associated pressures occurring simultaneously;

- it does not highlight the difference in the nature, severity, timescale or longevity of state changes in relation to pressure intensity, frequency or duration;
- complex task to undertake high level or quantitative assessments for management purposes, specific model may not have the resolution to apply a precise mechanism, nor do models currently include detail on habitats.

An improved understanding of the interactions between Drivers, Pressures and States (or, more particularly, the pressure-state change (P-S) linkage) would help to facilitate consideration of possible Responses. This is not something that is specifically provided for by application of the DPSIR approach.

5.5 *Cost Benefit analysis*

An economic cost-benefit analysis (CBA) is an appropriate method for evaluating public water policies, since government interventions are often related to the provision of public goods, having an impact on society as a whole. Such impacts should consequently be valued and evaluated from a societal perspective, not the perspective of the investor only such as a central or local government (e.g. municipality). Restored or 'natural' river corridors typically have the potential to provide a wide range of ecosystem services. It is the wider social value attached to these ecosystem services besides their ecological value that is often missing in information supply supporting river restoration policy and decision-making. CBA is carried out in order to evaluate and compare the various advantages and disadvantages of (alternative) river restoration projects in a structured and systematic way. The benefits from a restoration project are contrasted with the associated costs within a common analytical framework with clearly defined spatial and temporal boundaries. To allow comparison of these costs and benefits related to a wide range of impacts, measured in widely differing units, money is used as the common denominator. Strictly speaking, only those costs and benefits are included in a CBA that can be quantified in monetary terms. This is where usually most problems start for river restoration project appraisal since many effects, in particular ecological benefits, are often not priced in monetary terms. For many goods and services provided by restored or natural water resources, there is no market on which they are traded, and therefore no market price is available, which reflects their economic value. Hence, it will hardly be possible to monetize all impacts at all times. Those impacts that cannot be monetized are therefore often left out of the analysis.

It is important to point out that carrying out a CBA is a multi-disciplinary process, involving expertise from different fields and the input from policy and decision-makers. While economists are involved in all steps, environmental expertise of many kinds is also needed. Policy and decision-maker input is essential when defining objectives the policy measures are supposed to achieve, and when defining the baseline and policy scenarios, including current policy. A key role of the economist in the whole process is to frame the issue and develop the CBA framework so that all relevant socio-economic stakes and stakeholders are included and the multitude of environmental studies that need to be undertaken are working towards answering the following two questions:

1) Is river restoration economically speaking worthwhile, that is, do the benefits outweigh the costs?
2) And if there are alternative river restoration projects available from which to choose, which river restoration project yields the highest net benefit?

Some of the key issues related to the assessment of the costs and benefits of river restoration projects are discussed in D5.2 "Cost-effective restoration measures that promote wider ecosystem and societal benefits" and where possible, illustrated based on practical case studies (Brouwer et al. 2015).

5.6 *Identifying and prioritizing restoration in a watershed*

Decisions in river restoration face a range of conflicts when attempting to plan and achieve their objectives. As previously discussed, restoration project objectives may relate to a number of activities or strategic initiatives and be reflected in terms of societal, political, environmental, financial and economic measures. Thus, it is important to enhance the basis for integrative, multi stakeholder approaches to river restoration at the watershed scale. Involving stakeholders in the decision process to overcome conflicts and reach resolutions is a desirable process and has been used in '*Coos Bay lowland assessment and restoration plan*' (http://cooswatershed.org/publications.html), a good example of watershed assessment where additional, step by step information on planning and prioritisation can be found (Coos Watershed Association 2006). A number of factors need to be considered when prioritising restoration at a catchment or river basin level:

- Develop a communication plan,
- Ensue that the interests of stakeholders are understood and considered,
- Bring together different areas of expertise for identifying and analysing best opportunities,
- Ensuring conflicts are adequately identified.

The prioritisation process scores the top restoration actions to be considered based on a series of ecological and socio-economic criteria. In turn, the development of the initial list of potential restoration actions is based on watershed assessment through the DPSIR Table (Appendix 1) and the nested DPSIR approach as follows (Giannico & O'Hanley 2015):

- Step 1 – DPSIR, Identification of prioritization criteria
- Step 2 - Biological criteria and socio-economic criteria (collection of criteria constitute a filter)
- Step 3 - Restoration actions are scored based on degree they satisfy each creation

Step 1

Use the DPSIR and nested DPSIR approach to identify sector pressures at a catchment scale and how they have changed the ecological status of the watershed. Application of the nested DPSIR at this early stage will allow the drivers of change to be identified and the impacts understood, but more importantly for synergies to ameliorate these impacts to be integrated into decisions making.

Step 2

Outcomes from the DPSIR approach will identify which ecological processes are missing or degraded. This information is then used to build up biological criteria to improve river functioning and socio-economic criteria. An example from Coo Bay is used here (Coos Watershed Association 2006). Biological filters identified are (Giannico & O'Hanley 2015):

- Restore watershed processes
- Restore or improve watershed connectivity
- Remove limiting factors
- Have long lasting effects
- Restore or expand unique habitat
- Have well proven effectiveness.

Socio-economic criteria identified are (Giannico & O'Hanley 2015):

- Have a high likelihood of success
- Provide educational benefits
- Address landowner concerns
- Have measurable effects
- Are likely to be feasible
- Are likely to be funded
- Have an acceptable cost/benefit ratio

A group of experts and stakeholders should jointly decide on the importance of each biological and socio-economic criterion by weighing each criteria within each category (Figure 5.7). It is essential that each criterion has a definition to ensure all decision makers understand the same meaning. For example, 'connectivity' – the action improves or re-establishes habitat connectivity'. In addition, a scoring system and definitions (Table 11 & Table 12) need to be produced and where possible, definitions should be quantitative values such as endpoints (see D5.1).

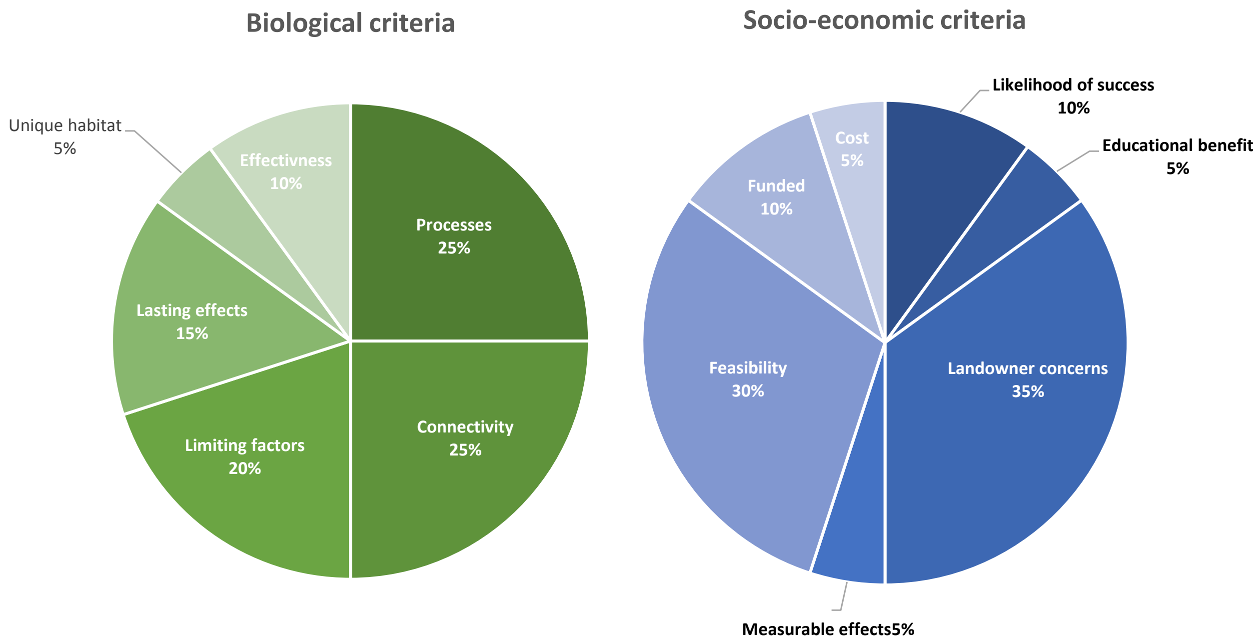

Figure 5.7. Weighted prioritisation criteria (Giannico & O'Hanley 2015).

Table 11. Prioritisation score definitions for biological criteria for coho-salmon (source: Coos Watershed Association 2006).

Biological criteria			**Scores**				
Weight	**Criterion**	**Statement**	**0**	**1**	**2**	**3**	**4**
25%	Processes	This action re-establishes natural watershed processes and maintains functional processes	Does not address any impaired processes	Partially improves at least one impaired process	Significantly improves at least 1 moderately impaired process	Significantly restores at least 1 highly impairs process	Significantly restores 3 or more highly impaired processes
25%	Connectivity	This action improves or re-establishes habitat connectivity	Does not restore any connectivity	Partially restores connectivity for some life stages/species to at least some moderate quality habitat	Significantly restores connectivity for some life stages/species to some high quality or lots of moderate quality habitat	Significantly restores connectivity of most stages/species to a moderate amount of high quality habitat	Restores full connectivity for all life stages for all species to a large amount of high quality habitat
20%	Limiting factors	This action will promote health coho populations by removing one or more limiting factor(s)	Does not address any coho life-history bottlenecks	Addresses one coho life-history bottleneck, but not the primary one	Addresses the primary coho life-history bottleneck, but low to moderate effect on the bottleneck	Has a high likelihood of significantly relieving the primary life-history bottleneck	Has a high likelihood of significantly relieving the primary and secondary life-history bottlenecks
15%	Longevity	The effects of this action will persist into the future	Expected life span ≤10 years	Expected life span 11-25 years	Expected life span 16-50 years	Expected life span 51-100 years	Project expected to be self-maintaining in perpetuity

Biological criteria			**Scores**				
Weight	**Criterion**	**Statement**	**0**	**1**	**2**	**3**	**4**
5%	Unique habitat type	This action will benefit or provide specifically needed or unique habitat types	Does not address any needed or unique habitat types	Partially addresses one needed or unique habitat type	Partially addresses more than one needed or unique habitat type	Completely addresses one needed or unique habitat type	Completely addresses more than one needed or unique habitat type
10%	Proven technique	This action will use a technique proven to be successful or test the effectiveness of a new restoration technique	Technique known not to be effective	Technique unproven but not experimental or innovative	Technique experimental and/or innovative, but efficacy unknown	Technique proven to be effective	Techniques proven to be effective and innovative

Table 12. Prioritisation score definitions for socio-economic criteria (source: Coos Watershed Association 2006).

Socio-economic			**Scores**				
Weight	**Criterion**	**Statement**	**0**	**1**	**2**	**3**	**4**
10%	Likelihood of success	This action is highly likely to fulfil its goals	Not likely to be successful	Small likelihood of success	Project likely to meet some goals	Project likely to meet most goals	Project likely to meet all goals
5%	Educational benefit	This action will provide educational or outreach benefits	No educational or outreach benefits	Few educational or outreach benefits	Local outreach and educational benefits	Regionally prominent outreach and educational benefits	Nationally prominent outreach and educational benefits
35%	Landowner concerns	This action addresses a stated landowner concern	Meets no landowner objectives in the sub-basin	Meets at least one landowner's objective. But may conflict with other landowner objectives	Meets more than one landowner's objective. But may conflict with other landowner objectives	Meets the majority of landowners objective and does not conflict with other landowner objectives	Meets all landowners objectives and will result in a synergistic effect for other projects
5%	Measurability	The effects of this action will be measurable through monitoring	Benefits of the project cannot be measures	Monitoring is possible. But beyond the capacity of the organisation to conduct	Monitoring will be expensive and require long-term study	Monitoring is feasible with known protocols	Monitoring has a high likelihood of leading to publishable results
30%	Implementation feasibility	This action is highly likely to be feasible, and political or social resistance to this action is unlikely	Unlikely to be implementable because of political and social constraints	Has potential to be politically or socially disruptive	Some people in the sub-basin will like the project and others will be neutral or oppose it	Most people in the sub-basin will be supportive of the project	Peoples in the sub-basin and local and political leaders will be supportive of the project

Socio-economic			**Scores**				
Weight	**Criterion**	**Statement**	**0**	**1**	**2**	**3**	**4**
10%	Funding	This action is highly likely to be funded. There are no significant social, political, or other constraints to funding this action	This project is un-fundable	This project is unlikely to be funded by known source	The project can probably be funded from known sources, but might be difficult	This project will likely be funded from known sources	This project is highly likely to be funded from a source we would like to develop
5%	Cost	This action provides an acceptable cost/benefit ratio and is within the abilities of the funding and implementation groups	>$1,000k	$250k-1,000k	$100k-$250k	$50-$100k	<$50k

Step 3
A weighted matrix can be produced to identify realistic and economically feasible options for restoration. The matrix cross references restoration measures against biological and socio-economic criteria. Score (0-4) each of the restoration measures against the definitions provided, decisions for each score can be based on survey data, field knowledge, and experience with landowners. Individual scores for each restoration action are then multiplied by the relative weights of the corresponding criterion and totalled for the two main categories. Using a threshold of two, the aggregated scores for biological and socio-economic criteria were used to determine the level of priority for each action (Coos Watershed Association 2006).

Concluding remarks
Weighted prioritisation matrices are easily understood, simple to apply and have the advantage of allowing various alternatives to be compared numerically. Nevertheless, there are a few disadvantages to this method, mainly because the evaluation procedure depends heavily on the weightings assigned and these can be subjective and open to bias. This can be overcome if scoring is based on existing information, both quantitative and qualitative, and incorporates the opinions of stakeholders, ecological specialists and economists. In addition, weighting matrices do not consider indirect impacts, but incorporating the prioritisation matrix into the early stages of the project planning framework (see WP5.1 & WP6 deliverable) will utilise existing catchment scale information collected on river characterization (e.g. river styles, historical maps) and river condition stage (e.g. DPSIR). Here, physical, chemical and biological aspects of broad-scale processes of freshwater rivers and interfaces between connecting ecosystems, such as natural habitat continuum from upstream to downstream catchments and between river and its surrounding land use will be considered during the scoring.

5.7 Integrating strategies for Programme of Measures

The WFD is a legislative tool that aims to prevent deterioration and improve status by achieving good ecological status (GES) of rivers by 2027 and has the potential to increase the number of restoration schemes undertaken across Europe. It is especially important because almost 60% of European water bodies are currently failing good ecological status (Haase et al. 2013). River Basin Management Plans (RBMPs) are a requirement of the WFD to reach GES through the Programme of Measures (PoM) by 2027. In some cases, where a considerable amount of modification has occurred, the river channel is classified as heavily modified water body (HMWB) and means that a surface water body cannot reach GES and therefore has to aim for 'good ecological potential' (GEP), other water bodies such as canals are further classified as artificial and also aim only for GEP.

The scope of the PoM is to highlight, at a basin level, all measures necessary to meet the environmental objectives of the WFD cost-effectively. The PoM are reviewed and made operational through a number of regulators, therefore, it is important that the planning

Table 13. Prioritisation matrix, biological and socio-economic criteria results (source: Coos Watershed Association 2006).

	Biological criteria							Socio-economic feasibility								Scores	
Criterion weight	25%	25%	20%	15%	5%	10%		10%	5%	35%	5%	30%	10%	5%			
Potential action	Restoration processes	Restore connectivity	Limiting factors	Longevity	Unique habitat	Proven technique	Raw score	Likelihood of success	Educational benefit	Landowner concerns	Measurability	Implementation feasibility	Fundability	Cost	Raw score	Weighted socio-economic	Weighted biological
Channel reconfiguration	3	2	2	4	2	2	15	2	3	1	2	1	3	2	14	1.5	2.55
Ditch maintenance	1	1	1	0	1	2	8	2	2	3	2	2	1	4	16	2.35	0.95
Fish passage	3	1	2	2	1	3	12	2	2	3	2	3	2	3	17	2.7	2.05
Implement farm plans	1	0	0	1	0	1	3	2	2	3	3	3	3	3	19	2.85	0.5
Large wood placement	1	0	1	2	1	2	7	1	1	1	1	1	1	3	9	1.1	1
Levee removal	4	2	1	4	3	2	16	3	2	1	2	1	3	3	15	1.6	2.65
Levee setback	1	1	1	2	1	2	8	2	2	2	1	2	2	2	13	1.95	1.25
Riparian fencing	3	0	1	1	0	3	8	3	2	3	2	3	3	4	20	2.95	1.4
Riparian planting	2	0	2	3	1	3	11	3	2	2	2	2	3	3	17	2.25	1.7
Tide gate relocation	3	2	2	2	2	2	13	2	3	1	2	1	3	1	13	1.45	2.25
Tide gate removal	4	4	3	4	3	2	20	3	4	1	2	0	4	1	15	1.4	3.55
Tide gate replacement	1	1	2	2	0	2	8	2	3	4	2	4	2	2	19	3.35	1.4
Water conservation	0	0	0	1	0	3	4	1	2	0	1	2	1	4	11	1.15	0.45
Wetland creation	4	4	3	4	3	3	21	3	2	1	2	1	4	2	15	1.65	3.65

Implementation would be easier and project would have a high biological return. Project funding available.

Implementation would be easier, but project would have a high biological return.

Implementation would be harder, but project would have high biological return. Partnership and educational demonstration opportunities.

These projects wither have low scores for biological returns and socio-economic feasibility.

leading up to the selection of PoM is clear and developed in association with regulators and other stakeholders. PoM categories for hydromorphological measures are (*REFORM WIKI* - http://wiki.reformrivers.eu/index.php/Category:Measures). Catchment scale planning will provide information on river characterisation, river condition and restoration potential all of which underpin the decisions made for PoM. Application of the DPSIR approach and prioritization matrices will provide a holistic approach to cross-sectoral restoration planning, especially as it will include numerous sectoral interests and needs in addition to improving cross-sectoral communication. For example, it should account for multiple sector policy objectives, such as flood protection, hydropower and sustainable transport, to be integrated. Furthermore, we need to move towards the "Working with nature" concept, a nature based restoration solution by restoring natural processes (EC 2012b). To do this requires (adapted from EC 2012b):

- project objectives that are more holistic in their scope and include an understanding of the environment;
- meaningful use of stakeholder engagement to identify possible win-win opportunities;
- prepare initial project proposals/design to benefit external sectors and nature
- focus on achieving the project objectives in an ecosystem context rather than assessing the consequences of a predefined project design;
- focus on identifying win-win solutions rather than simply minimizing ecological harm.

6. Conclusions and recommendations

Threats to rivers originate mainly from outside sectors, thus sustainable environmental improvement practices must be integrated in to the holistic management plans of (specific) aquatic ecosystems or watersheds. This requires integration of three domains: environment, society and institutions. Unfortunately, in many scenarios these three domains (including scientific research) are disconnected and sustainability is compromised (Cowx and Portocarreo 2011). If these components are to be integrated, river management and improvement measures have to be altered or adapted, which would, *inter alia*, also improve the dialogue between environmental managers on the one hand and various stakeholders, such as water resource users, on the other. Furthermore, cross-sectoral integration has considerable benefits for river restoration because working with other sectors opens up opportunities for restoration works that would otherwise be foregone because of lack of resources (financial, physical and manpower). For example, weirs and dams disrupt migration and trap sediments. However, hydropower developments are proposed for such structures, it is possible to engage with the developer to build fish pass facilities in association with the hydropower scheme thus facilitating upstream migration of fish. By proper allocation of flows to the fish pass the developer can maximise power production whilst supporting ecological objectives. These win-win scenarios are an area that needs to be encapsulated in restoration planning and development as they are key to maximising the benefits derived from river ecosystems. Key recommendations and conclusions from the assessment and development of methodologies to incorporate synergies between sectors in restoration planning are presented below.

Identifying relevant political and economic incentives can help overcome the inadequate budget situation for restoration

The management of river rehabilitation thus requires an approach that recognises the complexity of the system and accommodates multiple sectors and stakeholders. Insufficient budgets for river restoration are an increasing problem across Europe and restrict many RBMPs from being implemented to the full, but integrated planning can be a cost-effective option. Identifying political and economic incentives for the integration of restoration solutions into the development sectors (i.e. water resource management, flood protection, inland navigation and hydropower) can help overcome the inadequate budget situation by drawing on other sectors to contribute to restoration actions. Essentially, the approach aims to place human society as a central part in the ecosystem, and is a means by which the natural functioning and structure of an ecosystem can be protected and maintained while still allowing and delivering sustainable use and development to society (Atkins *et al*. 2011). Important within this process is the setting of explicit goals and practices, regularly updated in the light of results of monitoring and research activities". It is also "a strategy for the integrated management of land, water, and living resources that promotes conservation and sustainable use in an equitable way" as well as "a strategy …. to reach balance between conservation, sustainable use, and equitable sharing of the benefits arising from the utilisation of resources" (CBD 2000) (Figure 6.1).

Simple decision support methods are generally easier to use, but lack a full understanding of the economic and social interactions, while complex models incorporate these aspects but suffer from data paucity and need huge investments to achieve the required input.

Decision support tools, ranging from simple checklists and matrices to complex computerised models and networks, are available for identifying synergies between sectors and restoration measures. The simpler methods are generally easier to use, more consistent and more effective in presenting information, but lack a full understanding of the economic and social interactions and costs and benefits derived from, and by, each sector. Such tools do, however, provide an opportunity to engage with different sectors and the general public and to understand the drivers and motives of other sectors to harmonise development opportunities whilst maintaining the ecological integrity of the water body.

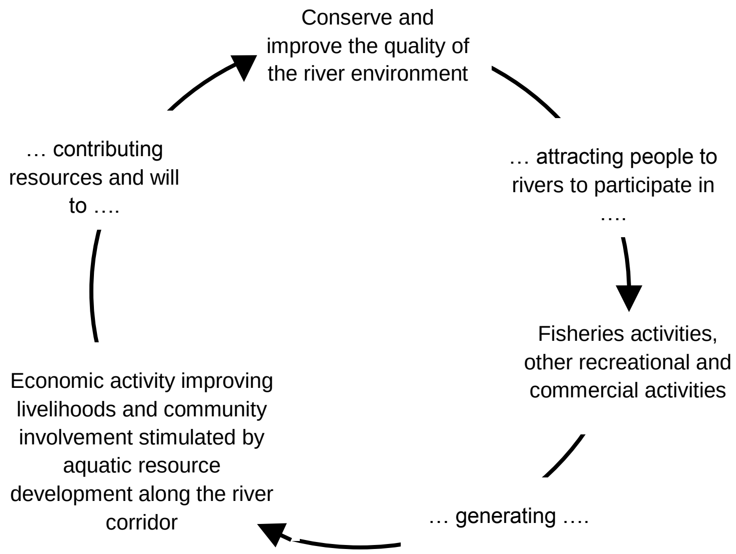

Figure 6.1. Cycle of benefits gained by adopting a synergistic ecosystem-based approach to river restoration

More complex models incorporate these aspects, but at the cost of immediacy. The use of Cross-impact Balance Analysis and Cost-Benefit Analysis are critical to help explore the interactions between sectors, but have yet to be used in earnest for making robust decisions on impacts and defining the opportunities for integrating cross sectoral policies to achieve win-win scenarios. The fundamental problem is there is a paucity of data required for input to the models at the river basin level and thus requires huge investment and active engagement with the sectors to achieve the input needed to apply the models. Consequently, there tends to be delays in implementation of application of such complex tools and a fall back on matrices and checklist.

Optimising ecosystem services in conjunction with the ecosystem approach appears to be a useful mechanism for selecting the best management options, but to convince other users of the importance of ecological services requires ecological and socio-economic information at a catchment scale and the more fundamental economic data to support the dialogue.

There is an urgent need for better analysis of cost-benefit data from river restoration measures and there potential economic impacts on cross-sectoral development. The recognition that river ecosystems provide vital services to society and that modifications to rivers to optimize water supply, navigation, flood protection, and drainage have been at the expense of these other services and the biota that deliver them, supports this argument. The concept of ecosystem services has received wide acceptance (MEA 2005) because it enables ecosystem management to be readily considered alongside other options by planners and decision-makers and given economic drivers. Recognising the benefits of these services and their intrinsic value to society offers an opportunity to realise the importance of biodiversity, in the multiple user environment (Rey Benayas *et al.* 2009). The ecosystem services concept, implemented through robust cost benefit analysis, provides a basis for identifying and assessing the services and societal benefits provided by the ecosystem and the consequences of endogenic and exogenic pressures on that system (Figure 6.1). Evaluation implies the need to identify those of the user community affected by the system or changes in the system; it aspires to complete coverage, a clear knowledge of the specific interests of user communities affected, provides a basis for exploring the legitimacy of these relationships and, in conjunction with scientific enumeration and monetary valuation, offers the opportunity for their quantification. In seeking to capture all of the user communities in any evaluation, it allows, in a comprehensive way, those managing conservation and biodiversity initiatives to engage with promoters of economic development proposals and to argue, and justify, the maintenance of biodiversity and ecosystem functioning.

Optimising ecosystem services through these strategies in conjunction with the ecosystem approach appears to be a useful mechanism for selecting the best management options, but the problem of convincing other users of the importance of ecological services remains, and requires the more fundamental economic data to support the dialogue. Deriving the full benefits of the ecosystem services delivered through healthy ecosystems opens up an opportunity to fill this fundamental constraint. Taking the time to collect ecological and socio-economic information at a catchment scale, will almost always provide considerable benefits to meet this fundamental requirement. Having stated this, guidance on the full array of ecosystem functions and services of multiple activities across a range of spatial scales is still needed (but see Brouwer et al. 2015; Reform D5.2). Both positive and negative effects need to be addressed given the trade-offs between conservation of ecosystem services and the lack of knowledge of thresholds at which ecosystem functions are no longer ecologically or economically sustainable. In many cases, data are not available, nor is there a suitable monitoring process in place to assess the long-term effects of development activities on aquatic systems or the potential services they provide, and vice versa. This suggests the need to match practices better with goals, and to optimize how decision-making is distributed between national and local levels. This can be achieved through the tools described above. It is important to understand how ecosystem services are interpreted by the different stakeholders, particularly in terms of economic development. This can only be achieved if all stakeholders understand the motives, modes of operation and reward systems of other spheres of society and engage in co-operative interchange, and vice versa.

Adopting a synergistic approach to river restoration will maximise multiple benefits between sectors that will enhance opportunities for restoration of rivers in resource limiting situations. Tools such as DPSIR help identify synergies but its application by river managers is generally lacking.

Adopting a 'synergistic versus trade-off' approach to river restoration with a specific focus on soft engineering or water resource allocation techniques in relation to climate change will enable planners to consider the links in integrated freshwater conservation planning and overcome constraints that might hinder other (or multiple) sectors. Synergistic approaches are now emerging in river restoration and cross-sectoral interactions, and are supported by various policy documents. For example, synergies between flood-risk and river management or between hydropower development and restoration of longitudinal connectivity for fisheries, or dam operation and setting of environmental flows to support not only reinstatement of ecosystem form and functioning but also to provide the flows required to ensure the restoration measures recreate the habitat endpoints required for success.

Nature based restoration provides innovative solutions for win-win scenarios between societal and environmental needs of rivers and should be the way forward. Restoring floodplains and re-connecting backwaters are options that should be considered as nature based flood mitigation measures. Flood-risk management is a the policy with good potential for synergies with other aspects of water management, provided that adequate strategies are implemented such as working with natural processes and nature-based restoration, allowing important opportunities for synergies between directives such as EU Floods Directive, WFD, Habitats Directive and Birds Directive, amongst others. These options are also encouraged in areas of navigation, agricultural practices, land use change, including urban development and hydropower development. Mimicking natural flow regimes and allocating sufficient water for fish passage solutions as mitigation measures for hydropower is essential to overcome problems with minimum flow and hydropeaking.

This deliverable has described tools to maximise synergies between sectors to benefit both the individual sectors but also the ecosystem form and function. One tool that is recommended as a first step to identifying this synergies is the DPSIR approach. This tool has the distinct advantage of identifying the drivers (economic and well are ecological), motives and impacts of various sectors on other sectors. Although the DPSIR concept has been widely promoted, its application as a tool by river managers is generally lacking. This is largely because the cross sectoral interactions have not been fully elucidated and sectors are reluctant to establish dialogue because of potential loss of their direct benefits to accommodate other services. In some instances the nested-DPSIR can be seen as an over simplistic representation of relationships between pressures and state changes, however, it is a valuable tool for practitioners that can be easily applied and generates win-win scenarios by harmonising restoration strategies and optimising the benefits gained for river ecosystems. It promotes stakeholder consultation and engagement to maximise benefits but also establishing trade-offs. In the future, it is critical that approaches such as DPSIR are developed and presented through consultation with the appropriate stakeholders and the motives and drivers of each sector are fully understood by all. The use of concept mapping and cross-sectoral DPSIR matrices using the nested approach will facilitate this interaction and potentially lead to great benefits being distributed amongst all sectors.

The consequences of climate change e.g. through more extreme discharge regimes create a moving target for planning and implementation and require an anticipating and adaptive strategy

One factor that must also be inbuilt onto the planning and implementation phases of any restoration is climate change. Climate change may increase the frequency and intensity of extreme precipitation events likely to cause significant flooding or result in extreme low flows, i.e. droughts. These will have serious implications of the efficacy of restoration measures but also provide the opportunity to find solutions to improve ecosystem health because resources are often directed at overcoming the societal impacts of these extreme events. For example, flood alleviation schemes to mitigate the increased prevalence of flooding in urban and peri-urban areas. The preferred solutions are tending to move towards use of nature-like options such as restoring wetlands and natural solutions that capture water such as strategic forestry planting (buffer zone). This acceptance has led to a better understanding for "Working with nature", as ways of achieving project objectives by working with natural processes to deliver environmental protection, restoration or enhancement outcomes (EC 2012b). Thus, within the planning framework it is essential to maximise the benefits from nature like solutions for resolving adverse effects of climate change on improving the ecological status in the RBMPs.

Identifying the impacts of different sectors and the potential synergies should be part of the project planning cycle and be inherent in the identification and formulation phases of the project development.

Finally, effective decision making, which allows policy makers to include a comprehensive view of ecosystem services trade-offs, should address the cumulative and synergistic effects of their decisions. In addition, policies need to acknowledge that, in many instances, short-term demands on ecosystem services will affect the longer-term, larger-scale provision of these or other ecosystem services. Successful management policies will be those that incorporate lessons learned from prior decisions into future management actions.

Policies can then be developed to take into account ecosystem services trade-offs at multiple spatial and temporal scales. Successful strategies will recognize the inherent complexities of ecosystem management and will work to develop policies that minimize the effects of ecosystem services trade-offs (Rodriguez et al. 2006). Synergies and trade-offs need to be considered in the planning framework and decision making processes (see Cowx et al. 2013; WP5.1). Identifying the impacts of different sectors and the potential synergies should be part of the project planning cycle and be inherent in the identification and formulation phases of the project development. This will allow both the constraints on success of the restoration measures to be highlighted but also the potential solutions using cross-sectoral interactions to be mapped. It is only when such interactions are presented to all partners will the true possibilities of finding win-win synergistic measures evolve. Ultimate people (society) create the problems, but people (societal interactions) are also the solution.

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APPENDIX 1: DPSIR framework for land use, agriculture, urban, flow regulation, flood protection, inland navigation and hydropower on freshwater rivers

Driver	Pressure	State	Impact	Response
Land use change (Agriculture, Urban & Industrial development)	**Land Cover Changes: Permeability and Connectivity** Increased impervious surface area (roads, roofs, grading, storm and sanitary sewers): Q_W^+, Q_W^-, Q_s^+, Q_s^- Uniformity of topography : Q_W^+, Q_s^+ Uniformity/fragmentation of land cover: Q_W^+, Q_W^-, Q_s^+, Q_s^- Disconnection/fragmentation (dams, levees, diversions): Q_W^+, Q_W^-, Q_s^+, Q_s^- *Q_W^+: increase in discharge Q_W^-: decrease in discharge Q_s^+:increase in bed material flow Q_s^-:decrease in bed material flow ** $w^{\pm}$: change in average channel width $d^{\pm}$: change in average depth $F^{\pm}$; change in channel width to depth ratio $\lambda^{\pm}$, change in meander wavelength $S^{\pm}$: change in channel slope	**Permeability change** Increased Impervious Surface Area (ISA) Increased discharge, reduced bed material flow: Hardened surfaces: $w^{\pm}$, d^+, F^-, $\lambda^{\pm}$, S^-, S_u^+ Soil compaction: $w^{\pm}$, d^+, F^-, $\lambda^{\pm}$, S^-, S_u^+ Increased discharge: Increased stormwater runoff: w^+, d^+, F^+, λ^+, S^- Reduced discharge: Reduced base flow: w^-, d^-, F^-, λ^-, S^+ Reduced bed material flow: Reduced sediment production: w^+, d^+, F^+, λ^+, S^- Decreased Vegetation Cover Increased bed load material flow: Increased sediment production (erosion): w^+, d^-, F^+, λ^+, S^+, S_u^- Increased discharge:	**Hydrology:** Runoff rate increase Seasonal runoff regime alterations Infiltration rate decrease Retention rate decrease Filtration capacity decrease Groundwater recharge decrease Shortened flow return periods Intra- and inter-basin flow regime alteration Sediment: Load delivery rate change Load size distribution change	**Land Best Management Practices (BMPs)** Conservation BMPs: Land use planning (growth management, zoning) Monitoring/evaluation Education (goods and services, management techniques, aesthetics) Funding (preservation, conservation) Design BMPs: Engineering design and construction (disconnection of impervious surfaces, limited grading and clearing, stormwater runoff control) Operation and maintenance for non-self-sustaining practices Funding (innovation) Prevention/Mitigation BMPs: Regulation (riparian buffer width requirements, ISA % and connectivity limits, steep slope and recharge zone protection)

Driver	Pressure	State	Impact	Response
	$S_u^{\pm}$: change in sinuosity (Schumm 1969)	Lowered vegetative water uptake: w^{+}, d^{+}, F^{+}, λ^{+}, S^{-} Fewer preferential infiltration pathways (roots): w^{+}, d^{+}, F^{+}, λ^{+}, S^{-} **Connectivity change** Longitudinal Disconnection: $S^{\pm}$ Slope alterations Reduced sediment transport Increased scour Channel/groundwater exchange altered Habitat fragmentation Lateral Disconnection : F^{-}, $w^{\pm}$, d^{+} Channel incision Channel/groundwater exchange altered Floodplain decrease Flood storage decrease Habitat fragmentation Planform Disconnection: λ^{-}, S_u^{-} Sinuosity decrease Channel/groundwater exchange altered Flood severity increase Habitat fragmentation	Turbidity increase Pollutant load increase Hydraulics: Increased flashiness Erosion rate increase (infrastructure, habitat loss) Deposition rate increase (navigation dredging, habitat loss) Other: Increased temperature Other water quality changes Reduced soil moisture Reduced CPOM and large woody debris in streams	Enforcement Funding (restoration, rehabilitation, mitigation) (Slawson 2003)
Agriculture land use	Hydrological regime modification	Lateral flooding prevented	Flood peaks become higher and shorter (Ex. Lower Danube: > 0.6-0.8 m?	
	Embankments, levees or dikes,	Change in hydrological regime low/ reduced or increased flow, artificial	Disruption to lateral connectivity,	Planning decisions

Driver	Pressure	State	Impact	Response
	Drainage works Forestation	discharge and level regime Change in erosion/ sediment/ transport/ silting Change in river profile (length and transverse profile) Change in connection with ground-water, alteration of ground-water level Changes in channel and floodplain morphology Land cover changes	detachment of wetlands Floodplain lakes and other water bodies isolated Depletions of riverine fish and fishery Migration pathways blocked Change in fish population structure Loss of habitat for fish breeding, feeding and refuge Young fish drift past suitable areas for colonization Decrease carbon storage	Planning controls and regulations Wetland restoration & protection <u>Ex. Lower Danube</u> The first Management Plan (2009) according to WFD: Planned measure: Link flood reduction with ecological restoration - Restore wetlands: 15,9% of the lower Danube floodplain (2015-2021) - Improve/Create water storage: 40.8% of the lower Danube floodplain by alternative use water storage/agriculture (>2021) <u>Ex. Danube Delta</u> Implemented Measures: Restore wetlands and Reconnect backwaters and wetlands 15% of the embankments in the Danube Delta reconnected to the river by 2014 Planned measures (first management Plan) Restore wetlands and Reconnect backwaters and wetlands 85% of the embankments to be reconnected by 2024
	Surface water abstraction (Irrigation)	Reduced surface water flows	Impingement, entrapment and entrainment of fish, particularly juveniles leading to high fish mortalities	Abstractors encouraged to use water more efficiently

Driver	Pressure	State	Impact	Response
Urban land use	**Hydrological** Water abstraction. Flow regulation. Discharge diversions and returns. Interbasin flow transfers. Hydrological regime alterations. Limited ground water. **Morphological** Morphological alteration. Hydraulic structures. Impoundments. Culverts. Changes in geometry of rivers and floodplains. Management of river flood plains. In-channel structures. Channel maintenance (dredging, weed cutting). Sediment management. Vegetation management. **Water quality**	**Reduced flows** Increased runoff from sealed or impervious urban surfaces. Higher discharge dynamic, increased in magnitude and frequency of occurrence. Increased flow velocities in the water courses. Increased risk of erosion. Decreased dry weather base flow feeding streams. Impounded river sections for different purposes (e.g. weirs). Increased loading of suspended solids and dissolved chemicals in discharge waters. Increased temperature in waters discharged to water course. Denaturalised stream alignments and gradients (e.g. spatial constraints from adjacent housing, industry and urban infrastructure, river canalisation). Bed and bank stabilisations. Culverted sections under infrastructure, building and portions of towns and cities.	Disturbance to normal breeding, feeding and growth patterns of aquatic fauna and flora Unseasonably high temperatures may raise production in areas close to water discharge (production depressed when temperature too high) Increased biological oxygen demand Disturbed conditions of temperature and radiation because of the discharge of cooling water and the absence of riparian vegetation. Risk to public health. Reduced availability of natural habitats (water body, river bank, river bed, flood plain, plants). Reduced habitat accessibility due to disturbed ecologic continuum (especially disrupted migration	Waste water treatment plants: planned, under construction or built. Ex. Lower Danube Assessment study of the impact for nuclear plant Cernavoda; Solutions for impact mitigation (2013). Industries, businesses and commercial enterprises need to be more involved in improving local water stretches to sponsor biodiversity improvements etc.

Driver	Pressure	State	Impact	Response
	Point source pollution (sewage treatment works, storm water runoff, industry) Diffuse pollution	Installation of urban infrastructure along or underneath the water course (sewer pipes, power supply lines, gas and water pipelines, roads etc.). Unbalanced sediment regime due to unnatural streambed erosion by increased flow velocity, decreased natural sediment input and increased entry of unnatural sediments and material from urban surfaces and temporary impact of construction sites. General loss of sediment transfer causing management problems. Loss of quality of urban open spaces by reduced aesthetic value. Emmission of various substances (e.g. nutrients, heavy metals, salt, organic compounds) from urban point (e.g. sewer overflows or direct waste water discharges) and non-point sources (urban surfaces drainage).	paths). Disturbed habitat renewal due to streambed and bank stabilisation, gradient adjustments and intensive management. Qualitative habitat degradation due to unnatural flow and sediment regimes. Disturbance of habitat development due to extensive and/or insensitive maintenance. Degraded riparian areas due to their functional separation from water course and extensive use within the urbanised area. Change and loss of biodiversity (fauna and flora)	
Flow regulation (Urban and industrial water supply) Irrigation farming	**Hydrological** Water abstraction. Flow regulation. Discharge diversions and returns.	Lower peak flows, reduction in magnitude and frequency of occurrence. Flow regime homogeneous, losing natural variability		Improve water discharge regime Develop environmental flow standards

Driver	Pressure	State	Impact	Response
	Interbasin flow transfers. Hydrological regime alterations. Limited ground water recharge. **Morphological** Morphological alteration. Hydraulic structures. Impoundments. Changes in geometry of rivers and floodplains. Management of river flood plains. Sediment management. Vegetation management. **Water quality** Anoxic dam bottom flow releases Reservoir Thermal stratification and bottom outlets	Increased low flows in magnitude and frequency of occurrence. Increased risk of flooding by regulated flows through false security that promotes the occupation and construction in flood plains. Impounded river sections transformed into artificial lakes Channel incision Unbalanced sediment regime due to dam sediment trapping Unnatural streambed erosion by ‘hungry waters released by reservoirs. Armouring of the riverbed. Riparian vegetation encroachment Reduction of riparian recruitment and aging of the forest. Sediment accumulation below tributaries, that reduced high flows are unable to move. Toxicity of various substances on reduced state (e.g. NO2, NH3, SH2, NH4). Disturbed conditions of water temperature.		

Driver	Pressure	State	Impact	Response
	Biological (river habitat and biodiversity) Altered habitat Introduced species Elimination of native species	Summer cold temperatures. Delay on maximum annual temperatures Reduced availability of natural habitats (water body, river bank, river bed, flood plain, plants). Reduced habitat accessibility due to disturbed ecologic continuum (especially disrupted migration paths). Disturbed habitat renewal due to streambed and bank stabilisation, gradient adjustments and intensive management. Qualitative habitat degradation due to unnatural flow and sediment regimes. Degraded riparian areas due to their functional alteration that promotes increasing growth but no recruitment. Species extinction and loss of biodiversity		
Flood protection	Increased flow Embankments	Increased flow velocities in the main channel Change in hydrological regime low/	Higher stream power, depth erosion, incised channels, armouring Disruption to lateral connectivity, detachment of	Rhitralisation of biotic communities, lowered ground water table, wetland dewatering Planning decisions

Driver	Pressure	State	Impact	Response
		reduced or increased flow, artificial discharge and level regime Change in erosion/ sediment/ transport/ silting Change in river profile (length and transverse profile) Change in connection with ground-water, alteration of ground-water level Changes in channel and floodplain morphology Land cover changes	wetlands Floodplain lakes and other water bodies isolated Depletions of riverine fish and fishery Migration pathways blocked Change in fish population structure Loss of habitat for fish breeding, feeding and refuge Young fish drift past suitable areas for colonization Decrease carbon storage	Planning controls and regulations Wetland restoration & protection
	Riparian vegetation alteration Sand & Gravel extraction	Bank erosion Sediment entrainment Vegetation de-rooting Thermal and nutrient changes Change in the flow of water Bank erosion failure Change in sediment transport	Change in channel width and depth, riparian continuity. Change in flood magnitude Lateral connectivity Thalweg altitude Substrate size	

Driver	Pressure	State	Impact	Response
		Vegetation encroachment Downstream sedimentation, upstream erosion	Riparian cover	
Inland navigation	**Hydrological** Flow regulation Impoundments	Increased flow velocities in the main channel Decreased flow velocities in the main channel	Higher stream power, depth erosion, incised channels, armouring Lower stream power, sedimentation of fines & organic materials	Rhitralisation of biotic communities, lowered ground water table, wetland dewatering Potamalisation of biotic communities, loss of coarse substrates and their adapted / depending communities and species
	Morphological Fragmentation/ Barriers Impoundments Morphological alteration	Migration barriers for fish, interrupted sediment transport, decreased flow velocities in the main channel Shortening planform, loss of instream habitats (e.g. islands), homogenised width and depth, oversized cross-sections, steep bank slopes, meander cut-offs, side channel fillings/cut-offs	Habitat fragmentation, lower stream power, sedimentation of fines & organic materials Decreased flow velocities, habitat loss, loss of habitat complexity, loss of lateral connectivity, single thread channels Depth erosion, incised channels, armouring	Loss of migratory species, lack of sediments /depth incision downstream, Potamalisation of biotic communities upstream, loss of coarse substrates and their adapted/depending communities and species . Ex. Lower Danube: Monitoring project on the effects of works for navigation improvement on sturgeons and other migratory fish (2011-2016) Homogenised faunas, loss of aquatic vegetation, decreased carrying capacity, loss of productivity, decreased shallow habitats for juvenile fish, inverts etc., depauperate faunas dominated by eurytopic generalists. Rhitralisation of biotic communities,

Driver	Pressure	State	Impact	Response
	Hydraulic structures Embankments Fairway maintenance (dredging) Sediment discharge from dredging	Narrowing fairway, increased flow velocity, stream power, depth Bed and bank stabilisation Homogenised width and depth, oversized cross-sections, removal of bars. Increased silt loading to the river Increased turbidity in water physically blocks out light	Armouring, interrupted side erosion, loss of shallow littoral habitats Loss of instream habitat structures. Habitat clogging Change in biological communities: decrease of richness and diversity of fish, benthic invertebrates and macrophytes	lowered ground water table, wetland dewatering Loss of aquatic macrophytes, juvenile fish carrying capacity, productivity, inverts … large losses of the ecologically most relevant and important littoral zone. Improved management of dredging and sediment discharge Ex. Danube Delta Planned measure to discharge sediments from dredging along to the river banks
	Operational Physical forces of the dynamic flow field induced by moving vessels Noise emission	Drawdown Return currents Wake wash Propeller entrainment Hull contacts Underwater noise	Dewatering of the banks High physical forces in the littoral High physical forces at the bank High physical forces in the water column High physical forces at the bank and in the water column High noise/stress levels	Stranding of invertebrates and fish, losses and restricted usability of littoral habitats, loss of diverse aquatic macrophytes, invertebrates and juvenile fish, depleted fish recruitment. Loss/injuries of water column species. Losses/damage of submerged and emergent plants. Impacted hearing of fish
	Water quality Point source and diffuse pollution	Increased turbidity due to forces	Fine sediment layers	Decreased growth/loss of submerged

Driver	Pressure	State	Impact	Response
		induced by moving vessels (e.g. propeller wash, wake wash). Re-suspension of materials Antifouling coating	on eggs, fish gills, invertebrates, plants, increased light attenuation. Resuspension of nutrients and/or toxic substances. Emission of toxic substances and/or endocrine disruptors	macrophytes, increased egg/juveniles mortality, loss of invertebrates. Eutrophication, stress, increased mortality. Stress, increased mortality, reduced fitness in fish populations
Hydropower	Hydropeaking Hydrological regime Modification	Disturbance of flow regimes Altered sediment and nutrient transport	Decrease habitat complexity and therefore, alter species development and change in biological communities (macrophytes, benthic invertebrates, fish) linked to the alterations of habitats. Reduce spawning areas for salmonid species. Restrict or hinder fish migration.	Improved water discharge regime to mitigate hydropeaking amplitude. Technical Advisory Group (TAG) has developed environmental flow standards for rivers based on macrophytes, invertebrates and fish (WFD 48 and 82; Acreman et al., 2008, 2009).
	Impoundments Fragmentation of longitudinal connectivity	Change in hydrological regime Lower flow velocities Altered sediment and nutrient transport Disruption in river continuum and sediment profile	Reduced habitat connectivity Loss of lotic-type habitats Loss of migratory pathways	Install fish pass/bypass/side channel for upstream migration Facilitate downstream migration Ex. Lower Danube Feasibility study (2014) for implementation of specific measures at Iron Gates I and II barrages

Driver	Pressure	State	Impact	Response
			Shifts in species composition Loss of habitat diversity Sediment entrapment	
	Channelisation / cross section alteration	Unnatural water course, altered bed and banks Changes in sedimentation and nutrients patterns	Loss and changes of habitats due to increased sediment and nutrients inputs Change in biological communities: decrease of richness and diversity of fish, benthic invertebrates and macrophytes	Increase naturalness of water courses and hydrology Ex. Danube Delta: Implemented measures for partial or total blocking of unnatural canals.
	Turbines	Mechanical damage	Fish mortality Delayed fish mortality due to turbine stress	Alter turbine design
	Construction phase	Removal of top soil and vegetation	Sedimentation Increased run off Altered water quality Increased flood risk	Silt traps