THEME: Environment (including climate change)

TOPIC: ENV.2011.2.1.2-1 Hydromorphology and ecological objectives of WFD

Collaborative project (large-scale integrating project)

Grant Agreement 282656

Duration: November 1, 2011 – October 31, 2015

REstoring rivers FOR effective catchment Management

Deliverable D1.2 Effects of pressures on hydromorphology

Title Review on pressure effects on hydromorphological variables and ecologically relevant processes

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Due date to deliverable: February 2013

Actual submission date: October 2013

Project funded by the European Commission within the 7th Framework Programme (2007 – 2013)

Dissemination Level

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

Summary

European rivers have been altered by means of changing their morphology (straightening and canalisation, disconnecting channels from flood plains, occupying riparian lands, building dams, weirs, bank reinforcements, etc.) to facilitate agriculture and urbanisation, to enable energy production and protection against flooding. Also, water has been abstracted from rivers and their natural flow regime to be used as a resource for irrigation and to supply urban and industrial needs. All these human activities have damaged fluvial habitats and have had severe and significant impacts on the status of the aquatic ecosystems. These hydromorphological (HYMO) pressures are the most commonly occurring pressures in European rivers, lakes and transitional waters, affecting more than 40 % of all river and transitional water bodies.

This report is a bibliographic review concerning the effects of HYMO pressures on hydromorphological processes and variables resulting from both degradation and restoration. Based on this review, we aim to identify the most significant HYMO pressures as well as relevant hydromorphological effects of the different pressure types on fluvial systems across spatial and temporal scales and in particular those that have a significant impact on aquatic biological elements.

This review further provides a tool to identify gaps in present HYMO knowledge, which is needed to improve our understanding of the mechanisms that control degradation-restoration processes. To illustrate relevant gaps conceptual schemes have been developed of the interactions between HYMO pressures, the main processes affected and the resulting quantified changes on HYMO variables. Referenced citation frequencies were used to relate the different elements of each scheme.

Hydromorphological pressures were grouped into the following types:

1. Hydrological regime pressures, including water abstraction and flow regulation
2. River fragmentation pressures
3. Morphological alteration pressures
4. Other elements and processes affected (physico-chemical)

The pressure effects were analyzed separately for each hydromorphological pressure by developing a diagram showing its direct effects on the processes and on the state variables, but in turn also the induced process changes with respect to HYMO variables. The following main HYMO processes were considered:

- Water flow dynamics
- Sediment dynamics (sediment entrainment, transport, deposition, armouring)
- Bank dynamics (bank erosion & failure, stabilization)
- Vegetation dynamics (vegetation encroachment, uprooting, recruitment)
- Large wood dynamics (entrainment, transport, deposition)
- Aquifer dynamics (aquifer recharge, discharge)

The quantitative variables provide the measures of the intensity of the processes and are useful to monitor river changes and to evaluate pressure effects. Whilst the biotic communities typically respond to the status of the variables, sustainable and successful river restoration should address the processes behind which determine the variables' state. Therefore, all pressure specific conceptual schemes developed have been incorporated into one single effect matrix and analyzed using Fuzzy Logic Cognitive Maps (FCM) to identify the most relevant HYMO pressures as well as the most affected processes and variables. FCMs are based on graph theory models of the causal relationships between defined variables and can be viewed as a combination of fuzzy logic and artificial neural networks. FCMs qualitatively incorporate expert knowledge to explore implications for ecosystem management.

The overall hydromorphological pressure-impact model very well depicted the present status of processes and variables corresponding to the commonly observed hydromorphological conditions in altered river systems. Dynamics of flowing water emerged as the most important hydromorphological process. This was not surprising, but it still underlines the necessity to rehabilitate a more natural flow regime to improve the hydromorphological status of the rivers and the related biological communities.

Vegetation encroachment emerged as second most important process which seems well in line with the natural river typology developed in WP2 and the identified importance of riparian vegetation in shaping riverine landscapes. The next important processes were all related to sediments underlining the key role of bedload transport and sediment dynamics in forming fluvial habitats.

To provide further guidance to river restoration, the effects of single pressure removals have been analyzed by simulating the system behavior in response to various management options, i.e. management simulations. Removing one of the pressures completely would cause on average a change of 57% of all hydromorphological variables considered (ranging between 31% for improving vertical connectivity and 68% for large dam removal).

These findings, however, did not only allow identifying the main pressures and most important processes, they also pose major challenges on identifying key variables and variables' changes which significantly affect the biotic response. Major knowledge gaps comprise the interplay between synchronously and asynchronously responding variables and the assessment of the finally resulting status of the hydromorphological variables in different river types. Closely related to that, assessing the resulting potential effects on biota as well as differential responses of different taxa to various variable changes and variable states provide additional challenges.

Acknowledgements

The work leading to this report has received funding for the EU's 7th FP under Grant Agreement No. 282656 (REFORM).

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1 Introduction

During the last centuries, European rivers have been altered by means of changing their morphology (straightening and canalisation, disconnecting channels from flood plains, occupying riparian lands, building dams, weirs, bank reinforcements, etc.) in order to facilitate agriculture and urbanization, to enable energy production and protection against flooding. Also, water has been abstracted from rivers and their natural flow regime to be used as a resource for irrigation and supply for urban and industrial needs. All these human activities have damaged fluvial habitats and have severe and significant impacts on the status of the aquatic ecosystems.

The status and pressure assessment made by European Environmental Agency (2012) in a review of the River Basin management Plans (RBMP) shows that hydromorphological pressures are the most commonly occurring pressures in rivers, lakes and transitional waters, affecting more than 40 % of all rivers and transitional water bodies. Hydromorphological or habitat alterations are changes to the natural flow regime and structure of surface waters by modifications to: bank structures, sediment/habitat composition, discharge regime, gradient and slope. Hydromorphological degradation of riparian zones and floodplains also reduce their natural retention of pollutants and can thereby increase the vulnerability of European waters to pollution. The consequences of these pressures can impact aquatic ecological fauna and flora and can hence significantly impact the water status.

Water pollution is an ancient impact for river systems that was significant since humans started to live in cities and need intensive farming and industrial products. However, significant progress has been made in numerous European waters in reducing contaminants and their effects, by means of improved wastewater treatment, reduced volumes of industrial effluents, reduced use of fertilizers, banned phosphate content in detergents, as well as reduced atmospheric emissions.

Pressure types, pollution and hydromorphology (HYMO), often occur together in rivers, but the effects of the former one overrides the impacts of hydromorphology alteration. The fact that water quality of European rivers has been recently improved is revealing that more needs to be done in order to achieve good ecological status. We are faced with the need to understand how the hydromorphological alteration is affecting biological communities by itself and which are the HYMO processes and variables that more affect in the loss in biodiversity and in the resilience of aquatic populations.

The knowledge base to evaluate the ecological status and impacts due to these HYMO pressures, isolated, 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. However, this knowledge is vital to diagnose root causes of HYMO alteration and the limiting factors for the biological elements that define its deteriorated ecological status. Once a HYMO problem is properly diagnosed, then we are able to design the restoration measures for those causes. The selection of appropriate measures demands to know which the precise limiting HYMO processes are and also to quantify their intensity through the quantitative measurement of the variables affected by these processes.

This is a bibliographic review concerning the effects of HYMO pressures on hydromorphological processes and variables resulting both from degradation and restoration. Based on this review, we aim to identify the most relevant hydromorphological effects of different HYMO pressures types on fluvial systems across spatial and temporal scales, and, in particular, those that have a significant impact on aquatic biological elements.

1.1 Definitions

As different approaches exist to describe the interactions between society and the environment, we have followed the commonly used causal DPSIR framework, based on the PSR framework model proposed by OECD in 1993 and selected by EEA (2007). The following definitions are considered:

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).

Hydromorphological indicators

Hydromorphological quality elements for the classification of ecological status of rivers defined by the Water Framework Directive (Annex V).

These hydromorphological elements supporting the biological elements are:

- Hydrological regime

  Quantity and dynamics of water flow

  Connection to groundwater bodies
- River continuity
- Morphological conditions

  River depth and width variation

  Structure and substrate of the river bed

  Structure of the riparian zone

These definitions and concepts are taken into account through the present document and have guided the meta-analysis of literature concerning hydromorphological pressures and impacts on river ecosystems that is presented below.

However, we must bear in mind that river systems are especially dynamic and often, there are not clearly defined limits between which river reaches and fluvial traits are natural respectively impacted. Thus, the first practical challenge in assessing the effects of human pressures and resolving their impacts is that they are superimposed on natural spatial and temporal variation (Stewart-Oaten & Bence 2001; Braatne *et al.* 2008).

1.2 Objectives

In this report we present a literature review and meta-analysis concerning the effects of pressures resulting both from degradation and restoration of hydromorphological processes and variables. Based on this review, we aim to identify the most relevant hydromorphological effects on fluvial systems across spatial and temporal scales, and, in particular, those that have a significant impact on aquatic biological elements.

Also, this review acts as a tool to identify gaps in present HYMO knowledge, that is needed to improve our understanding of the mechanisms that control degradation-restoration processes. In order to detect these gaps we present a conceptual scheme of the interactions between HYMO pressures, the main processes affected, and the resulting quantified changes on HYMO variables. The gaps are detected by comparing reference citation frequencies in relation to the different elements of this scheme.

The pressure effects are analyzed separately for each hydromorphological pressure. For this purpose we used the pressure typology developed in the FORECASTER project, although with some modifications. For each pressure type we have developed a diagram showing its explicit and direct effects on the processes and on the state variables, but also in turn its induced process changes with respect to HYMO variables.

These quantitative variables are the ones that we measure in order to monitor river changes and evaluate pressure effects.

2 Hydromorphological Pressures

From a holistic point of view, a typical river network directly and asymmetrically connects the upland and riparian landscape to the rest of the lowland fluvial ecosystem, estuaries and coastal systems. As headwater streams compose over two-thirds of total stream length, they have particular importance. The large-scale ecological effects of altering headwaters are amplified by land uses that alter runoff and nutrient loads to streams, and by widespread dam construction on larger rivers, which frequently isolates free-flowing upstream portions of river systems essential to sustaining aquatic biodiversity (Freeman et al. 2007).

Often, human pressures affecting rivers do not come alone, as many elements of the riverine environment co-vary (Vaughan et al. 2009). 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 and Meyer, 2001; Gurnell *et al.*, 2007). Concomitant ecological changes in such situations (e.g. reduced taxonomic diversity or increased decomposition rates; Paul and Meyer, 2001) could be a response to any or all of the changes associated with the land use. Their effects could be additive, subtractive or multiplicative.

Although multiple pressures affect rivers simultaneously and at the same time human activities stress many components of the hydrological cycle which have different time-scale responses within fluvial ecosystems, for practical reasons we have reviewed the available literature trying to distinguish single river pressures and their most direct impacts on ecosystems.

The pressures have been grouped into the following classes, bearing in mind the WFD HYMO elements and processes affected:

1. Hydrological regime
   - 1.1 Water abstractions
   - 1.2 Flow regulation
2. River fragmentation
3. Morphological alterations
4. Other elements and processes affected (physico-chemical)

2.1 Hydrological Regime: Water Abstractions

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 (see 2.2 Flow regulation), 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 phreatic levels rapidly shows signs of water stress, leading in extreme cases to widespread riparian plant death.

Discharge diversions and returns

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 conducted through a near horizontal bypass channel into turbines that are located downstream at a much lower altitude.

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.

Although in temperate regions water abstractions may have relatively minor impacts, 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).

A review of low flow river conditions during dry periods of the year, as well as the problem of changing minimum river flows as a consequence of climate variability is presented by Smakhtin (2001).

2.2 Hydrological Regime: Flow Regulation

River regulation imposes fundamental changes on flow and sediment transfer, which are the principal controls on fluvial morphodynamics (Church, 1995).

Inter-basin flow transfers

An *inter-basin transfer* or *transbasin diversion* takes place when water is withdrawn from one river basin (a *donor* basin), distributed for use in another river basin (a *receiving* basin) and not returned to the basin of origin. Inter-basin transfers involve a consumptive use of water from the donor basin.

The main purpose of such schemes is usually water supply to urban or industrial areas, but transfers are also used for hydropower production and, in the Mediterranean region and semiarid basins, for irrigation or for alleviating water shortages during drought years.

Since conveyance of water between natural basins comprises both a flow reduction in the source catchment and an addition at the destination, such projects may be controversial in some places and over time, due to their scale, involve costs and environmental or developmental impacts.

Hydrological regime modification (flow timing or quantity)

In order to significantly modify the natural flow regime, 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 humid 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.

Hydropeaking

The production of electricity by hydropower plants is often implemented to satisfy peaks in electricity demand. 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 weekly and daily rhythm.

Reservoir flushing

Flushing flows are peaks of flow released from reservoirs to imitate elements of the natural flow regime downstream in order 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. Flushing flows are necessary to maintain ecological integrity, especially increasing the availability and quality of fish spawning habitat and the production of benthic macroinvertebrates.

In contrast, the common practice of reservoir flushing to get rid of accumulated fine sediments has detrimental effects on the habitats and aquatic communities downstream of the dam. Depending on the sediment transport within the system, reservoir flushing for cleaning is a rather rare event occurring once every 10-20 years.

Sediment discharge

Many human activities (e.g. farming, forestry, road construction) can cause erosion in catchment areas that often cause sediment runoff. Mining operations directly or through escapes in their settling ponds often produce sediment discharges to the river. Also, directly dredging operations on rivers release suspended sediment into the water column by agitation of the bed and by discharging overflow slurries. There are four reasons for undertaking dredging works: flood alleviation, land drainage improvement, navigation and gravel and sand mining. In all cases the effect is to increase the river channel capacity and thus its ability to convey water.

2.3 River fragmentation

River fragmentation is caused by discontinuity in any of the river's three spatial dimensions: longitudinal, lateral and vertical. Such discontinuities disrupt hydrological connectivity (Pringle, 2003), interrupt the transfer of water, mineral sediment, organic matter and organisms within and between elements of the river system, and thus impact on the river's biotic and physical components (Bunn and Arthington, 2002).

Longitudinal fragmentation may be produced directly by the presence of *dams* or *artificial barriers,* but it may also be produced indirectly by certain conditions caused by HYMO processes and water quality degradation. Hydrological connectivity is water-mediated. For example, reduction of flows, especially of base flow, during some periods may disconnect habitats and species' populations. Anoxic water conditions along stream reaches, or thermal discharges may also act as barriers for riverine aquatic organisms.

Lateral fragmentation is caused by the presence of lateral barriers such as levees and dikes that disconnect river ecosystems from their floodplains by preventing overbank flooding. The integrity of both riparian and aquatic ecosystems is thought to be dependent, in part, upon exchanges of energy and matter between the main river channel and adjacent floodplain surface and the patches present within and between them during periods of flooding (Amoros and Roux, 1988; Junk et al., 1989, Junk and Wantzen, 2004). Disturbances or flow regulations that eliminate or reduce flood flow magnitude, or lateral barriers that limit the extent of inundation of the floodplain, disrupt connectivity between river and floodplain. In addition, certain indirect effects of pressures, through their correpomding HYMO proccesses, may cause floodplain isolation. For example, restriction in sediment supply to a river may induce river bed incision, which in turn reduces hydrological connectivity between river and floodplain. Processes such as channel bed incision or riparian and floodplain accretion, which both disrupt river-floodplain connectivity are frequently found in disturbed rivers.

Vertical fragmentation can be produced by physical processes that reduce river bed permeability such as siltation of the riverbed surface and clogging of pore spaces within stream bed gravels (Hancock 2002). This may result from increased delivery of fine sediment to the river as a result of for example changes in land use or agricultural practices, as well from reduced flow energy, for example due to flow regulation. In either case, the balance between sediment supply and sediment transport is disrupted, leading to the accumulation of fine sediments within the river bed (Kondolf and Wilcock, 1996). In addition, physical modification of river channels, such as straightening and simplifying channel form (Kondolf et al., 2006) may reduce water depth and retention within the channel, adversely affecting vertical connectivity.

Henceforth, this review will only focus on the pressures involved in longitudinal fragmentation, as lateral fragmentation will be incorporated in pressures related to channelization (embankments and levees) and vertical fragmentation will be incorporated in pressures related to substrate siltation and clogging, and riparian soil sealing and compaction.

2.4 Morphological alterations

Impoundment

Any transverse barrier to the flow in a river impounds water upstream. When this barrier is small (e.g. less than 10 m high) it may be called a weir, dike or small dam. Barriers that are taller than 15 m are all termed dams. All of these barriers are used for retaining water for many purposes and the river is transformed into an impoundment upstream.

Natural flow velocity is reduced due to the presence of the impoundment, resulting in the deposition of transported sediments. The effectiveness of a reservoir as a sediment trap is mainly dependent upon its storage capacity and the length of time that it stores water (Brune, 1953), but even the smallest reservoirs are likely to trap most sand sized and finer particles, and large reservoirs are likely to trap close to 100% of transported mineral sediment particles.

Large Dams and Reservoirs

The environmental effects of dams and the reservoirs they impound vary greatly with their regional or environmental setting, which controls the natural flow regime, and their size (morphometry and capacity) and purpose, which affect spillweir characteristics and operational procedures, of the dam and its reservoir. All of these factors affect the trophic level of the water body and the possibility of thermal stratification, and affect the flow, sediment, oxygen and thermal regimes of the released waters, with severe impacts on downstream ecosystems (Ward and Stanford 1983, 1995) including the hydromorphological characteristics of downstream river channels and their riparian zones (Petts and Gurnell, 2005, 2013).

Flow regulation by dams is often accompanied by other modifications such as levee construction, which normally results in reduced connectivity and altered successional trajectories in downstream reaches (Ward & Stanford 2006). These effects are even more dramatic as flood peaks are typically reduced by river regulation, which further reduces the frequency and extent of floodplain inundation

Channelization: Cross section alteration

Channelization refers to river and stream channel engineering undertaken for the purposes of flood control, navigation, drainage improvement, and reduction of channel migration potential (Brookes, 1990). When channelization involves cross section alteration, this includes activities such as channel enlargement through widening or deepening, the reduction of flow resistance through clearing or snagging of riparian, and sometimes aquatic, vegetation and other roughness elements, and the introduction of bank facing and reinforcement materials. These forms of morphological modification typically transform channel cross profiles into uniform, smooth, trapezoidal or rectangular forms.

Cross section alteration can also include embankment, levee or dike construction, which further enlarge the channel capacity, prevent channel-floodplain connectivity, and can induce very high flow velocities within the river channel during floods.

Channelization: Channel realignment

In this type of channelization the river planform is modified, through procedures such as the cutoff of meanders, channel straightening and generally relocating pre-existing stream channels. These procedures tend to increase stream gradients, remove or simplify bed forms such as pool-riffle sequences, and realign the channel thalweg.

Alteration of riparian vegetation

Many different pressures impact on riparian vegetation driven by processes acting at local up to global scales from. In this particular context we are specifically referring to activities carried out immediately adjacent to the river (e.g. cultivation of crops) or in the riparian zone itself (e.g. logging, grazing and trampling, gravel and water extraction, and recreation).

Alteration of instream habitat

Natural instream habitats offer refuge and shelter, food resources and spawning grounds to aquatic biota. Recognition of instream habitat alteration should be based on changes in surface flow type, hydraulic attributes (flow depth, velocity and bed roughness, shear velocity, Reynolds and Froude numbers), channel morphology, and bed substrate calibre.

Instream habitat degradation may be an effect of a hydrogeomorphological process (natural or caused by other pressures), or of a direct human activity (e.g. channel dredging, gravel bed extraction). The latter activities are those pressures we are refering to here.

Embankments, levees or dikes

Levees or dikes along a stream or river channel are longitudinal structures designed to prevent water passing from the river channel to the floodplain. Frequently river banks are reinforced and their level is raised by the construction of a bank top mound for flood control. Such bank stabilization eliminates river planform dynamics, and the addition of levees or dikes prevents lateral hydrological connectivity, which is crucial to hydromorphological complexity and the provision of diverse habitats, including refugee, for aquatic organisms.

Sand and gravel extraction

Sand and gravel are crucial resources for economic development activities, such as road building and concrete production. As a result, sand and gravel mining is a major economic activity that is often carried out within river channels and floodplains. Because annual extraction rates often greatly exceed fluvial transport, these activities lead to river bed incision, disconnection of the river from its floodplain, depression of water table levels in the alluvial aquifer, and sometimes a complete change in channel style, for example from braiding to single thread planforms.

Floodplain Soil Sealing and Compaction

Riparian and floodplain soils may lose their infiltration capacity (vertical connectivity with groundwater) as a result of urban development, road and pavement construction, the weight of vehicle traffic, soil trampling, and recreational activities.

2.5 Other physico-chemical pressures

Different pressure types can modify the state conditions and hydromorphological processes of rivers. Also, their impacts on fluvial ecosystems may produce effects in synergy with the hydromorphological degradation.

Thermal changes

Temperature is a significant control on the physical and hydraulic environment, affecting properties such as viscosity, density, solution, and gas saturation that influence HYMO processes and thus impact on both the physical and biological habitat. Changes in water viscosity modify the sediment erosion-transport-sedimentation equilibrium and thus alter the bed substrate (benthic habitat is an essential element for most aquatic species). Temperature also controls the rate of evaporation and the gas saturation point of dissolved solids and therefore influences the concentration of elements and vital substances (such as oxygen or nutrients) and / or toxic substances in the water column.

Eutrophication (Nutrient enrichment)

An increase of the plant nutrients nitrogen (N) and phosphor (P) in the water favours the growth of macrophytes and riparian plants. Vegetation encroachment in turn influences HYMO processes and thus river forms.

Organic discharge

Coarse organic material provides an important habitat for benthic invertebrates. However overloads of organic material typically show detrimental effects, because organic matter accumulating in rivers is oxidized. This can lead to a deficit of oxygen in the water, and this anoxic environment favours reduction of dissolved substances to forms that are always more toxic. Organic matter may also indirectly affect the biological component of rivers, because it affects metabolism, growth and reproduction of organisms at all trophic levels of the aquatic ecosystem.

3 Hydromorphological variables and processes

HYMO pressures alter fluvial systems in their structure and composition through changes in the natural HYMO processes, which can be characterized by changes in particular HYMO variables.

A HYMO process is an event that results in a transformation in a physical component of the fluvial system. These transformations can be observed as changes in the morphology and structure of the river, but also they create a different environment that promotes changes in the biological communities. Therefore, process-based analysis of impacts relies on understanding systematic relationships between underlying physical components of hydrology and geomorphology, and subsequent biological responses.

Table 1. Hydromorphological processes considered and their associated variables for evaluating their effects.

PROCESSES	**VARIABLES**
Water flow dynamics Sediment dynamics a. sediment entrainment b. sediment transport c. sedimentation d. armouring Bank dynamics a. bank erosion & failure b. bank stabilization c. bank accretion Vegetation dynamics a. vegetation encroachment b. vegetation uprooting c. vegetation recruitment Large wood dynamics a. Large wood entrainment b. Large wood transport c. Large wood deposition Aquifer dynamics a. Aquifer recharge b. Aquifer discharge	**1. Hydrological Regime** Flow Regime variables: Magnitude of average flows Flow variability Flood variables Channel Drought variables Sediment Regime variables Connection to groundwater **2. River longitudinal continuity** **3. Morphological conditions** Channel variables Planform variables Thalweg variables Structure & caliber of the river bed Bank variables Water variables Structure of the riparian zone Structure of the floodplain
OTHER PROCESSES Primary production Heat Exchanges REDOX	**4. Physico-Chemical variables** Nutrient concentration Water temperature Dissolved Oxygen

HYMO processes are always dynamic properties of the river and are characterized by system attributes such variables and parameters. Every process is comprised of input and output values of the affected variables. We may evaluate the effects of these processes through selected state variables (Table 1) that can be changed directly by the HYMO pressure. Usually, the modified variable triggers processes which in turn transform the values of that or other variables.

3.1 HYMO Processes

Water flow dynamics

Water flowing through the channel or through the floodplain and riparian areas during floods is the fundamental process that drives fluvial dynamics. We consider effects of pressures on this process in relation to baseflows, average flows and their temporal variability. However, high flows have the greatest influence on HYMO changes.

Sediment dynamics

a. *Sediment entrainment*. Channel erosion may take place at the banks or bed. Channel bed ***incision*** is part of denudation, drainage-network development, and landscape evolution. Rejuvenation of fluvial networks by channel incision often leads to further network development and an increase in drainage density as gullies migrate into previously non-incised surfaces (Simon and Rinaldi, 2006).

b. *Sediment transport*. Sediment transport is the process that mediates between erosion and deposition based on the carrying capacity of the flowing water. The amount and size of sediment transported through a river channel depends on three river traits: ***competence*** *(*largest sediment particle size that the flow is capable of moving*),* ***capacity*** (maximum amount of sediment of a given size that a stream can move) and ***sediment supply*** (the amount and size of sediment available for sediment transport.

c. *Sedimentation*. Sedimentation is a geomorphic process in which sediments carried by flow are deposited in the river channel and its floodplain, and thus produce changes in their geometry. However, deposition on different landform units has different effects on re-shaping of the channel. Sediments may come as coarse particles (bed load), or in suspension as fine sediments (washload). This last sedimentation is also called ***siltation***. Wolman and Leopold (1957) subdivided deposition on floodplains into two broad categories: ***vertical accretion*** and ***lateral accretion***. However, because an alluvial river corridor is comprised of three main landform units: riverbed, floodplain and riverbank, fluvial sedimentation can be subdivided into three categories: vertical overbank deposition, vertical deposition on the riverbed and lateral deposition on the riverbank (Xu, 2002).

d. *Armouring*. An armoured river bed results from the selective erosion and removal of finer particles to leave a continuous layer of coarse particles on the river bed. This coarser layer creates a bed surface that is resistant to erosion and, therefore, is very stable and protects the underlying sediments, including fine particles, from erosion.

Bank dynamics

a. *Bank erosion and failure*. River bank erosion is a process which occurs in channels as they adjust their size and shape to convey different water and sediment flows. Bank erosion includes two main groups of processes: bank scour and mass failure. **Bank scour** (bank undercutting, bed degradation, basal cleanout) is the direct removal of bank materials by hydraulic forces. **Mass failure** (bank collapse, slumping, slides, slab and cantilever failures) results from bank material becoming unstable and toppling into the bed of the channel under gravitational forces in single events.

b. *Bank stabilization*. Bank stability increases with a reduction in bank gradient and an increase in the compaction and cohesiveness of bank materials. It is greatly enhanced by the presence of dense bank vegetation.

c. *Bank accretion*. Bank accretion occurs where banks build up by alluvial deposits as added by horizontal progression and is the result of the interaction of flow regime, sediment transport, riparian vegetation and sediment compaction.

Vegetation dynamics

Living vegetation interacts with flowing water and sediment and acts as the third natural control on river morphodynamics (Gurnell et al., 2012; Gurnell 2013a):

a. *Vegetation recruitment*. The effectiveness of vegetation as a control on river morphodynamics depends on the ability of vegetation to colonize the disturbed environments of river channels and floodplains through sexual (seeds) or asexual (vegetative) recruitment processes. Interactions between vegetation recruitment and growth, and fluvial disturbances may result in:

b. *Vegetation encroachment*, whereby vegetation recruitment and growth result in the trapping and stabilisation of fluvial sediments as the vegetation advances into the active river channel and positive feedbacks in the form of channel narrowing and bed aggradation around the encroaching vegetation, or:

c. *Vegetation uprooting,* whereby fluvial processes counteract vegetation encroachment by removing vegetation to widen or deepen the channel. Vegetation uprooting is achieved by two main mechanisms: drag on the plants imposed by river flows can exceed the resistance of plants and uproot them directly; or erosion and removal of sediments by the flow can undermine plants until they are no longer firmly anchored and they topple.

Large wood (LW) dynamics

'Large wood' refers to the largest pieces of organic matter (> 1m in length, > 0.1 m in diameter) found in fluvial systems, which can have a profound impact on river morphodynamics (Gurnell, 2013b). Much LW is dead, providing a physical element that also decomposes, but wood pieces from some tree species can also sprout, increasing their stability, anchorage and potential to interact with physical processes.

a. *LW deposition* results in the development of distinct physical structures that influence patterns and strengths of flow velocity and thus the entrainment, transport and deposition of sediment, finer organic matter and plant propagules. As a result, LW deposits, particularly in smaller streams where key pieces can be jammed into the entire channel cross profile, have profound effects on landform and habitat structure and complexity and on the sedimentary structure of the river channel and floodplain. Deposited wood that sprouts creates its own root anchorage and so can have important impacts on the morphodynamics of river channels of all sizes. Whether dead or living, deposited wood often provides a starting point for riparian and bank vegetation recruitment and colonization.

b. *LW entrainment*. If LW is entrained, this can lead to the exposure of retained sediment and the simplification of the adjacent river bed and bank habitats. Alternatively, wood pieces may become undermined but remain in place, leading to bed and / or bank scour and the creation of scour pools and / or undercut banks.

c. *LW transport*. Once LW is mobilised, it may be transported large distances downstream during floods. This is particularly true for the majority of tree species whose wood is less dense than water. The wood from these species floats and so is transported until it is snagged in a roughness element within the channel or flood plain, or it is stranded on the river bed as water depth decreases during falling flood stages.

Aquifer dynamics

The connectivity between surface water and groundwater aquifers is mediated by the permeability of the intervening sediments, and depends on the hydraulic gradient through these sedimentary layers.

a. *Aquifer recharge* is the volumetric flow rate of water through the land surface into the aquifer. When this process is achieved from water bodies on the land surface, it either takes the form of flow from the river through the hyporheic zone beneath the river bed, banks and riparian zone or as a result of direct infiltration of water that inundates floodplains during flood events. High rates of recharge occur through river beds when water tables become depressed below bed level during dry summers, inducing preferential downward and lateral flow out of the river channel. This process is particularly characteristic of many Mediterranean rivers.

b. *Aquifer discharg*e is the volumetric flow rate of groundwater from the aquifer to the land surface. This may take the form of flow through the hyporheic zone into the river channel, of flow through seepage lines and springs at points where a downward sloping water table intersects the land surface, or of flow under pressure from confined aquifers through faults and cracks to the land surface.

3.2 HYMO variables

Hydromorphological variables are changed by the hydromorphological processes (section 3.1) and represent the quantitative state of the fluvial system. Also, HYMO variables may be modified directly by various pressures, causing alterations in prevailing HYMO processes. HYMO variables are measured in order to monitor river changes and evaluate pressure effects. In turn, these changes in HYMO variables represent environmental alterations that provoke changes in the biological elements (impacts).

The following Table 2 lists the HYMO variables that we have considered grouped into: flow, flood, flow variability, drought, sediment flow, hydraulic, connection to groundwater, longitudinal connectivity, channel dimensions, thalweg, planform, bed substrate, bank, hydraulic energy, riparian, floodplain and physico-chemical variables. Water physico-chemical variables are included with hydromorphological ones because the impacts caused by some HYMO pressures (e.g. large dams) cannot be understood without them.

These variables may be recorded on three different spatial scales (Feld, 2004):

a. **Catchment-related** variables consider the whole catchment from the stream source to the sample site. Feld (2004) listed 27 different variables including distance to source, stream order, catchment geology, and catchment land use.

b. **Reach-related** variables, whose longitudinal dimension (up-/downstream) depends on the size class of a stream type. For small streams (10–100 km^2 catchment area), a stretch of 5 km up- and downstream of the sample site was taken into consideration (= 10 km), whereas in the case of middle sized streams (100–1000 km^2 catchment area) a stretch of 10 km up- and downstream was analyzed (= 20 km). Feld (2004) listed 22 different variables including percent (%) length of impoundments, lack of natural vegetation, or water abstraction.

c. **Site-related** variables were recorded for each sampling occasion separately. They refer to a stretch of 250 m up- and downstream (= 500 m) of the sample site for small streams and 500 m up- and downstream (= 1000 m) in the case of middle sized streams. Feld (2004) listed 32 different variables including habitat composition and physico-chemical variables.

Table 2. Hydromorphological variables considered.

1. Hydrological Regime	
Flow variables: quantity and dynamics of water flow	
Flow Magnitude Daily average, Monthly average, Annual minimum base flow.	*Flow Variability*: Coefficient of variation of magnitude variables Rate of change (recession & rise)
Flood variables Flood duration Flood frequency Flood magnitude Flood timing	*Channel Drought variables* Duration Frequency Timing
Sediment flow variables Bed load, Suspended load Intercepted sediment	*Hydraulic variables* Water depth Water velocity Wetted perimeter

Connection to groundwater Infiltration rate Phreatic level Phreatic stability	
2. River continuity	
Isolated segment size Nº isolated segments (by dams and obstacles)	
3. Morphological conditions	
Channel dimensions Channel depth Channel width Channel width/depth ratio	Planform variables Sinuosity Braiding / Anastomosing index Lateral mobility
Thalweg variables Thalweg altitude Channel slope Slope variability	Substrate of the river bed Grain size Interstitial capacity Fines, sand & gravel % Bed form variables LWD; POM
Bank variables Bank size (% channel width) Bank structure variability Bank stability Bank area colonized by young vegetation	Water energy variables Shear stress Stream power
Structure of the riparian zone Riparian canopy area Riparian corridor width Riparia corridor continuity (%) Woody Vegetation age structure Woody vegetation mortality	Structure of the floodplain Lateral connectivity Oxbow drought Oxbow filling Secondary channels Height of the floodplain
4. Other variables (physico-chemical)	
Nutrient concentration Water temperature Channel insolation Dissolved Oxygen	

Scale and variability

The dynamic nature of alluvial **floodplain** rivers is a function of flow and sediment regimes interacting with the physiographic features and vegetation cover of the landscape. During seasonal inundation, the flood pulse forms a 'moving littoral' that traverses the flood plain, increasing productivity and enhancing connectivity (Ward & Stanford,2006).

4 Effects of pressures

Anthropogenic impacts such as flow regulation, channelization, and bank stabilization, by (1) disrupting natural disturbance regimes, (2) truncating environmental gradients, and (3) severing interactive pathways, eliminate upstream-downstream linkages and isolate river channels from riparian/floodplain systems and contiguous groundwater aquifers. These alterations interfere with successional trajectories, habitat diversification, migratory pathways and other processes, thereby reducing biodiversity (Ward, 1998).

For each pressure we have presented a theoretical scheme of the pressure effects on the fluvial hydromorphological (HYMO) interactions system. This system is described by:

a. the HYMO processes involved (but also physico-chemical processes are considered if they are affected),

b. the altered variables (HYMO and physico-chemical) and

c. the possible impacts on the biological elements responsible for changes on ecological status.

In some cases the Pressures affect the HYMO variables directly (without the processes) and then, these variables are shown in red. Also, some impacts are caused by the absence of processes that would exist in the absence of the pressures.

4.1 Effects of Water abstractions

Dewson et al. (2007) found that water abstraction decreased water velocity, water depth, and wetted channel width and changes in thermal regime and water chemistry in 90 % of the case studies analysed; James et al. (2008) found that flow reduction significantly decreased water velocity (60–69%) in all streams, while depth (18–61%) and wetted width (24–31%) also tended to decrease. Kleynhans (1996) described loss of fast flowing instream habitat types in streams affected by water abstraction.

Sedimentation process may increase and fine sediment deposition increases the most in farmland streams affected by water abstraction (James et al. 2008). Also, with decreased flows the Coarse Particulate Organic Matter (CPOM) retention rate is increased (Dewson et al, 2007).

If floods are reduced in main stem river channels, fine sediments delivered by less abstracted tributaries may no longer be flushed downstream but may accumulate on the river bed, reducing its permeability (Kondolf and Wilcock 1996).

When water abstraction is intense, channel drought impacts may be disproportionately severe, especially when certain critical thresholds are exceeded. For example, ecological changes may be gradual while a riffle dries but cessation of flow causes abrupt loss of a specific habitat, alteration of physico-chemical conditions in pools downstream, and fragmentation of the river ecosystem (Boulton, 2003).

A theoretical framework describing the effects of water abstraction is shown in Figure 1.

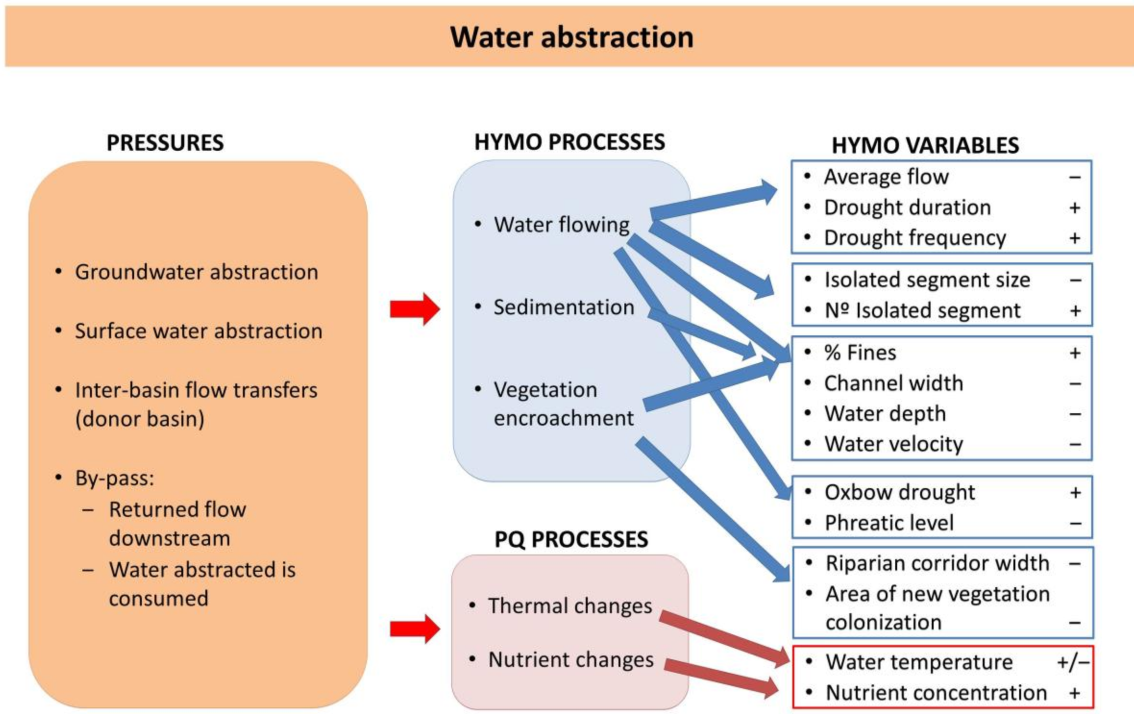


Figure 1: Conceptual framework representing water abstraction effects on HYMO processes and variables and their ecological impacts (HYMO is for Hydromorphological and PQ for Physico-chemical).

In dry countries, deterioration of riparian habitat integrity is a widespread consequence of water abstraction: during droughts tree deaths are common (Kleynhans, 1996).

Changes in thermal regime and water chemistry were found in rivers affected by flow withdrawals by Dewson et al, (2007), and James et al. (2008) found that flow reduction decreased the water temperature range by 18–26%, although it had little effect on average surface water temperatures.

Reduced flows within some river reaches may present impassable obstacles for fish migrations, either by decreasing water depths to below critical levels or by completely drying up entire reaches of river, as occurs on the San Joaquin River of California as a consequence of diversions from Friant Dam (Cain 1997). Also, where baseflows are artificially reduced, dissolved oxygen levels fall to lethal levels in reaches affected by eutrophic or high temperature discharges (e.g., Loire River, France), or dredging (e.g., the Lower San Joaquin River, California), preventing anadromous salmonids from migrating upstream to suitable habitats (Kondolf et al., 2006).

Water extraction can also entrain aquatic organisms. For example, Pringle and Scatena (1999) showed that water extraction removes more than 50% of migrating shrimp larvae in a river located in the Caribbean National Forest in Puerto Rico.

In relation to macroinvertebrates, flow reduction has not been observed to impact on the abundance of common pool macroinvertebrates or on the abundance, vertical distribution or community composition of hyporheic macroinvertebrates. James et al. (2008) found that aquatic macroinvertebrates are resistant to short-term, severe flow reduction as long as some water remains. However, in general, invertebrate abundance may increase or decrease in response to decreased flow, whereas invertebrate richness commonly decreases because habitat diversity decreases (Dewson et al, 2007). Furthermore, Muñoz & Prat (1996) found a highly significant reduction of macroinvertebrate density and taxon number at disturbed stations as consequences of increased pollutant concentrations under abstraction conditions.

Groundwater abstraction
While surface water abstractions directly affect river flows, groundwater abstractions (both from shallow and deep aquifers) indirectly lower the discharge of streams and rivers, thereby decreasing the flow velocity and water depth in these water bodies. Acreman et al. (2000) stated that large groundwater abstractions have a detrimental effect on rivers and wetlands. Additionally, status assessments of groundwater bodies in Denmark (Fyn region) and Scotland (East Lothian area), have shown reductions in base flow by 11% and 52%, respectively, due to groundwater abstractions (Henriksen et al., 2007; Ward and Fitzsimons, 2008).

Groundwater abstractions for irrigation can pose significant risks to groundwater conditions, and hence baseflow (Taylor et al., 2012). For example, in two sandy lowland catchments in the Netherlands, groundwater abstractions have caused a base flow reduction of 5-28% (Hendriks et al., in review), even though the density of groundwater abstraction points for spray irrigation in these catchments is relatively low compared to some sandy catchments in the province of Noord-Brabant that show stream discharge reductions of 22% to 56% due to intensive spray irrigation (> 6 irrigation points per km^2) (De Louw, 2000). Importantly, since spray irrigation occurs mainly during the summer growing season, it mostly affects groundwater levels and stream discharge during naturally low flow periods when water availability in streams is crucial for aquatic life.

4.2 Effects of Flow regulation

Predictions and quantification of geomorphic and biotic responses to altered flow regimes are, at the present state of our knowledge, difficult. One obvious difficulty is the ability to distinguish the direct effects of modified flow regimes from impacts associated with land-use change that often accompany water resource development (Bunn & Arthington, 2002). For example, the geomorphic consequences of changes in flow vary according to the nature of any changes in sediment supply to the river, and any consequent adaptation in channel size, form or stability may also be strongly influenced by riparian vegetation colonization, growth and resistance to uprooting (Petts and Gurnell, 2005, 2013).

The natural flow regime of a river influences aquatic biodiversity via several interrelated mechanisms that operate over different spatial and temporal scales. Bunn & Arthington (2002) have proposed four principles for understanding how the flow regime influences the life cycle of aquatic populations (Figure 2). The relationship between biodiversity and the physical nature of the aquatic habitat is likely to be driven primarily by the typical high flows that determine channel size, form and dynamics and thus the complexity and disturbance of physical habitats (principle 1). However, droughts and low-flow events are also likely to play a role by limiting overall habitat availability. Many features of the flow regime influence life history patterns, especially the seasonality and predictability of the overall pattern, but also the timing of particular flow events (principle 2). Some flow events trigger longitudinal dispersal of migratory aquatic organisms and other large events allow access to otherwise disconnected floodplain habitats (principle 3). The native biota have evolved in response to the overall flow regime. Catchment land-use change and associated water resource development inevitably lead to changes in one or more aspects of the flow regime resulting in declines in aquatic biodiversity via these mechanisms. Invasions by introduced or exotic species are more likely to succeed at the expense of native biota if the former are adapted to the modified flow regime (principle 4).

Flow regulation in dry countries changes dramatically natural flow regimes. To compensate their impacts water managers have implemented minimum flows or environmental flows. Nowadays, scientists recognize that arbitrary ‘‘minimum’’ flows are inadequate, since the structure and function of a riverine ecosystem and many adaptations of its biota are dictated by patterns of temporal variation in river flows (the ‘‘natural flow-regime paradigm’’; Richter et al. 1996, Poff et al. 1997, Lytle and Poff 2004). There is now general agreement among scientists and many managers that to protect freshwater biodiversity and maintain the essential goods and services provided by rivers, we need to mimic components of natural flow variability, taking into consideration the magnitude, frequency, timing, duration, rate of change and predictability of flow events (e.g., floods and droughts), and the sequencing of such conditions (Arthington et al. 2006).

Governments, citizen groups and the private sector now seek answers to more specific questions: ‘‘How much can we change the flow regime of a river before the aquatic ecosystem begins to show decline? How should we manage daily flows, floods and interannual patterns of variability to achieve the desired ecological outcomes?’’ Scientific uncertainties associated with these and related questions can be addressed through carefully planned, long-term, adaptive flow management experiments (e.g., Grand Canyon flow release, [Rubin et al. 2002], Snowy River flow restoration program [Pigram 2000]). However, these experiments typically do not suit short management time frames.

“Such simplistic guides have no documented empirical basis and the temptation to adopt them represents a grave risk to the future integrity and biodiversity of the world’s riverine ecosystems. For example, despite ample precautionary advice in applying the ‘‘two-thirds’’ target to rivers other than the Murray (Jones 2002), some water managers in Australia have, predictably, come to regard a third of a river’s median annual flow as a legitimate target when allocating water for abstraction. Similarly, implementing the suggested flow targets to achieve ‘‘fair’’ ecological condition at 20–30% MAR (mean annual runoff) for arid-zone regions with highly variable flow regimes, and up to 50% MAR for rivers in equatorial regions and some lake-regulated rivers (Smakhtin et al. 2004) would almost certainly cause profound ecological degradation, based on current scientific knowledge (Poff et al. 1997, Pusey et al. 2000, Bunn and Arthington 2002, Nilsson and Svedmark 2002, Petr et al. 2004). Indeed, such static rules defy fundamental understanding of the critical roles of flow variability in sustaining riverine ecosystems. Extracting a third to a half of a river's annual discharge (mean or median) would almost certainly alter the timing and range of variation of ecologically important flow events. Furthermore, in arid-zone streams and rivers with very high interannual variation in MAR, such levels of abstraction would lead to complete dewatering in years of low runoff and severe ecological impacts (Arthington et al. 2005, Hamilton et al. 2005, Bunn et al. 2006)." (Arthington et al. 2006).

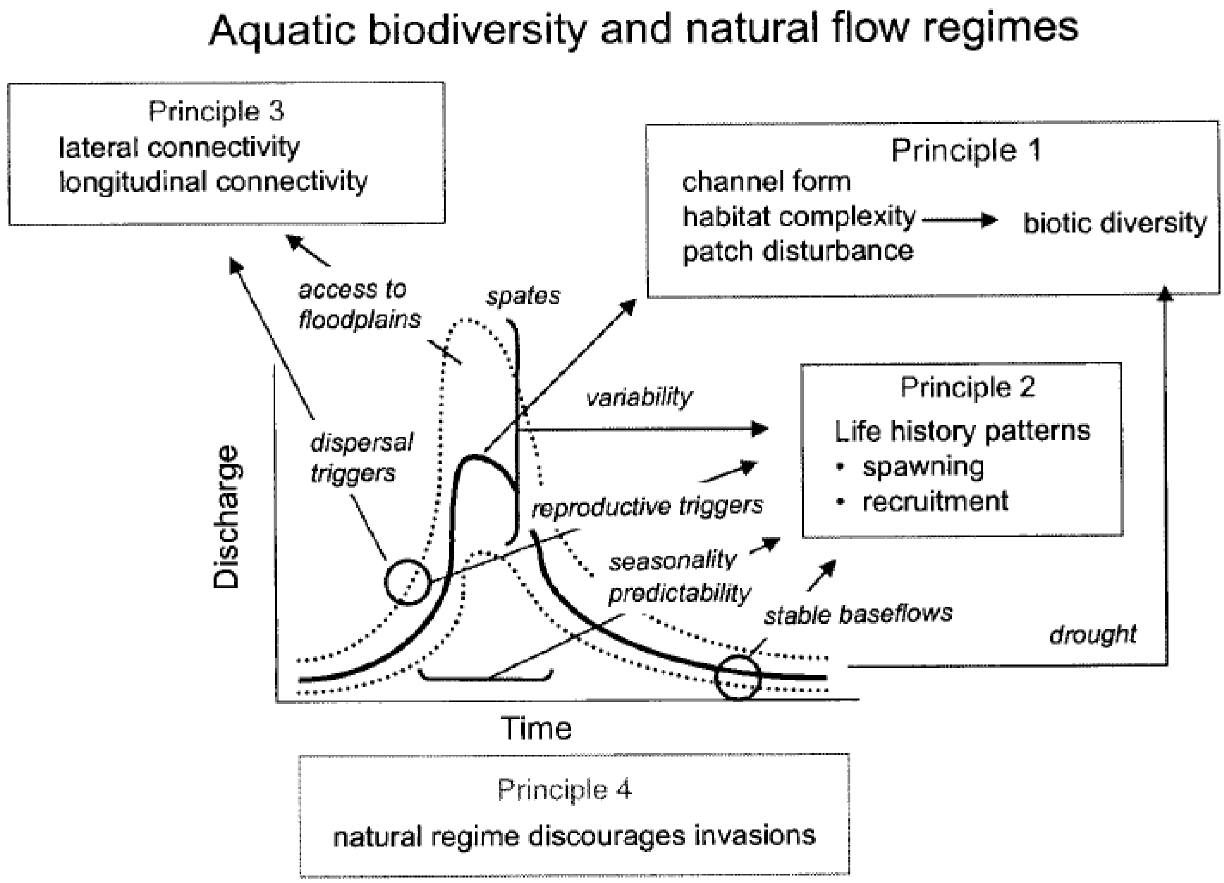


Figure 2. Influences of natural flow regime of a river on aquatic biodiversity via several interrelated mechanisms that operate over different spatial and temporal scales. Proposed four principles for understanding how the flow regime influences the life cycle of aquatic populations (Bunn & Arthington, 2002)

In Spain, River Basin Management Plans fix ecological flows at much lower percentages of natural flows (% MAR), far away from thresholds of biotic sustainability. In Figure 3 the frequencies of water bodies are shown and their ecological flows (in terms of % mean annual flow) for the River Duero Basin. The most frequent ecological flow is lower that 10 %, and 90 % of the water bodies have an ecological flow that is lower than 25% of the MAR.

Flows reduced by reservoir regulation also affect water quality as spill pollutants become concentrated. From a quantitative point of view, the low flow phase is of critical importance for the state of the river ecosystems, while drastic discharge fluctuations during the low flow phase do not significantly influence the water ecosystems (Dakova et al. 2000).

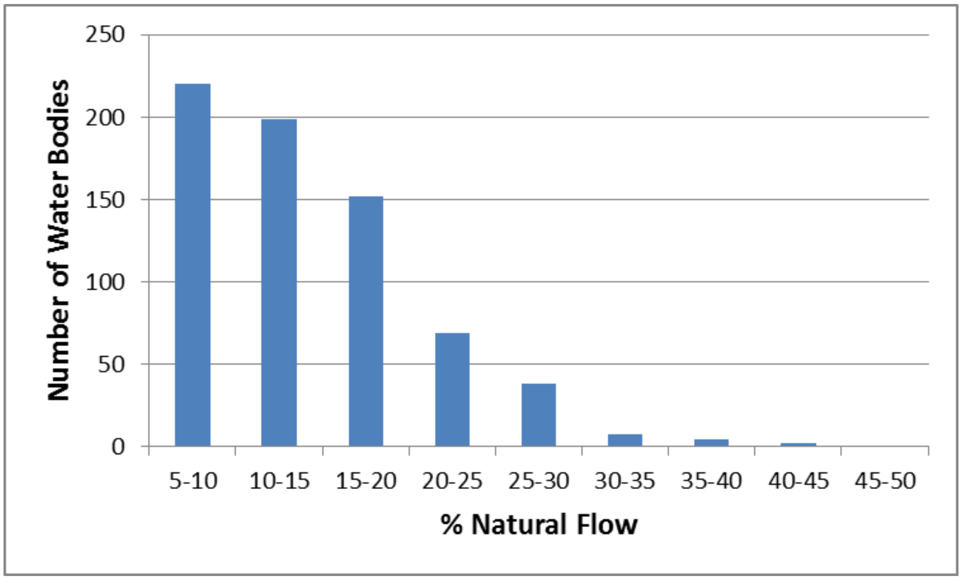


Figure 3. Histogram representing the percentage of mean annual natural flow fixed as ecological flows related to the number of Water bodies in the Spanish River Duero Basin.

4.2.1 Increased Flow

The effects of increased flow are summarised in Figure 4.

For example, Church (1995) described the impact of flow increases through diversion of water into the Kemano River, Canada. The increased discharge mobilized bed material causing gradual channel enlargement, which became particularly noticeable following the occurrence of a competent flood (Church, 1995).

Dominck & O'Neill (1998) studied tributary basins of the upper Arkansas River in which peak annual floods were augmented and flows of a given magnitude were sustained over longer periods of time. The geomorphic response detected was an increase of bankfull channel width and width to depth ratios; substrate size on depositional bars at augmented sites substantially increased; river sinuosity shifted from highly sinuous meandering channels to less sinuous or braided channels; loss of riparian vegetation cover, that primarily occurred along channel margins, with commensurate increases in exposed depositional bars and active channel features.

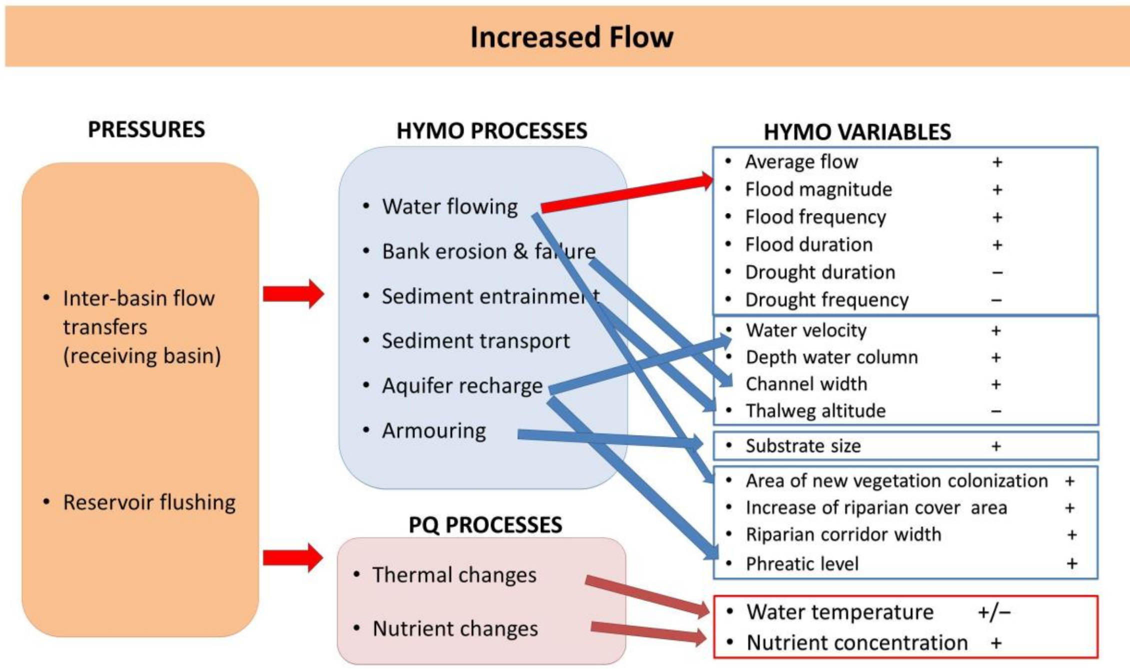


Figure 4. Conceptual framework representing increased flow effects on Hydromorphological (HYMO) and physico-chemical (PQ) processes and variables.

The time-scale for such geomorphic responses mainly depends on the nature and severity of the increased flows in comparison with the pre-existing flow regime, the erodibility of the river bed and banks, including the reinforcing effects of vegetation, and the sediment supply to the regulated river reaches. Channel responses are inevitably complex in space and time, as fluvial processes and landforms (physical habitats) interact and those interactions propagate along river channels. Furthermore, these complex adjustments to a new geomorphic state can extend over timescales ranging from decades to millenia (Petts and Gurnell, 2005, 2013).

The ecological response to increases in flows can also be varied and complex. For example, in a large interbasin water transfer system in northern Texas, Matthews et al. (2003) found out that there was little overall change in abundance of individual fish species within a week before and after artificial high flows were produced. However, at some stations the quantitative or qualitative change in composition of the local assemblage was substantial.

4.2.2 Flow Regime modification

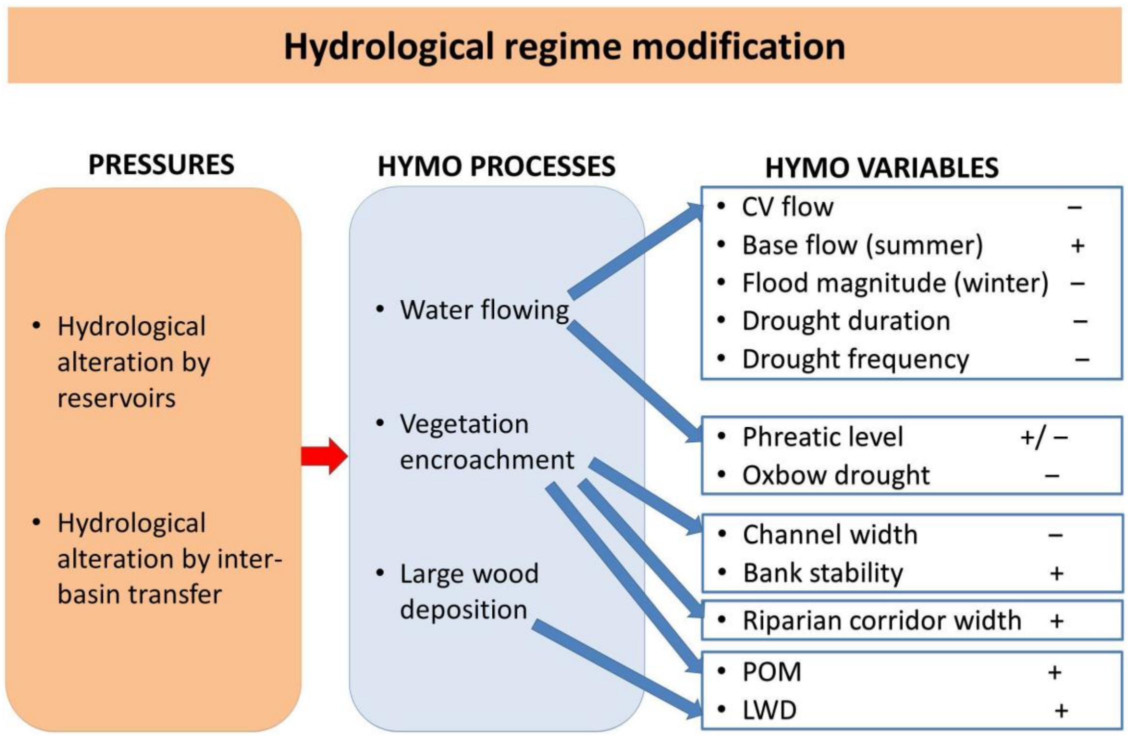


Figure 5. Conceptual framework representing aggregate impacts of impoundments and interbasin transfers on hydromorphological (HYMO) processes and variables.

The implementation of river impoundments and inter-basin transfers may increase or decrease flows, but they also have aggregate effects on other properties of the flow regime, including flow variability and timing (Figure 5). Magilligan and Nislow (2004) reviewed pre- and post-dam hydrological changes downstream of dams that covered the spectrum of hydrological and climatic regimes across the United States. In general, the most significant changes occurred in minimum and maximum flows of different duration. The 1-day through 90-day minimum flows increased significantly and the 1-day through 7-day maximum flows decreased significantly following impoundment. Other significant adjustments across the majority of sites following impoundment included: an increase in the number of hydrograph reversals; an increase in the number of flow pulses but a decrease in their duration; and a decrease in the mean rate of hydrograph rise and fall.

At a basin scale, Batalla et al. (2004) showed that the presence of 187 large dams in the Ebro basin, with a total capacity equivalent to 57% of the total mean annual runoff, reduced flood magnitude, with Q_2 and Q_{10} reduced over 30% on average, particularly in rivers with higher values of the impounded runoff index, (i.e., reservoir capacity divided by mean annual runoff). Also, they found that the variability of mean daily flows was reduced in most cases due to storing of winter floods and increased baseflows in summer for irrigation.

The important role of physical stability, defined in relation to hydrological (frequency, duration and timing of inundation) and channel parameters (channel dynamics, bedform and sediment size) on fluvial ecosystems was emphasized by Petts (2000). Thus, regulated flows disturb the bedform, surface-water and groundwater interactions and the channel form dynamics and associated changing hydraulic conditions that alter both benthic and riparian community patterns.

Decreased flow dynamics can reduce vertical hydrological connectivity by reducing hydraulic gradients (Kondolf et al. 2006).

Flood peaks are typically reduced by river regulation, which reduces the frequency and extent of floodplain inundation and flow through side channels (Gergel et al. 2002, and Henry et al. 2002). The reduction in channel-forming flows reduces channel migration, an important phenomenon in maintaining high levels of habitat diversity across floodplains (Ward & Stanford, 2006): the rich mosaic of habitat patches across the floodplain due to a wide range of successional stages is transformed into an uniform mature riparian forest. Hydrological connectivity with the remaining floodplain geomorphic features is also reduced, as illustrated by flow regulation on the lower Macintyre River, Australia. Here flow regulation has limited exchanges between the river and its floodplain, (Walker & Thoms 1993), including a reduction in the frequency of hydrological connections to a series of anabranch channels by up to 22% (Thoms et al 2005); induced a stepped profile in the main channel; and changed the nature of the littoral zone, creating an environment inimical to many native species, notably fish (Walker & Thoms 1993).

Flushing flows are often employed in an attempt to impede or reverse some of these effects. Such flows are particularly effective in removing fine particulate materials and chemicals that may have accumulated under supressed flow conditions. For example, flushing flows from Beervlei Dam on the Groot River were effective in removing accumulated salts from riverine pools. The flushing flows were followed by reduced flows which initiated spawning of the potamodromous minnow species in the riffle areas (Cambray 2006).

4.2.3 Hydropeaking

Hydropeaking is a unique form of flow regulation, in that it introduces frequent, short duration, artificial flow events to the river. The theoretical framework related to the effects of hydropeaking is shown in Figure 6. The impacts of hydropeaking on channel size and morphology are highly dependent on the size and frequency of hydropeaks in relation to size of geomorphological effective flows prior to regulation. Where extreme hydropeaking leads to frequent geomorphological-effective flows (i.e. flows close to the bankfull stage), the hydropeaks dominate channel size and form because they readily mobilize bed sediments until the bed becomes heavily armoured by very coarse particles or scoured to bed rock. Such severe hydropeaking leaves few alluvial habitats and in-channel vegetation, and an abrupt transition between unvegetated and vegetated surfaces at the channel boundary. However, where hydropeaks are smaller and thus less competent to move bed sediment and the pre-existing geomorphologically-effective flows are significantly less frequent or no longer occur under the new hydropower dominated regime, physical adjustments may occur within the pre-existing channel. Sear (1995) describes an example of the latter situation, where the observed adjustments to the gravel-bed North Tyne River are indicative of channel narrowing and retention of fine sediment in the bed, in response to diurnal adjustments of river stage by approximately 0.6 m from hydropeaking:

a) the development of fine sediment berms along channel margins,
b) the aggradation of pools,
c) the encroachment of vegetation on former gravel shoals
d) the growth of tributary confluence bars.
e) degradation of riffle spawning grounds: characterized by higher percentages of fines within spawning gravels, coarsening of surface gravels and the development of a stable, strong bed fabric.

Hydropeaking has been found to have other more indirect hydromorphological impacts beyond those on channel morphology and sediments. Thus, Curry et al. (1994) found that short-term flow fluctuations affected hyporheos dynamics. Fluctuating flow levels altered groundwater pathways, chemistry, and flow potentials within the river bed. Rising river levels introduced river water into the bank where various degrees of mixing with groundwater occurred. Subsequent recessions of river levels increased the potentials for groundwater flow into the river channel. They found that these effects were significant at spawning and incubation sites and were thus potentially important for river ecology.

Further indirect hyporheic effects were identified by Arnzten et al. (2007) who found empirical evidence of how changes in flow regime and in bed sediment permeability, relating to ingress of fine sediments, altered the vertical hydraulic gradient and water quality of the hyporheic zone within the Hanford Reach of the Columbia River in response to 2 m daily water level fluctuations due to hydropower generation.

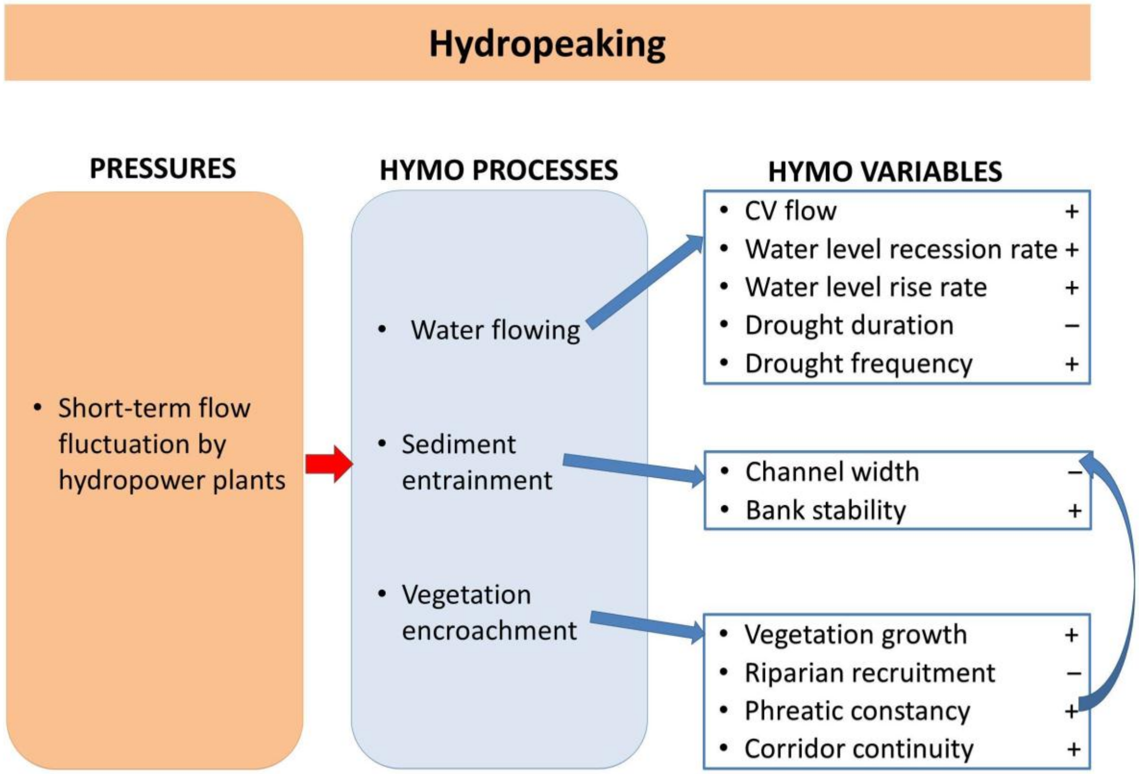


Figure 6. Conceptual framework of hydropeaking effects on hydromorphological (HYMO) processes and variables.

A range of ecological consequences of hydropower development have also been recorded. Nilsson et al. (1991) evaluated the effects of an old hydropower reservoir on river margin vegetation. While he found no difference in mean annual discharge, number of types of substrate, and width and height of the river margin (relative to the summer low-water level), the regulated river had fewer frequent and more infrequent species, and the proportion of annual plus biennial species-richness was higher, while the proportion of perennial species-richness was lower. Also, vegetation cover was lower in the regulated river.

Reduced biotic productivity in reaches below hydroelectric reservoirs may be due directly to flow variations or indirectly to a variety of factors related to flow variations, such as changes in water depth or temperature, or scouring of sediments. Many riverine fish and invertebrate species have a limited range of conditions to which they are adapted. The pattern of daily fluctuations in flow imposed by hydropeaking is not one to which most species are adapted; thus, such conditions can reduce the abundance, diversity, and productivity of these riverine organisms (Cushman, 1985).

Thus, Trotzky & Gregory (1974) focussed specifically on the effect of severe low flows associated with flow fluctuations on the upper Kennebec River. In particular they observed that the very slow currents during low flows between hydropeaks appeared to limit the diversity and abundance of swift-water aquatic insects (*Rhyacophila,* *Chimarra, Iron, Blepharocera, Acroneuria,* and *Paragnetina*) on the river-bottom below the dam.

In relation to high flows, Robertson et al. (2004) subjected Atlantic salmon par to simulated short term flow fluctuations and found that fish habitat use was not affected; there was little effect on fish activity within diel periods; and stranding rates during flow reduction were also very low. However, most research has indicated significant impacts of hydropeaks on both macroinvertebrates and fish.

Bain et al. (1988) found that the fish guild of small-species and size classes that occupied habitats characterized as shallow in depth, slow in current velocity, and concentrated along stream margins, were eliminated or reduced in abundances at a study site subject to large flow fluctuations.

Furthermore, Moog (2006) identified significant impacts of intermittent power generation on the fish fauna and benthic invertebrates of several Austrian rivers. Hydropeaking was found to disturb long sections of rivers, with a breakdown of the benthic invertebrate biomass of between 75 and 95% within the first few kilometres of river length, and a reduction of between 40 and 60% of biomass within the following 20–40 km. The reduction of the fish fauna was of the same order of magnitude and correlated well with the amplitude of the flow fluctuations.

Similar biotic effects were detected in a Pyrenean river affected by a hydropower impoundment by Garcia de Jalón et al. (1988). At a single sampling station 2.4 km below the dam, there was a significant ($p < 0.05$) decrease in total macrophyte biomass, although the species composition remained dominated by two species (*Myriophyllum verticillatum* and *Ranunculus fluitans*), and the macroinvertebrate community exhibited a significant ($p < 0.05$) decrease in taxonomic richness, total density and total biomass. In general, planarians, ephemer-opterans, coleopterans, plecopterans and trichopterans disappeared or decreased their abundances. Scrapers (as relative biomass) were the functional feeding group most adversely affected by the new flow regulation. With regard to the fish community, the most significant change was the absence of all resident coarse fishes (cyprinids, primarily) at the sampling site during the 1990 and 1991 sampling surveys.

4.3 Effects of River fragmentation

River fragmentation is mainly assumed to be caused by barriers that interrupt the longitudinal gradient or by lateral dikes that disconnect the channel and floodplain. Thus the fragmentation effects of large dams is superimposed on their effects on the flow, sediment and physico-chemical regimes and is recognizable along the entire river continuum and laterally across floodplains (Ward and Stanford, 1983, 1995). However, reaches of river channel that are subjected to artificial drought or heavy pollution can also act as river fragmentation factors. Furthermore, riparian corridors are frequently fragmented by forestry and farming activities.

River fragmentation is of wide significance, since most large rivers of the world are fragmented due to flow regulation schemes, and only a few river systems in the northern third of the world are free flowing (Dynesius & Nilsson 1994). The theoretical framework associated with the effects of river fragmentation is shown in Figure 7, highlighting:

- Artificial barriers upstream from the site
- Artificial barriers downstream from the site
- Collinear connected reservoirs

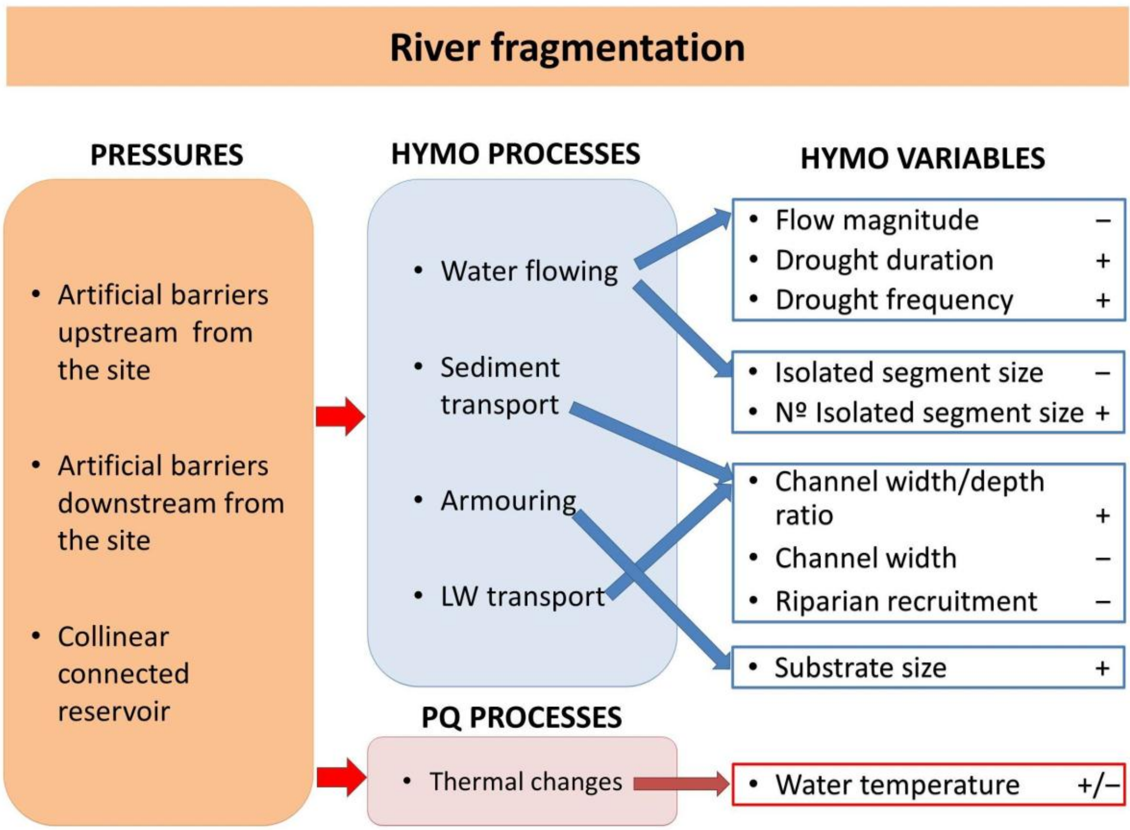


Figure 7. Conceptual framework of river fragmentation effects on HYMO processes and variables.

The impact of dams and related flow regulation and fragmentation on riparian vegetation has been well-studied. Andersson et al (2000) found that riparian floristic continuity was reduced below dams, and Merritt et al. (2010) suggested that water dispersal of plant propagules may be reduced and the long-term species richness of the riparian community may decrease. However, there is no evidence that dams reduce the abundance and diversity of water-dispersed propagules by acting as barriers for plant dispersal (Jansson et al, 2005).

The construction of weirs and other embankments on the lower Macintyre River floodplain has had lateral fragmentation effects by preventing water movement through a series of anabranch channels thereby reducing the availability of these floodplain patches by 55% (Thoms et al 2005), and thus reducing the potential dissolved organic carbon supply from some anabranch channels to the main channel by up to 98% (Thoms et al 2005).

The ways in which dams and weirs act as physical barriers to the migration of fish and other biota have long been recognized (Kingsford 2000a,b). Barriers located near the river mouth have the greatest impact on fish with diadromous life histories while those located near the center of the river network have the most impact on fish with potadromous life histories (Cote et al. 2009).

Sanches et al. (2006) showed a clear decline in densities and number of fish species caught after the closure of the Porto Primavera dam, Brazil. Also, larvae of migratory species, were restricted to the confluence of non-dammed tributaries, indicating that the closure of the dam had caused negative impacts on fish reproduction downstream of the dam.

In a fish population modeling experiment Jager et al. (2001) found that increased fragmentation by dams produced a reduction in genetic diversity and an exponential decline in the likelihood of persistence, but no extinction threshold that would suggest a minimum viable length of river. They also found that migration patterns played a significant role in determining the viability of riverine fishes, with those populations with high downstream, and low upstream, migration rates showing a higher risk of extinction.

4.4 Effects of Morphological alterations

4.4.1 Impoundment

Here, we refer to the water body that is impounded by relatively small structures. This type of pressure changes the hydraulic conditions on the impounded river reach, from lotic to lentic. A transverse obstacle such as a weir increases water depth and reduces water velocity, and as a result fine sediment is deposited, clogging interstitial habitats. However, when high flows occur, these fine sediments can be mobilised and washed out over these relatively small structures.

The theoretical framework relating to the effects of such impoundments is shown in Figure 8.

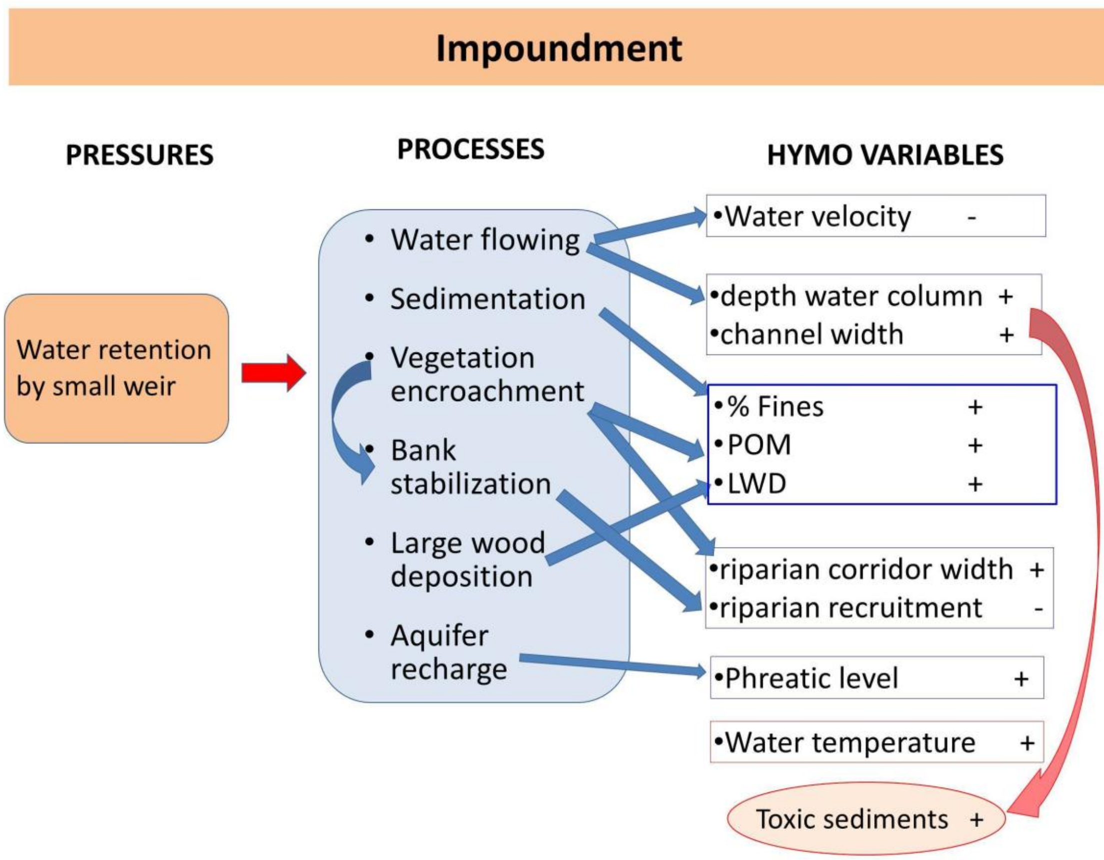


Figure 8. Conceptual framework of impoundment effects on HYMO processes and variables.

Small impoundments flood areas that were previously part of the channel margin and floodplain. Such flooding can have physical and chemical effects both within the impoundment and downstream. For example, in relatively dry environments, more frequent inundation can exaccerbate salinization, as was observed in association with flooding of once-temporary wetlands in Australia (Walker & Toms 1993).

Increased inundation can benefit native fishes, as was observed in southwestern streams of the USA, by disproportionately displacing non-native fishes (Schultz et al. 2003). Moreover, the beneficial effects of impoundments for certain species can have indirect effects on HYMO processes such as suspended load chemical composition. Barton et al. (2000) found significantly higher concentrations of suspended inorganic matter in the outflows than the inflows of three impoundments along an urban stream in southern Ontario during baseflow conditions, due to carp (*Cyprinus carpio*) feeding activities.

The impact of small impoundments can also be assessed by observing the impact of their removal and the restoration of natural flow dynamics. Stanley et al. (2002) observed a significant decrease in the width of the active channel within the impoundment (from 59 m^2 to 11 m^2) as a result of the removal of a low-head dam at Baraboo River, Wisconsin. There was an increase in the extent of 'loose' bed sediments including an increase in the sand fraction immediately following dam removal, but the channel adjusted rapidly to an equilibrium form, particularly following the occurence of the first significant flood. Overall, only small and transient geomorphological and ecological changes and no alteration of channel dimensions were observed in downstream reaches. Within one year of removal, there were no significant differences in macroinvertebrate assemblages among the formerly impounded reaches, an upstream reference site, or reaches downstream of the dam site. The small changes and rapid recovery reflect the relatively large channel size and the small volume of stored sediment associated with this relatively small impoundment.

4.4.2 Large Dams and Reservoirs

Unsurprisingly, large impounding structures have stronger and more far-reaching effects within the impounded reach than their smaller counterparts. The theoretical framework summarizing these effects are shown in Figure 9.

Impoundment of water behind large dams has global impacts. Since 1950, the construction of large dams has induced by far the largest anthropogenic hydrological change in terms of the mass of water involved. This water mass redistribution contributes to geodynamic changes in the Earth's rotation and gravitational field. For example, Chao (1995) quantified a significant effect of 88 major reservoirs on day length, polar drift, and low-degree gravitational coefficients over the last 40 years. As previously noted, Vörösmarty et al. (1997) estimated that in the mid 1980s the maximum water storage behind 746 of the World's largest dams was equivalent to 20% of global mean annual runoff and the median water residence time behind these impoundments was 0.40 years. Vörösmarty et al. (1997) also estimated that more than 40% of global river sediment discharge is intercepted by 633 of the world's largest reservoirs. More recently, Vörösmarty (2003) estimated that more than 50% of the basin-scale sediment flux in regulated basins is trapped in artificial impoundments, with discharge-weighted sediment trapping due to large reservoirs of 30%, and an additional 23% trapped by smaller reservoirs.

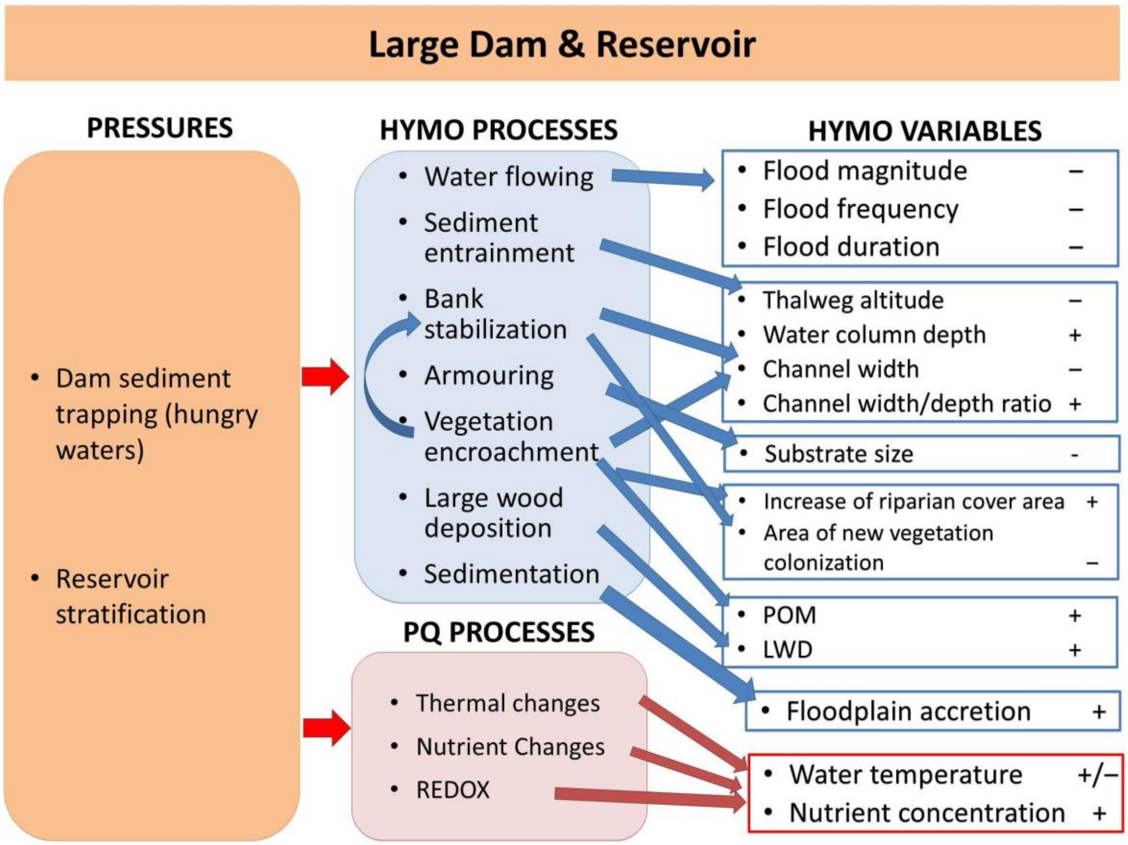


Figure 9. Conceptual framework of large dams and reservoirs effects on HYMO processes and variables (POM=Particulate Organic Matter; LWD=Large Woody Debris).

There are many comprehensive reviews of the hydromorphological effects and ecological impacts downstream of dams (e.g. Ward and Stanford (1979), Petts (1984), Williams and Wolman (1984), Ligon et al. (1995), Grant et al. (2003) and Grant (2012)).

Rood et al. (2005) suggested that downstream ecological impacts of large dams often follow from three types of environmental alterations: 1) changes in the released flow regime (quantity and timing); 2) reduced passage of alluvial materials and particularly suspended sediments, and 3) the fragmentation of the river corridor, with interruptions in downstream and upstream passage of biota (Ward and Stanford 1995a, 1995b). Alterations to the water flow regime are determined by dam operations, while sediment trapping and interruption to corridor connectivity are largely unavoidable consequences of the presence of major dams and the vast reservoirs of water that they impound (Braatne et al., 2008). Changes in the flow regime (the first set of alterations identified by Rood et al. (2005)) incorporate the pressures associated with water abstraction, flow regulation and hydropeaking, which were analysed earlier.

Petts (1980, 1984) proposed a framework to evaluate long-term effects of large reservoirs on the fluvial environment, which comprised three orders of impact. First-order impacts are those that are the direct physical and chemical consequences of dam closure: changes in the flow regime, particularly flood magnitude and frequency; the quantity and calibre of sediment supply; and the quality of the water (including temperature and oxygen content) delivered from the reservoir. These first-order impacts induce second order impacts, notably adjustments in channel morphology (including vegetation encroachment) and in ecology in response to the changes in flow, sediment and water quality supplied to downstream reaches. Third order impacts include the further adjustments of the biota in response to the second-order morphological and bed sediment adjustments that lead to a completely different assemblage of hydraulic and morphological habitats.

Numerous studies illustrate the severity of the first-order impacts induced by large impoundments. The Ebro River provides such an illustration at a basin scale. Guillen & Palanques (1992) estimated that the sediment load entering the delta of the Ebro river represented only 1% of the sediment discharge prior to dam construction in the Ebro basin. The mean annual flow of the lower Ebro River decreased by 29% during the 20th century as a result of increased water use and evaporation from reservoirs within the river basin. Water losses due to irrigation account for 74% of the decrease, whereas losses by evaporation in the reservoirs explain another 22%. Decreased flow in the lower Ebro River has resulted in encroachment of the salt wedge in the estuary: permanent low flows from July 1988 to April 1990 caused the continuous presence of the salt wedge for 18 months. Before the construction of large reservoirs in the lower Ebro at the end of the 1960s, the sediment transport was estimated to be around 1.0×10^7 Mt yr^{-1}. This amount was reduced to around 0.3×10^6 Mt yr^{-1} after construction of the dams. Currently, this amount ranges from 0.1 to 0.2×10^6 Mt yr^{-1}, which represents a reduction of more than 99% in sediment transport from natural conditions. On a seasonal scale, the effects of the dams have been the standardization of the river flow and the virtual suppression of peaks in sediment transport. River regulation and hydropower generation have also changed the hydrology of the river at a daily timescale, suppressing the impact of rain storms on river flows (Ibañez et al. 1996).

Another important example of the first-order impacts can be found on the Yangtze River since the closure of the Three Gorges dam. In the period 2003-2006, ~60% of sediment entering the reservoir has been retained (Xu & Milliman, 2008). Although periodic sediment deposition continues downstream of the dam, substantial erosion has also occurred, supplying ~70 million tons per year (Mt.y^{-1}) of channel-derived sediment to the lower reaches of the river. During the extreme drought year 2006, sediment discharge drastically decreased to 9 Mt (only 2% of the 1950–1960s level) because of decreased water discharge and trapping by the dam. Severe channel erosion and a drastic decline in sediment transport have resulted in major pressures on the coastal areas at the mouth of the river and on the East China Sea (Xu and Milliman 2009).

Numerous studies have also illustrated the first-order effects of dam closure on water quality and temperature. Although, the creation of large storage reservoirs is typically coupled with the release of cool hypolimnetic water and related downstream cooling, warming can occur at some sites (Quinn et al., 1997). For example water temperature increases were observed by McAdam (2001) on the Columbia River downstream of the Hugh L. Keenleyside Dam. Elevation of outflow temperatures from the Arrow Lakes Reservoir, also on the Columbia River, were attributed to the increased transit time of near surface water during the heating season, whereas this effect was absent for Kootenay Lake because the transit time was greater than the heating period and less cold water was drawn into the outflow during the reduced spring freshet (Hamblin and Adam 2003). Lastly, Doledec et al (1996) observed a water warming effect caused by three hydroelectric schemes on the River Rhone, which had pronounced impacts on the macroinvertebrate community.

Crisp (1971) observed both water temperature and dissolved oxygen in Cow Green reservoir, UK, and also changes caused by impoundment to water temperature, chemistry, dissolved oxygen and discharge of the River Tees immediately downstream of the dam. Although thermal stratification in the reservoir was rare, the river's temperature regime showed reduced amplitude in annual and diel temperature fluctuations and a delay of the spring rise in water temperature by 20–50 days and in the autumn drop by 0–20 days. Furthermore, below dam fluctuations in ionic content were much smaller than in water entering the reservoir.

O'Keeffe et al. (1990) assessed dam effects on spot temperatures and annual temperature ranges downstream of South African reservoirs in reltion to their position on the river network. Upper river impoundments behaved similarly despite different release patterns, and were associated with only weak chemical effects which recovered rapidly (within 3 km). Middle reach impoundments also behaved similarly despite different release characteristics, but they caused more pronounced changes and recovery distances were longer (up to 30 km).

A variety of physicochemical changes have been observed in water flowing through impoundments. Soltero et al. (1973) found a large reduction in turbidity and in the concentration of most dissolved constituents in water affected by the Bighorn reservoir. Water stored in the reservoir was much more resistant to seasonal temperature changes than water in the stream entering the reservoir. The presence of a reservoir on the Elan river, mid-Wales, UK caused increased concentrations of iron- and manganese in downstream reaches (Iverarity, 1983). Creation of hydroelectric reservoirs by enlargement of riverine lakes and flooding of forested areas along the Churchill River resulted in a notable increase in methyl mercury production by microorganisms in sediments (Jackson, 1988).

Choi et al. (2005) illustrated the second-order geomorphological impacts of dam construction through a comparison of pre- and post-construction surveys of the Hwang River, Korea. A common morphological response to large dam construction is channel bed incision over a stream length of many km immediately downstream of the dam, as the river erodes its bed to replace sediment trapped by the dam (Ward & Stanford, 2006). Deepening of the channel lowers the water-table, which affects riparian vegetation dynamics and reduces the effective base level of tributaries, leading to rejuvenation and erosion. These effects are often accompanied by significant encroachment of riparian vegetation onto previously active bar surfaces, leading to channel narrowing. However, such responses are only sustained until inputs from unregulated tributaries become sufficiently important for a variety of complex changes to be induced according to their role in changing the mainstem flow regime and / or the supply of sediment.

The nature and rate of morphological adjustments depend on environmental conditions within the affected river basin as well as before and after dam closure. Wellmeyer et al (2005) analyzed the Trinity River of eastern Texas below Lake

Livingston (the most downstream of 30 reservoirs). They found no changes in high flow conditions following impoundment, but low flows were elevated, probably as a result of significantly higher rainfall during the entire post-dam period. They also found that channel activity did not indicate a more stable planform following dam closure; rather they suggest that the Trinity River is adjusting itself to the stress of Livingston dam in a slow, gradual process that may not be apparent in a modern time scale. In contrast, Micheli et al. (2004) compared bank migration rates in the Sacramento River over approximately 50 years before and after the construction of Shasta dam and found that they increased by approximately 50%, despite significant flow regulation. They attributed this to the conversion of floodplains to agriculture. A comparison of migration rates for reaches bordered by riparian forest and agriculture between 1949 and 1997, indicated that the latter showed bank erosion rates that were 80 to 150% higher than the former.

First and second order effects of dam closure can propagate laterally across the downstream floodplain. Nislow et al. (2002) found that reduced flooding in the Upper Connecticut River as a result of post-impoundment hydrologic alteration had particularly marked effects on higher floodplain terraces, where a reduction in inundation frequency from once in 20 years pre-impoundment, to ≥100 years post-impoundment, isolated them from riverine influence. At the pre-dam five to ten year floodplain elevations, they observed smaller differences in predicted flood frequency but significant differences in the total area flooded and in the average flood duration.

Nichols et al. (2005) studied the first, second and third order effects of a series of three impoundments on a rocky upland stream in southeastern Australia. First-order effects were decreased median monthly discharges and floods of smaller magnitude. The second-order effect on channel morphology was a decrease in bank-full cross-sectional area by up to 75%; and the development of a predominantly cobble armoured streambed. The discharge required to initiate movement of the streambed surface sediments was estimated to be 40% less frequent following dam closure, implying third-order alteration to the natural disturbance regime for benthic biota. Benthic algal growth appeared more prolific directly below the dams. Fewer macroinvertebrate taxa than expected and modified assemblages were further third order effects within 1 km of all three dams. Compared to reference conditions, macroinvertebrate samples from the sites directly below the dams had relatively more Chironomidae larvae, Oligochaeta and Acarina, and fewer of the more sensitive taxa: Plecoptera, Ephemeroptera, Trichoptera and Coleoptera. Biological recovery to the macroinvertebrate assemblage was evident within 4 km downstream of the second dam. Such responses vary along different reaches below impoundments as tributary channels support complex morphological responses, which in turn provide different habitat assemblages which can support, for example, different macroinvertebrate group and species (e.g. Greenwood et al., 1999).

Dam removal also impacts on HYMO processes, producing spatially and temporally variable changes in the magnitude and extent of river morphological adjustments. Borroughs et al. (2008) observed progressive headcutting of sediments within a former impoundment in Michigan, USA, which involved the net erosion of 92000 m^3 of sediment from within the previously impounded area over 10 years following dam removal. This constituted an estimated 12% of the reservoir sediment fill. Downstream, approximately 14% of this eroded sediment was deposited within 1 km, leading to channel bed aggradation and widening, with the remaining sediment being transported further downstream or deposited in the floodplain. Headcutting proceeded upstream, leading to a narrower, steeper, incised channel, with higher mean water velocity and coarser bed material.

Predicting the geomorphic response of rivers to the introduction of large dams is complex but such predictions are needed to mitigate and restore regulated rivers. Grant (2012) provides a recent review of knowledge, which has largely been generated over the last 30 years. Early empirical analysis of observations drawn from multiple rivers by Williams and Wolman (1984) revealed general trends in bed incision depth and its downstream progression below dams. Petts (1984) adopted a geomorphological approach to build a conceptual model of channel response to large dam construction, which incorporated potential adjustments at different sites along the river below the dam and through time in response to relative (before-after) changes in discharge and sediment delivery, bed material composition, bank erodibility, floodplain connectivity, the influence of unregulated tributaries, and the riparian vegetation. These ideas have been recently updated (Petts and Gurnell, 2005, 2013) and also predictive quantitative models have been proposed. For example, Schmidt and Wilcock (2008) determined that river bed incision occurred below dams when the ratio of the pre-dam to post-dam slope needed to transport the quantity and caliber of supplied sediment at the imposed discharge was greater than one, but also, the post-dam flows needed to be competent to transport the post-dam bed sediments (which may be armoured) in order to actually incise the bed.

4.4.3 Channelization: Cross section alteration

Channelization involves changes in channel planform and gradient (usually straightening); channel cross profile form and flow resistance (usually channel enlargement and removal of morphological and vegetation roughness elements); and in some cases it involves the introduction of artificial materials to reinforce the modified channel form (e.g. concrete, metal, stone, bricks). Thus, McIninch and Garman (2001) defined three significant aspects of channelization of streams in Illinois: stream alteration (the extent to which the stream channel form has been altered or modified (Barbour et al. 1999); sinuosity (the extent to which the stream channel has been straightened); and riparian canopy (the degree to which the stream coverage by vegetation has changed).

These physical changes not only increase the flow energy (increased gradient, decreased flow resistance), but they may modify sediment supply, remove important habitats within the channel, and restrict both lateral and vertical connectivity, leading to severe ecological effects (e.g. Poole et al., 2006). Hydromorphology and ecology are not only directly impacted by channelization, but channelization induces a range of hydromorphological responses that also have ecological significance.

Hydromorphological responses to channelization are as complex as those following dam construction and river impoundment and vary with the type of channelization scheme and its impact on channel gradient, the flow regime, the calibre of bed and bank materials, the supply of sediment, and the ability of the riparian vegetation to colonise and reinforce disturbed sediments.

If any adjustment is to occur, the affected stream has to have sufficient energy to move sediment and thus to remodel the form of the channelized stream. Research by Urban and Rhoads (2003) on the Embarras River basin of east central Ullinois, illustrates that where stream gradients are very low (typically between 0.001 and

0.0001 m m^{-1} in their study site), channel responses to widespread and severe channel straightening and enlargement are extremely slow and channels persist in their modified state for decades following channelization. In such environments, further human modification by river restoration is essential to the re-establishment of a healthy ecosystem.

However, in moderate to high energy environments, responses to channelisation are rapid, far-reaching and complex. One example of this complexity is provided by Simon's (1989) model of channel evolution following channelization of sand bed rivers in Tennessee. The model identifies six stages of morphological development from (i) the premodified channel and its modification to form (ii) the constructed channel, through a phase of (iii) degradation leading to a (iv) bank slope threshold stage and then a phase of (v) aggradation until (vi) restabilization is reached. Following channel 'construction', which usually involves realignment, deepening and bank steepening, channel degradation occurs within the affected reach and propagates upstream. This involves channel bed incision accompanied by erosion of the bank toe, which together steepen the banks. Eventually the banks reach a critical angle and enter the threshold stage, during which bank failures are widespread and the channel widens. Widening slows and ceases as the bank angles reduce and the channel width allows sediment to be retained at the bank toe. Sediment deposition at the toe and across the bed is enhanced by vegetation colonisation leading to significant bed aggradation and recovery to a restabilised state. Aggradation is often achieved by the formation of alternate bars, which are sediment stores that guide channel planform development. All of these phases are observed within the modified channel and they propagate upstream with bed incision and knick point retreat, leading to widespread morphological impacts.

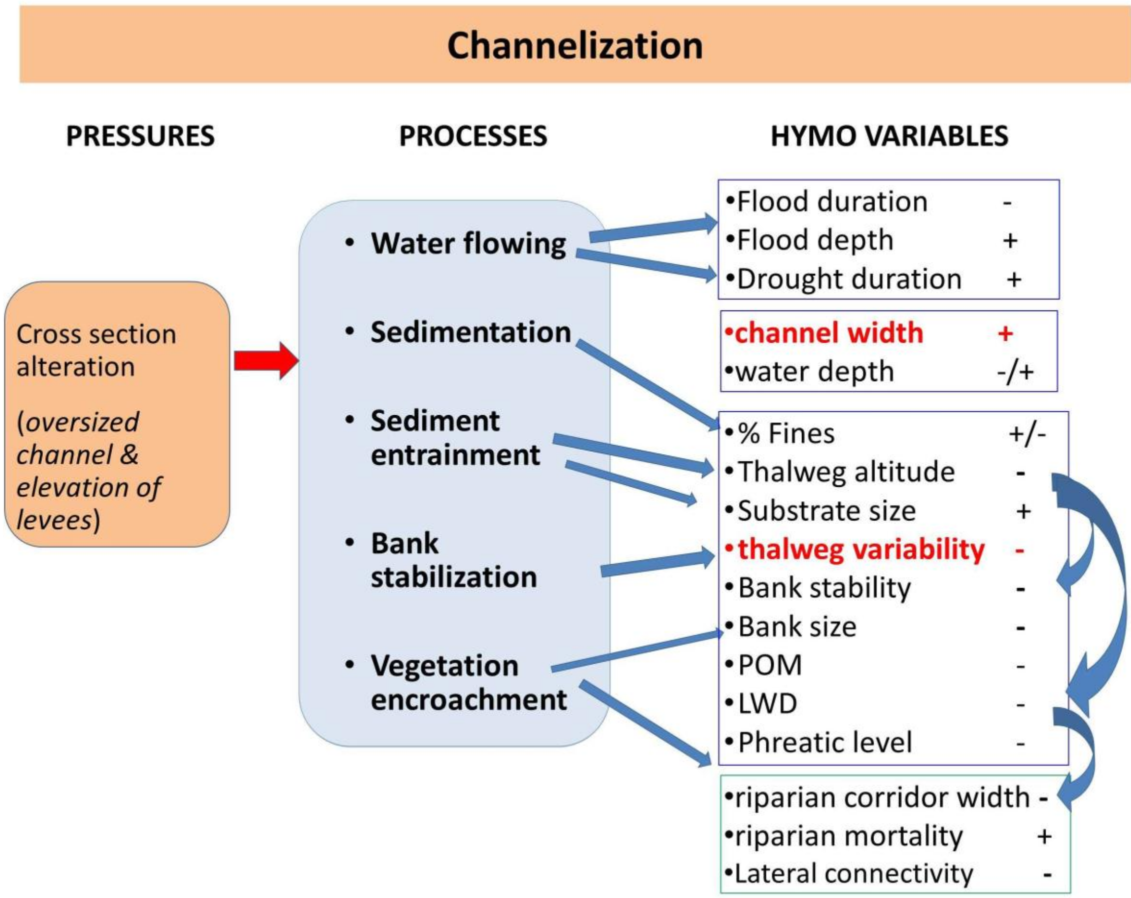


Figure 10. Conceptual framework of channelization effects on HYMO processes and variables (POM=Particulate Organic Matter; LWD=Large Woody Debris).

Although Simon's (1989) model provides an excellent conceptual framework, responses to channelization deviate from it with local circumstances. For example, Simon and Thomas (2002) illustrate a significant downstream response to channelization following the propagation of the degradation and threshold stages upstream that provides an important extension to the model. They observed that the upstream migration of knick points associated with the degradation phase on the Yalobusha River, Mississippi, resulted in the delivery of large quantities of sediment and woody vegetation to downstream reaches from bank failures. These materials accumulated at the downstream end of the channelized reach to form a large sediment/debris plug at the junction with an unmodified sinuous reach. Such a plug has the potential to produce a local higher base level which may accelerate the propagation of bed aggradation and channel recovery upstream. Furthermore, plug removal could reactivate incision and bank failure, with the potential for enhanced failure due to groundwater drainage through the basal bank layers. In addition, the presence of erosion resistant clay beds in some reaches, rather than the sand beds of the original model, was observed to restrict bed incision and knick-point propagation, leading to channel adjustments that were more dependent upon channel widening and bank failure.

In the coarser-bed, steeper, rivers of northern Italy, Surian & Rinaldi (2003) found rather different and even more extreme responses to those recorded by Simon (1989). While Simon's (1989) research focused entirely upon the effects of channelization, Surian and Rinaldi (2003) observed responses to a range of human interventions including dam and weir construction, in-channel gravel mining, reforestation and more general flow regime changes as well as river channelization and embanking. They proposed a classification of adjusted channel types, which were combined into a model of stages of channel adjustment (Figure 11). The model describes how progressive bed incision of typically 3-4 m (up to 10 m in some examples) and narrowing (by up to 50%) of single-thread, transitional and multi-thread (braided) rivers lead to the development of a sequence of degraded channel types. These responses reflect not only channelization processes but also a heavily reduced supply of sediment, and in many cases a modified flow regime.

Observations of adjustment in the Raba river, Poland, by Wyzga (1993) provide a detailed record of the processes similar to those that have contributed to the changes observed in the Italian rivers. Wyzga observed up to 3 m of bed incision, with the progression of headcutting increasingly moderated by energy-dissipating mid-channel bars in upstream reaches. Incision was accompanied by the erosion and removal of finer bed material, and a reduction in the susceptibility of the remaining, armoured bed to particle entrainment. Incision resulted in an increasingly efficient channel cross profile and a consequential magnification of peak discharges and more flashy flood waves. The increase in channel depth, bed coarsening and decreased bed gradient that was created as erosion propagated upstream led to re-establishment of a new equilibrium at higher flow velocities and stream power than before channelization.

These examples illustrate that channelization by straightening, steepening and simplifying the cross profile of stream channels generally increases flow velocities and therefore often significantly alter bed sediment by removing silt and other easily moved particles to create an armoured bed. In urban rivers, the quality of the bed material may also change, as has been observed on the River Tame, UK, where heavy metal concentrations within the urbanized matrix sediment are up to 3000 times greater than background levels (Thoms 1987). Straightening of stream channels

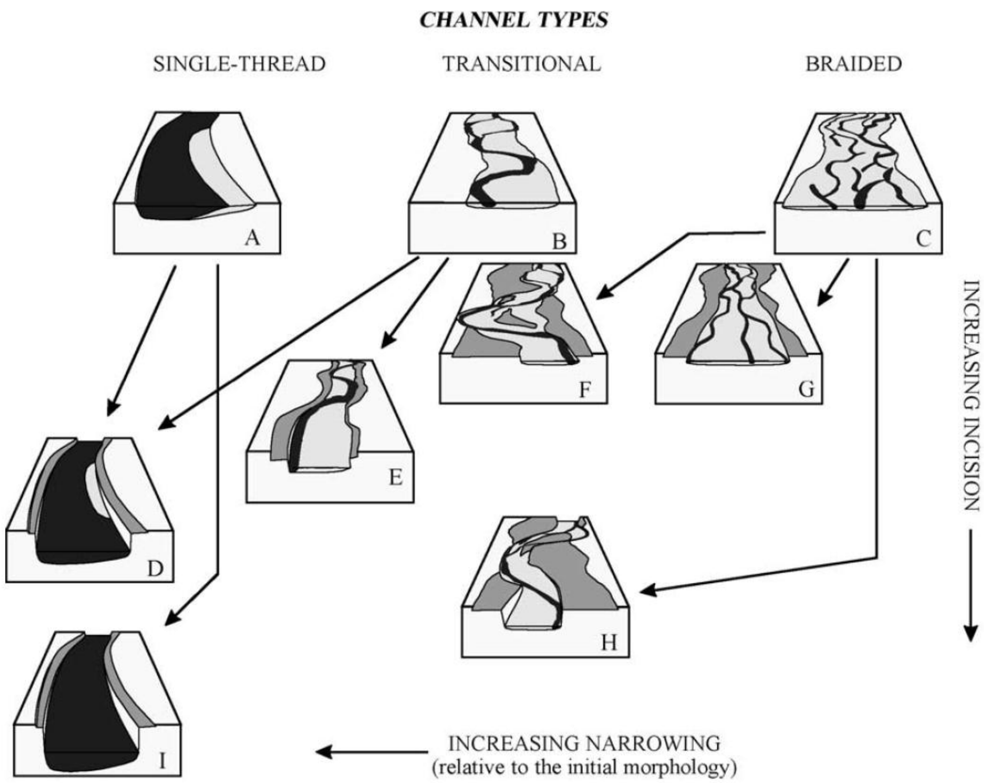


Figure 11. Scheme of channel adjustments for Italian rivers. Starting from three initial morphologies (A, B and C), different channel adjustments take place due to variable degrees of incision and narrowing (Surian and Rinaldi, 2003).

generally reduces the amount of substrate available for epifaunal colonization by reducing the roughness of the channel boundary (through removal of woody debris and other potential habitat such as rocks and boulders) and by removing stream bends where pool development, bank undercutting and exposure of vegetation roots supply a variety of habitats (e.g. Figure 12).

Some channelization schemes incorporate in-channel structures, such as weirs and rip-rap at the bank toe, to reduce the channel gradient locally, increase the flow resistance and thus dissipate the increased flow energy that may otherwise accompany channelization. These structures increase the physical complexity and thus habitat diversity of channelized reaches (Silva-Santos *et al.* 2004). Research by Bombino and others (Bombino *et al.* 2007, 2008, 2009) has investigated the sedimentary and plant ecological changes induced by the introduction of check dams into steep, confined mountain torrent streams in Calabria, Italy. They found pronounced increases in channel and riparian zone width, decreased channel gradient and fining of bed sediment calibre upstream of the check dams, which was associated with an increase in plant species richness, and in vegetation cover and development relative to reaches downstream of or unaffected by check dams. In this case, the physical changes induced by the check dams have increased the range of habitats available for plant colonization, and have provided a range of lower energy, more water retentive patches, where a variety of species can establish.

The effects of grade control structures (GCS: weirs with stone-protected stilling basins) combined with streambank protection were assessed in the much lower gradient environment of Twentymile Creek, Mississippi by Shields and Hoover (1991). Here bank-line woody vegetation cover increased by 8% in 4 years on the more stable channel margins, reaches immediately upstream and downstream of GCS were deeper with slower flow velocities, and differences in aquatic habitat diversity among sites along the river were primarily due to the bed scour holes downstream of GCS and inthe low-flow channel. Comparison with reaches without GCS, showed a 29% higher index of fish diversity, which was positively correlated with substrate diversity and mean depth, and with fourteen species collected exclusively at GCS. Abundance of several of the numerically dominant species was positively associated with deeper water and lower flow velocities.

Despite the positive impacts of some channelization structures in some environmental settings, the ecological impacts of channelization are usually negative. The simplified channels that are created, particularly in association with land drainage and flood alleviation, lead to significant ecological degradation. For example, the main channel of the River Morava (a tributary of the Danube) has been totally isolated by channelization from its flood plain and regulated by weirs. Here, Jurajda (1995) found that the young of the year of phytophilous species (pike *Esox lucius* L., rudd *Scardinius erythrophthalmus* (L), silver bream *Blicca bjoerkna* (L), tench *Tinea tinca* (L), carp *Cyprinus carpio* (L.) had almost disappeared, and a decline in density was also found for rheophils, such as vimba *Vimba vimba* (L.), barbel *Barbus barbus* (L.) and nase *Chondrostoma nasus* (L.), previously the dominant species in the river. Such degradation may affect riparian as well as aquatic habitats and species, and can feed through to impacts on birds as well as terrestrial organisms (Frederickson, 1979).

However, morphological recovery from channelisation is accompanied by vegetation and other ecological recovery that is also complex but has some characteristic features. Hupp (1992) observed vegetation recovery in the same Tennessee channels studied by Simon (1989). In particular, he noted the importance of riparian vegetation in facilitating recovery through the aggradation and restabilisation stages. He noted that woody vegetation initially establishes on lower bank surfaces in association with bank toe accretion, helping to trap and stabilise the depositing sediment. At this early phase, the vegetation is dominated by hardy, fast growing, pioneer species that can tolerate moderate amounts of slope instability and sediment deposition (e.g. Betula nigra, Salix nigra, Acer negundo, and Acer saccharinum). They grow in dense stands with dense root-mass development that enhances bank stability. As aggradation progresses and banks become increasingly stable, other species colonise the channel margins, and the analysis of tree rings suggested that 65 yrs may typically be required for restabilsation to be complete.

Morphological and vegetation recovery are accompanied by recolonisation by macroinvertebrate and fish species, and such recovery can be enhanced by deliberate, appropriately-designed, restoration. For example, Friberg et al. (1994) found that two years after restoration of a meandering course to a 1.3 km straightened and channelized reach of the River Gelså, macroinvertebrate density and diversity was greater than in the upstream control reach and species preferring a stony habitat seemed to favour the new reach, including *Heptagenia sulphurea* Müll., *Ancylus fluviatilis* Müller and *Hydropsyche pellucidula* Curtis.

4.4.4 Channelization: Meander Realignment

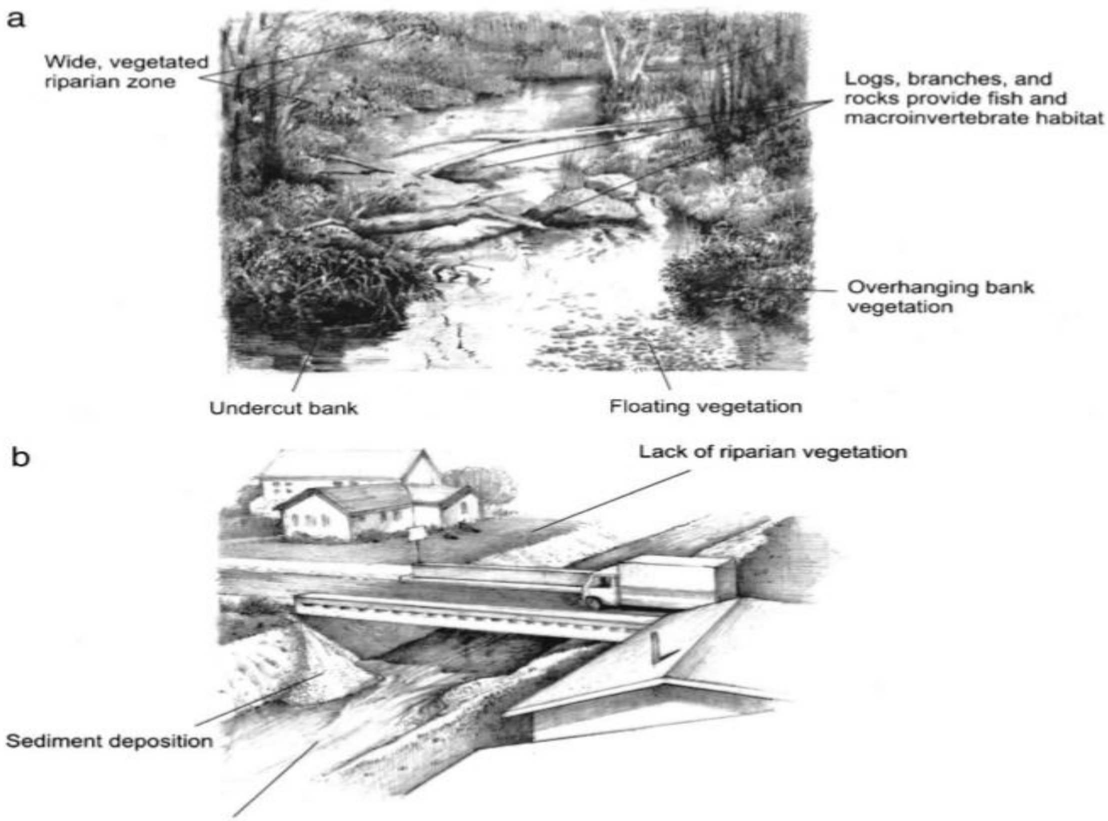


Figure 12. The physical habitat properties of (a) a naturally-function channel prior to channelization and (b) a heavily channelized river:

a. Rocks, fallen branches, and undercut banks provide fish with niches for feeding, laying eggs, and refugia. Snags, submerged logs, and other hard substrates provide habitat for macroinvertebrates (epifaunal substrate). A variety of velocity–depth combinations provide a stable and diverse aquatic environment and moderate flow surges during floods. Diverse, abundant bank vegetation provides habitat (e.g plant roots, overhanging vegetation, undercut banks) and organic material (leaves and twigs provide food for shredders and other macroinvertebrates), and helps to stabilise banks and prevents bank erosion.

b. Lack of habitats associated with riparian vegetation. Buildings and roads are sources of poor quality, often very fine sediment, which can infiltrate the coarsened bed sediments and degrade these habitats. Straightened channels have fewer velocity–depth combinations. Lack of submerged branches, rocks, and undercut banks reduces habitat for fish or macroinvertebrates (in-stream cover, epifaunal substrate). Shallower water depth at baseflow, affects water temperature and whether habitats such as cobbles, overhanging bank vegetation, and undercut bank roots are submerged and thus available for aquatic fauna. (from Rogers et al. 2002).

Channel 'self-rectification' or meander cutoff is a natural process that occurs on some rivers as part of natural channel evolution (e.g. Petit, 1992). However, channel meander re-alignment is also a very common component of channelization practice that increases the channel gradient. As sediment transport capacity is a power function of channel gradient, meander realignment is associated with an increase in sediment load that is supplied by bed and bank erosion. Meander re-alignment also reduces flow resistance, because of reduction in the curvature of the channel boundaries and also the simplification of channel bed and bank form. This further increases flow velocity and, therefore, sediment transport capacity (Thorne, 1989).

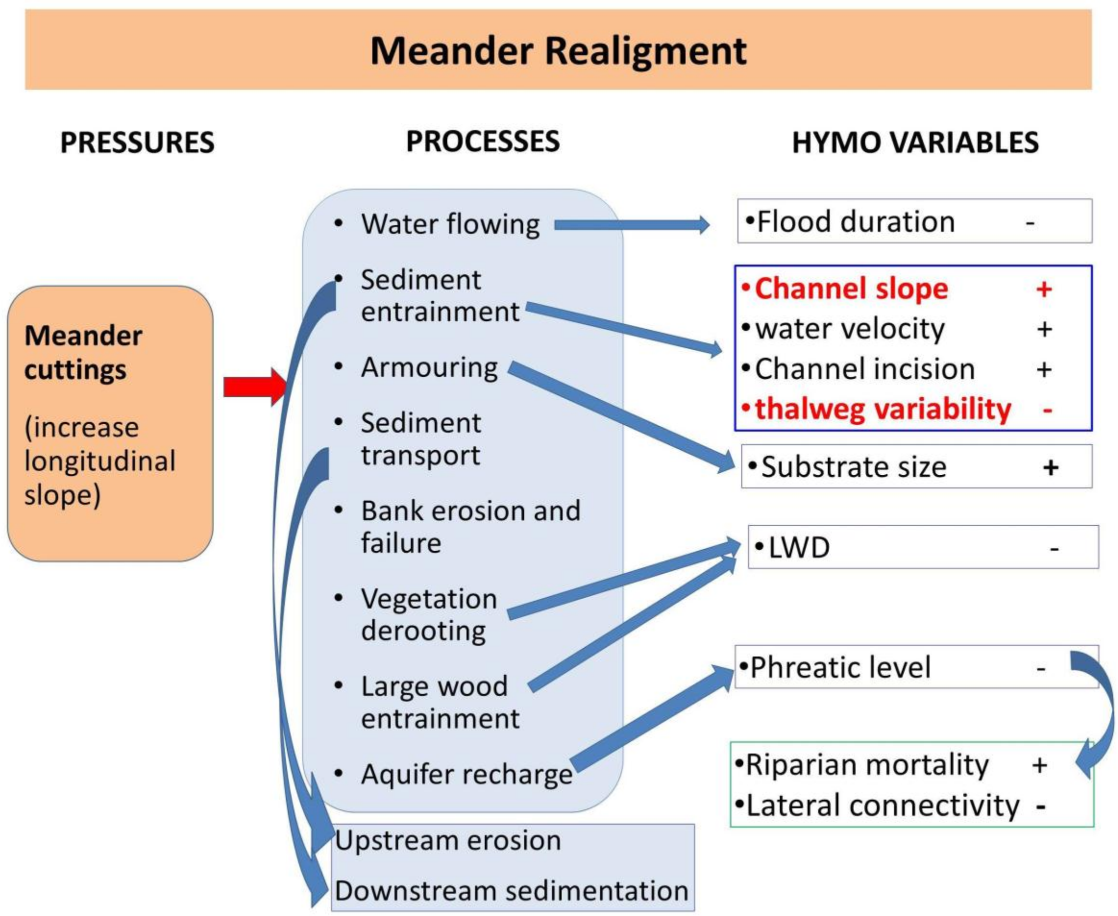


Figure 13. Conceptual framework of meander realignment effects on HYMO processes and variables (LWD=Large Woody Debris).

Meander realignment was a key component of extensive river training works undertaken on a ca. 80 km section of the upper Hunter River, Australia between 1956 and 1978 in response to rapid lateral migration and channel widening caused by a series of large floods between 1949 and 1955. The impact of the river training, which involved artificial cutoffs, extensive realignment, structural bank protection works and tree planting, are reported by Erskine (1992). Channel length and sinuosity was drastically reduced through artificial cutoffs and realignment, leading to an overall length reduction of less than 5% but a 17% reduction in one section. The channel straightening directly increased slope, decreased roughness and consequently increased flow velocity, and converted an actively migrating stream into a laterally stable channel. Bed incision of up to 1.1 m occured, with the preferential removal of sand and fine gravel to produce a coarse gravel armour layer, that is only mobilised by floods with a recurrence interval of over 5.6 years (Erskine, 1992). Similarly, Talbot and Lapointe (2002) described an advancing wave of 'pavement coarsening' (i.e. bed armouring) down a reach of the Sainte-Margarite River, in response to channel rectification in the 1960s. This accompanied 1m of bed incision in the upper 4km of the 8 km realigned reach and 2 m of bed aggradation in the lower 2 km of the reach. Since the realignment, meanders have reformed, lengthening the realigned reach by 7% and eroding sediment into the channel. Eaton and Lapointe (2001) observed that the channel morphology now remains qualitatively similar after floods as a result of a greater degree of channel stability attributable to the adjustments that have followed the realignment.

4.4.5 Alteration of riparian vegetation

The encroachment of agriculture has had a major effect on river margins. This is particularly true of lowland floodplain rivers, where river margin soils are often moist and rich. As a result, the edges of many rivers are directly in contact with agriculture and, as a consequence, riparian zones are fragmented and are often reduced to narrow strips or isolated trees on the river banks. Agricultural practices of tilling and harvesting prevent riparian vegetation regeneration and lead to degradation of the riparian seed bank.

The rough canopy of natural riparian vegetation traps sediment from flood waters, leading to bank aggradation and extension. At the same time, the roots of riparian vegetation reinforce river banks, limiting their erosion during high flows, and enabling channel banks to extend into the channel and aggrade vertically. In particular, riparian vegetation retains and stabilizes fine sediments and narrows river channels to increase flow velocities. Both of these processes reduce fine sediment supply and settlement within the channel and thus its potential to infiltrate channel bed sediments causing interstitial siltation and clogging of the bed.

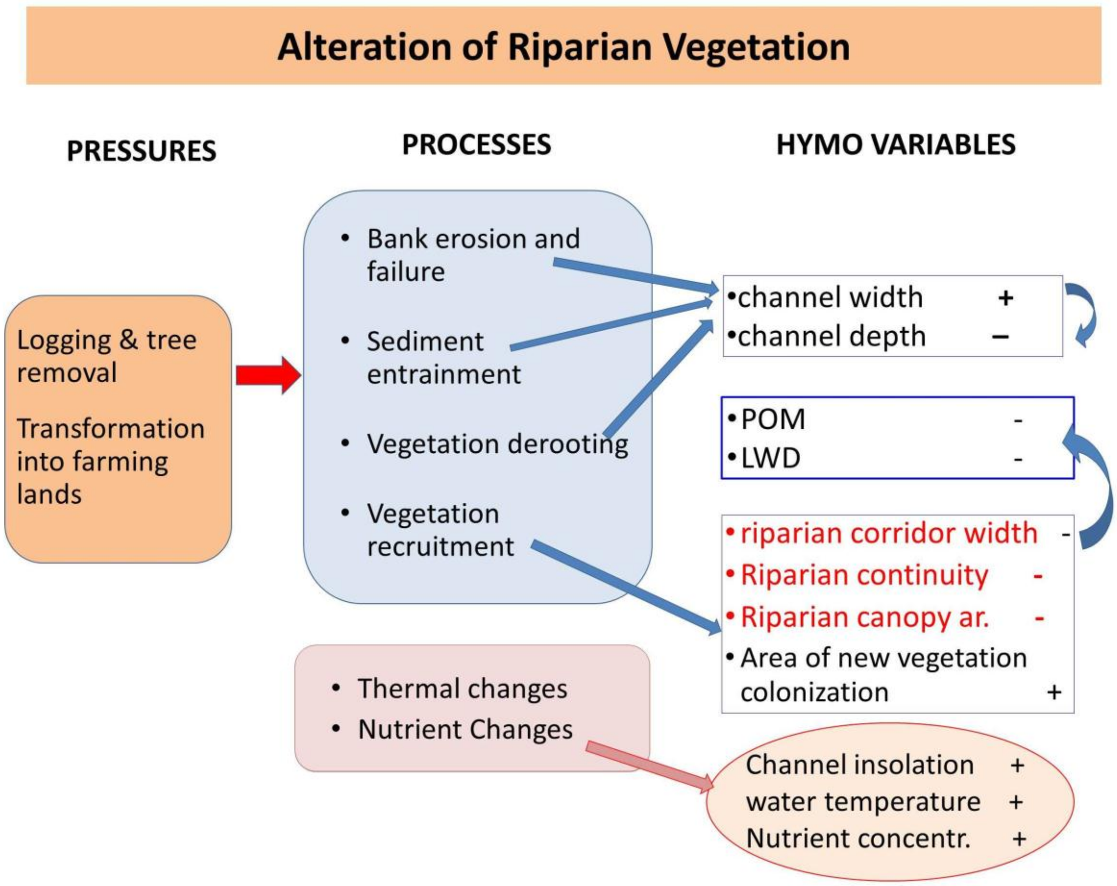


Figure 14. Conceptual framework of alteration of riparian vegetation effects on HYMO processes and variables (POM= Particulate Organic Matter; LWD= Large Woody Debris).

4.4.5.1 Logging & tree removal

The presence of riparian woodland is crucial to the structure, morphology and dynamics of river margins, since it interacts with flows of water and sediment to create and reinforce river margin landforms (Gurnell, 2013). As a result, clearance of riparian woodland can lead to simplification of river margins, channel widening, and in extreme cases a change in river planform from meandering to braiding. These fundamental morphological impacts affect the moisture regime of river margins; exchanges of water, suspended and dissolved material between the river and its riparian zone; as well as numerous biogeochemical and ecological processes (Gurnell and Petts, 2011).

Removal of riparian trees has an immediate effect on river ecosystems by reducing shading and thus increasing stream temperatures and light penetration. Removal also decreases bank stability, inputs of litter and wood, and retention of nutrients and contaminants; reduces sediment trapping and increases bank and channel erosion;

alters the quantity and character of dissolved organic carbon reaching streams; lowers retention of benthic organic matter owing to loss of direct input and retention structures; and alters trophic structure (Allan, 2004).

Sabater et al. (2008) studied the effects of riparian vegetation removal on algal dynamics and stream nutrient retention efficiency by comparing NH4-N and PO4-P uptake lengths from a logged and an unlogged reach in a forested Mediterranean stream. Their study showed that the elimination of riparian vegetation altered in-stream ecological features that lead to changes in stream nutrient retention efficiency. Moreover, it emphasizes that alteration of the tight linkage between the stream channel and the adjacent riparian zone may directly and indirectly impact biogeochemical processes with implications for stream ecosystem functioning. In this context, the role of the riparian vegetation in filtering nutrients coming from agricultural watersheds, is well known, and underpins the use of buffer strips to prevent river eutrophication (Osborne & Kavacic, 1993).

Removal of riparian vegetation inevitably leads to a severe reduction in the supply of wood to the aquatic system. Furthermore, large wood is often deliberately removed from forested rivers for flood defense purposes. Large wood plays a complex and important role in aquatic ecosystems. It affects flow hydraulics, sediment dynamics and sorting, channel morphology and stability, physical habitat composition, dynamics and diversity, and nutrient cycling (Gurnell et al., 1995), with effects varying with channel size and planform, and with riparian tree species (Gurnell et al., 2002; Gurnell, 2013). Loss of large wood debris in a stream alters flow hydraulics, causing a simplification of channel bed sediments and habitats, a reduction in organic matter retention, and often a reduction in bed and bank stability. Diez et al. (2001) identified large wood as the main hydromorphic element in river channels in forested basins.

4.4.5.2 Transformation into farming lands

Riparian vegetation acts with flow, sediment and topography to influence channel form, instream habitat, nutrient dynamics, and temperature and flow patterns. Therefore, removal of upland and riparian vegetation through farming and urbanization disrupts land-water linkages leading to reductions in water quality, simplification of stream channels, less stable thermal and flow regimes, and ultimately, reduced biological integrity (Snyder et al. 2003). However, removal or modification of natural riparian vegetation where trees are not naturally present, may not result in such deep-seated and long-lasting effects because agriculture in such areas usually consists of grazing (Williamson et al. 1992).

Riparian ecological degradation and transformation to agricultural uses often leads to invasion by alien plants (Planty-Tabacchi et al., 1996). Plant invasions are increased directly or indirectly by many types of human-mediated disturbances to rivers and riparian zones (Richardson et al., 2007). Once introduced and established in a catchment, many alien plants can exploit opportunities provided both by natural flood events and by anthropogenic disturbances to which they are better attuned than native species (Planty-Tabacchi et al., 1996).

4.4.6 Alteration of instream habitat

All hydromorphological pressures affect instream habitat, but in this section, we refer to those pressures that directly destroy the aquatic habitat, such as channel dredging and mining, and the reinforcement of channel bed and banks with introduced materials such as concrete or rip-rap. These activities generally reduce channel boundary roughness, leading to increased flow velocities and other consequences similar to those resulting from channelization. Assessing the effects of these specific pressures is difficult due to their association with other potential habitat-altering variables. For example, increases in turbidity and siltation can easily arise from agricultural land use (i.e. cattle grazing) in both channelized and reference streams.

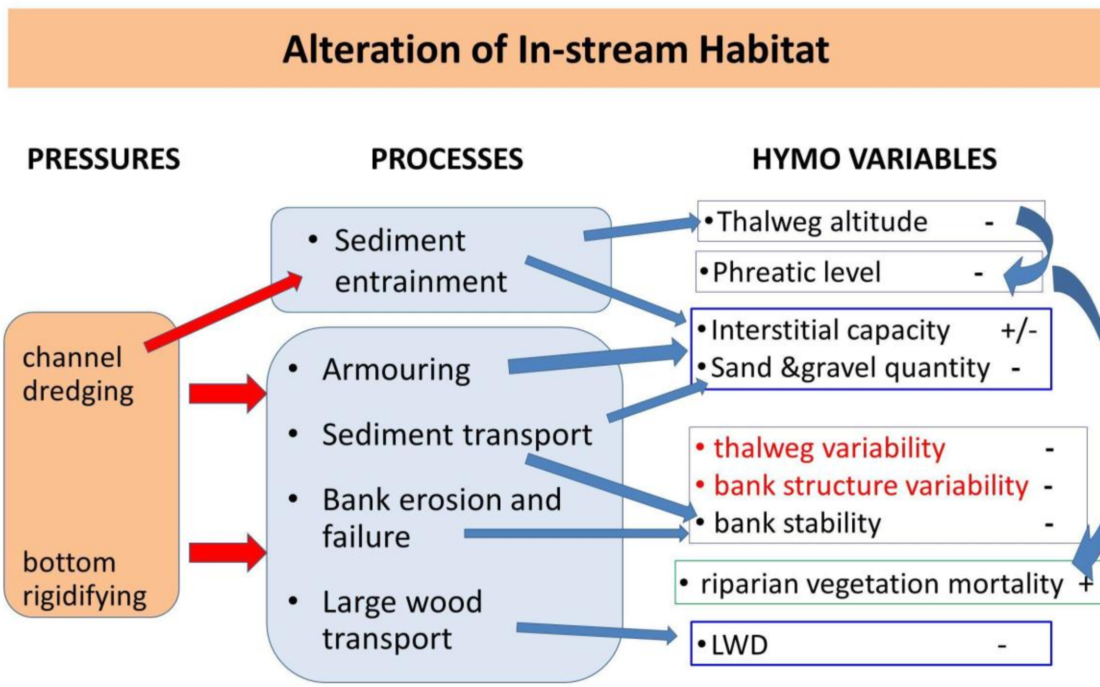


Figure 15. Conceptual framework of alteration of in-stream habitat effects on HYMO processes and variables (LWD = Large Woody Debris).

4.4.6.1. Channel dredging

Channel dredging lowers and usually steepens the channel bed. Even if further incision is not induced, channel banks become higher and more exposed to erosion and, as a result, bank erosion is a likely consequence of dredging. The degree of impact of the dredging depends on the quantities of sediment delivered by the river to the dredged reach. The smaller the ratio of dredged to supplied sediment the smaller the likely HYMO effects. Lagasse and Winkley (1980) concluded that gravel dredging in the lower Mississippi River caused bed degradation, reduced flow resistance and thus reduced flood heights and groundwater table levels. Lou et al. (2007) identified increased grade slope, bank instability, and brackish-water intrusion as negative HYMO effects of dredging, while positive effects included decreased flooding. They also cited a study by Han et al. (2005, in Chinese) that identified changes in the river regime as a result of dredging, including lowered water levels, alteration of surface water and groundwater recharge, and re-balancing of salt and fresh water in tidal regions.

4.4.6.2 Bed Reinforcement

Not many references dealing with HYMO processes and variables have been found.

Urban development transforms the hydrological system through construction of impervious surfaces and stormwater drainage systems, and river channels are completely reinforced precluding any morphological adjustment. Gurnell et al (2007) have analyzed of Urban River Survey data from 143 urban channel reaches in three European rivers (the River Tame, UK; the River Emscher, Germany; and the River Botic, Czech Republic) and have demonstrated the strong influence of river channel engineering on channel structure, physical habitat features and vegetation patterns.

4.4.7 Embankments, levees or dikes

Figure 16 shows the main processes and affected variables due to the construction of embankments and levees in rivers.

Artificial bank protection affects channel morphology and dynamics by restricting the channel width and ability to migrate, by reducing energy consumption as a result of bank friction, by restricting bank sediment sources and thus sediment supply, and so enhancing erosion of the river bed (Winterbottom, 2000; Rinaldi, 2003). Extensive levee construction along both banks also contributes to greater stresses on the riverbed. High flows are associated with deeper water depth and higher flow velocities and hence, greater shear stresses on the river bed that lead to bed incision.

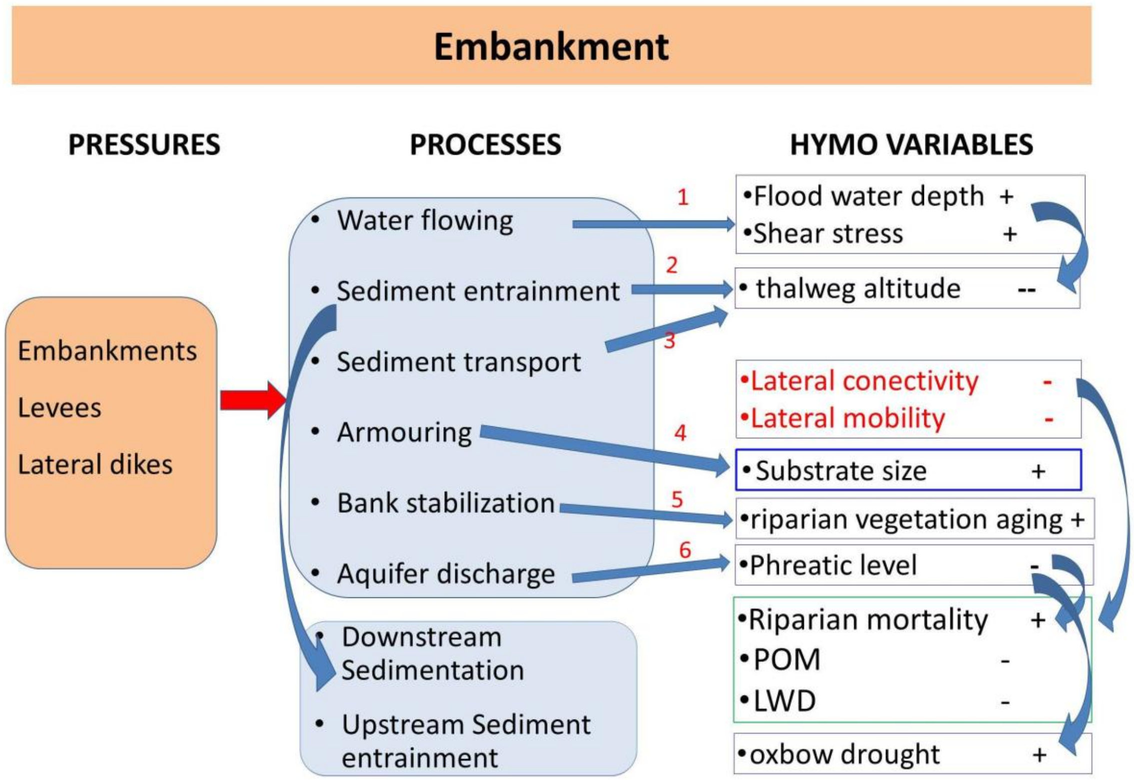


Figure 16. Conceptual framework of alteration of embankments, levees or dikes effects on HYMO processes and variables (POM=Particulate Organic Matter; LWD=Large Woody Debris).

Bed incision associated with bank reinforcement and levee construction reduces connectivity between the river and its floodplain, but levee construction also directly reduces connectivity by increasing channel capacity (Gergel et al. 2002, Henry et al. 2002). The consequent loss of the floodplain as flood storage reduces downstream attenuation of flood peaks, potentially increasing flood risk. Such reductions in lateral connectivity not only damage functioning of the riparian zone but also reduce productivity, nutrient exchange, and dispersal of biota more widely across the floodplain (Jenkins and Boulton 2003).

4.4.8 Sediment addition

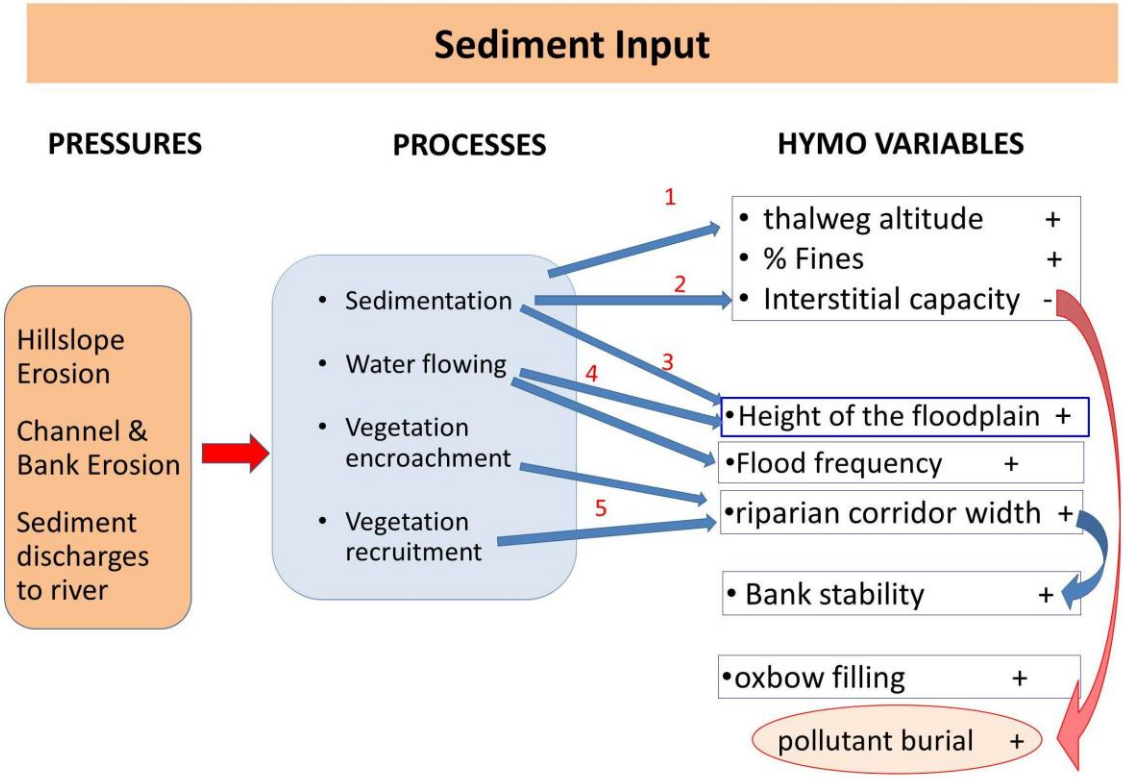


Figure 17. Conceptual framework of sediment input effects on HYMO processes and variables.

4.4.8.1. Hillslope erosion

Delivery of sediment from hillslopes to river systems is heavily disrupted by human activities. The nature of the disruption varies widely according to the broad environmental context as well as the nature of the human activities.

Silt and fine sediments that clog interstices in river beds and cause colmation are mainly produced by forestry and agriculture (Brunke and Gonser, 1997). Clogging reduces the numbers and activity of hyporrheic invertebrates, which in turn, affects the porosity of interstitial sediments through the absence of their feeding and burrowing (Brunke and Gonser 1997). Jacobson and Gran (1999) found that agricultural development in the Ozarks, USA, contributed gravel-sized sediments to the Current River, Missouri. Fine sediment inputs to rivers come from bank erosion of fine floodplain sediments and erosion of the soil surface. The latter is strongly affected by land use and management, and increases for the same soil and land use with increases in topographic slope. As soil erosion becomes increasingly accelerated (i.e. exceeds the rate of soil production), finer soil particles are removed and gullies develop, channeling flows of water and allowing mobilization of coarser sediments. Where drains are constructed to remove surface water, these make delivery of sediment to river systems more efficient, and if their gradient is sufficiently steep, they may become sources of both fine and coarse sediment, as has been observed in drains associated with commercial forestry. Superficially, delivery of coarse sediment might offset gravel losses from river bed mining, but both processes would have to be in balance. Large accumulations of instream sediment can lead to channel instability, a decrease in channel capacity, and remobilisation of silt stored in floodplain sediments by overbank flows (Jacobson and Gran 1999, after Hancock 2002).

Dirt roads, particularly those associated with forestry have been widely recognized as important sediment sources, conduits for sediment and water, and potential locations from which landslides may be triggered (Brunke and Gonser, 1997; Forman and Alexander, 1998).

4.4.8.2 Sediments discharges to rivers

Sudden discharges of sediments to rivers can occur in relation to natural processes such as major bank erosion, slope mass movements and glacial meltwater outbursts. However, these natural events cannot be viewed as 'pressures' unless they are accelerated by human activities. Slugs of sediment are also introduced into rivers directly as a result of human activities such as accidental dam breaching or deliberate dam removal. Bednarek (2001) showed that dam removal produced an increased sediment load causing suffocation and abrasion to various biota and habitats. However, observations of several dam removals suggest that these increased sediment loads are a relatively short-term effect.

Deliberate flushing of sediment from reservoirs can release excessive fine sediment pulses into the river causing fine sediment infiltration and burial of the river bed. The Cachí Reservoir on the Reventazón River, Costa Rica, is flushed on an almost yearly basis. The material was found to both deposit in between flushings and to be eroded during flushing, mainly in the uppermost and lowermost parts of the old river channel. A major factor in explaining the amounts and distribution of deposits was shown to be the phase lag between water discharge and suspended-sediment concentration peaks (Brandt and Swenning 1999). Such sediments can be mobilized by larger flow releases from reservoirs, and methods are available to clean fine particles from gravel at specific sites, including pump-washing, high-pressure jet washing, and tractor rotovating. However, local loosening of gravel by such methods can lead to resuspension of silt to cause colmation in downwelling zones downstream (Hancock 2002).

4.4.9 Sand and gravel extraction

The extraction of sand and gravel from river beds, banks and floodplains is driven by human needs for raw materials for concrete, glass and paint making, and construction works.

Direct extraction of alluvial material from river channels causes far greater impacts than floodplain extraction. According to Rinaldi et al. (2005), the effects of bed sediment mining are more severe: where material is extracted at a rate greatly exceeding the replenishment rate where extraction is from single-thread rivers, that are generally associated with relatively low rates of catchment sediment supply; from channelized reaches, where sediment supply is also limited; from channels where there is only a thin cover of alluvium over bedrock; and at locations where mining coincides with other human activities that reduce upstream sediment delivery (especially large dams).

Bed sediment mining alters flood magnitude and frequency (Rinaldi et al., 2005) and local flow hydraulics, inducing supplementary erosion on both sides of the extraction pit (Rivier and Seguier 1985); reduces sediment availability, changing sediment dynamics and inducing bed incision (Kondolf, 1997) and armouring (Kelly et al., 2005). These changes in sediment dynamics can lead to either bed siltation or armouring downstream (Rinaldi et al. 2005), local destabilization of the substratum (Rivier and Seguier 1985), and upstream erosion (López 2004, Rinaldi et al. 2005). In addition, bed incision lowers alluvial water tables and affects vegetation dynamics (Kondolf, 1994, 1997). These effects extend well beyond the sites affected by extraction, including reduction in flood levels, changes in longitudinal and transverse channel profiles, and alterations in stream bed, bank and riparian community characteristics.

Gravel extraction from the river bed can also lead to bank erosion and failure. Altered bank dynamics change the bank profile and stream course, potentially inducing a loss of vegetation on stream banks and reduced delivery and retention of large wood.

The nature of channel adjustments depends on local factors, most notably the local sediment budget and the method of gravel extraction (Wishart et al., 2008). However, Brown et al. (1998) reported that stream morphology is changed after gravel mining mainly by a lack of gravel bedload to replace the mined sediment, rather than by how the bed material removed. Examples of the effects of morphological degradation caused by gravel mining are numerous. Erskine et al. (1985) predicted imminent channel degradation as a result of rates of extraction from temporary sediment stores within the Hunter River, Australia, upstream of Denman, greatly exceeding contemporary transport rates. Similarly, gravel extraction from Stony Creek, California, USA that greatly exceeds delivery rates has induced channel incision of over 5 m of channel bed incision, necessitating bridge repairs costing US$1.4 million (Kondolf and Swanson 1993).

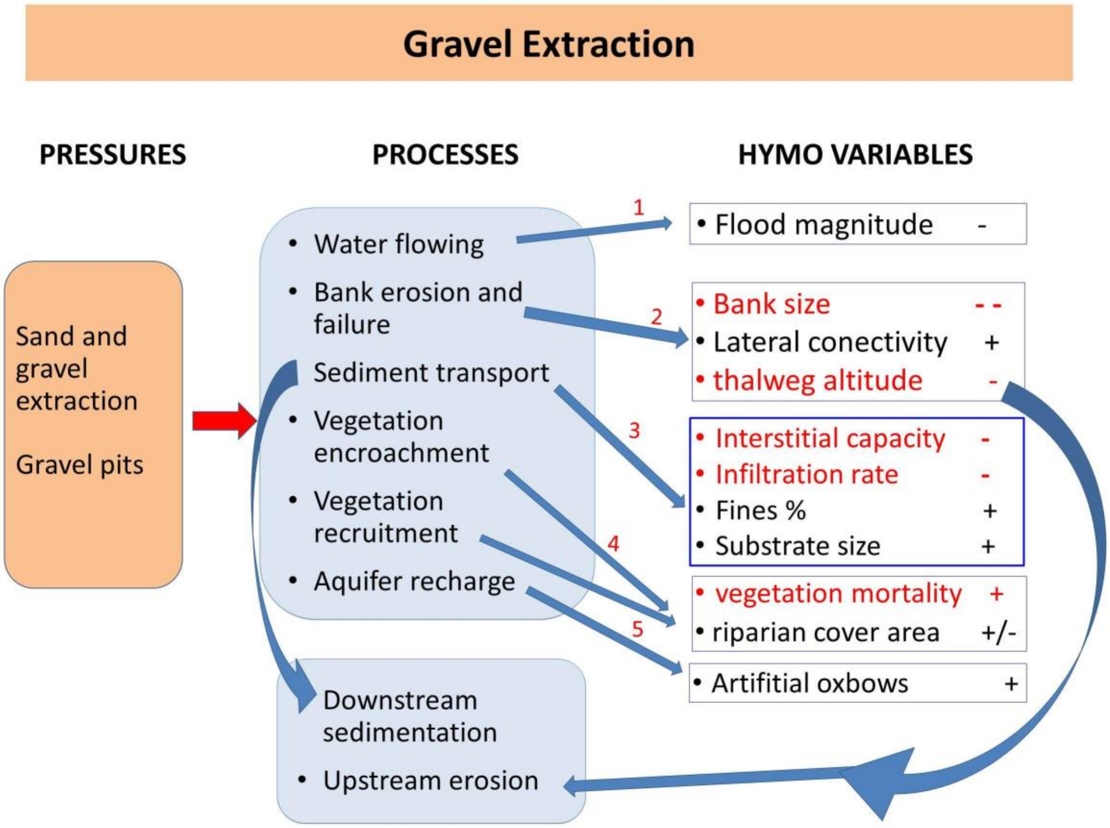


Figure 18. Conceptual framework of gravel extraction effects on HYMO processes and variables.

In addition to channel incision and degradation, gravel extraction can lead to changes in the patterns of water exchange between surface and subsurface (Mori et al. 2011) and indirect effects that include a reduction in shading and bank cover; an increase in stream temperature that favours the rapid growth of algae and weeds that cover the water surface; release and redistribution of adsorbed pollutants; and changes in the turbidity of the water column (Rivier and Seguier 1985, Tamunobereton-ari and Omubo-Pepple 2011). In downstream locations, a decline in the level of the alluvial water table can result in salt water intrusion, as was observed by Mas-Pla et al. (1999) within the aquifer-river system close to the coast of the Baix Fluviá area (NE Spain).

While in-channel mining commonly causes bed incision and severe upstream and downstream effects, floodplain gravel pits produced by gravel extraction have more local effects and have the potential to become wildlife habitat. However, they may be captured by migration of the active river channel (Kondolf 1997) and eventually contribute to the morphological and ecological changes observed in the main channel.

4.4.10 Loss of vertical connectivity

Colmation of the upper layers of the channel bed and riparian and floodplain soils by fine sediment particles can hinder exchange processes between surface water and groundwater (Brunke and Gonser 1997).

Natural colmation processes usually occur through the siltation of fine material during low flow episodes; whereas spate or exfiltration episodes reopen the interstices and reverse the process. Increased current velocities can flush fine material out of the surface layers of the river bed, but bedload movement is needed to reopen deeper interstices (Brunke and Gonser 1997). Due to the position of the surface bed layers between surface water and groundwater, the balanced alternation between colmation and scour can be disturbed by impacts affecting both surface and groundwater habitats (Hancock 2002), which can cause permanent colmation.

The most common causes of colmation are organic and fine sediment inputs to the river channel, river channel engineering, and increased filtration through the channel margins during water extraction for drinking, industrial and irrigation water (Petts, 1988). External colmation can result from increased sewage loading that promotes the development of dense algal mats, or causes sedimentation of an organic layer on the river bed. Internal colmation is caused by the infiltration / intrusion of fine particulate organic or inorganic matter into the cavities within the bed sediments (Schalchli, 1993, after Brunke and Gonser 1997). Land use practices which increase seston and sediment loading are directly responsible for the extent of the unbalanced colmation processes (Karr & Schlosser, 1978; Platts et al., 1989, after Brunke and Gonser 1997).

By preventing the communication between surface and groundwater, cascading effects in ecosystem structure and function may occur (Brunke and Gonser 1997). For instance, siltation of the interstices reduces the shelter for invertebrates, and thus the impacts of natural and anthropogenic disturbances, such as urban stormwater runoff, are magnified. Sealed interstices cannot function as nurseries for the benthos. Colmation can diminish or prevent the reproductive success of fish spawning on gravel.

On the other hand, a clogged bed may act as an intrusion barrier that prevents the contamination of groundwater by polluted surface water (Younger et al., 1993; Komatina, 1994, after Brunke and Gonser 1997).

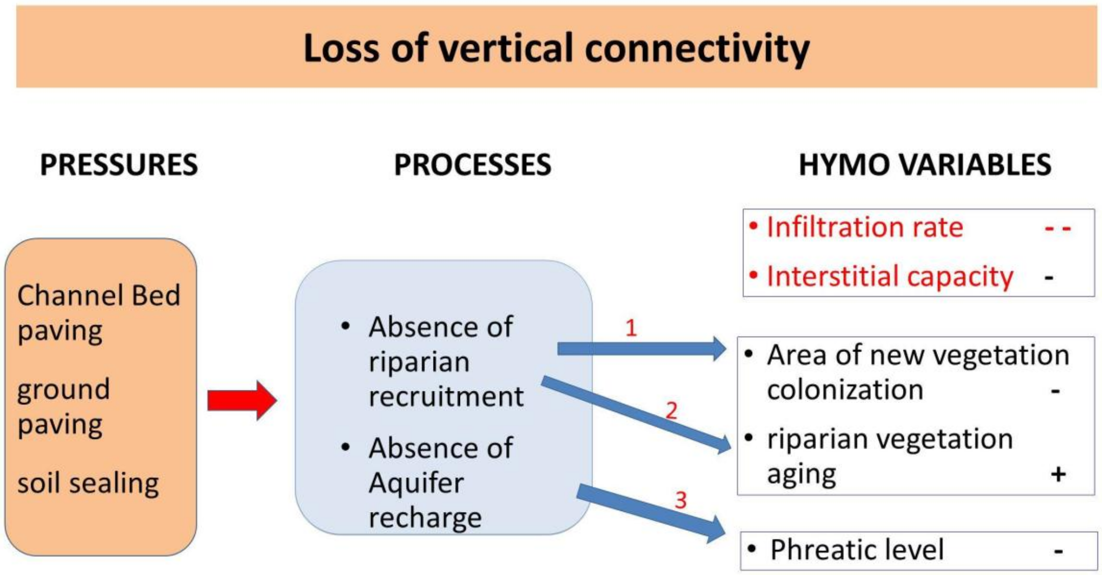


Figure 19. Conceptual framework of loss of vertical connectivity effects on HYMO processes and variables.

Colmation might not be the only cause of the loss of vertical connectivity. The water velocity near the most superficial sediment layers determines the dominant flow direction between the surface and groundwater. If the temporal distribution of water velocities change, more subtle disturbances in the flow between both systems can be noticed. For instance, Curry et al. (1994) found that discharge fluctuations caused by hydroelectric power generation alter the mixing relationships between surface water and groundwater in the hyporrheic zone. And this could have severe impacts on the reproductive success of gravel spawning fish. This effect was found to occur naturally in some reaches along an upland salmon spawning catchment by Malcolm et al. (2005). They found that at sites dominated by surface water, hyporrheic DO remained high throughout and rates of embryo survival were correspondingly high.

Restoration actions have been conducted and benefits in both the hyporrheos and the groundwater table near the river have been reported. After restoration programs, Sarriquet et al. (2007) detected an increase in vertical exchanges of water between surface and interstitial habitats, with an increase in the depth of hypoxia. Golz et al. (1991, after Brunke and Gonser 1997) reported that the mechanical opening of a clogged section of the Rhine's stream bed near a drinking water bank filtration site induced a 1 m rise in the groundwater table near the river, but after a few weeks the opened section had become sealed again. Therefore, the viability of such restoration works may be associated with catchment management designed to reduce fine sediment inputs to the river (Sarriquet et al. 2007).

Loss of vertical connectivity not only affects interactions between channel and adjacent terrain but also between the land surface and underlying and aquifers. In urbanised areas, previously permeable surfaces are replaced by paved impermeable surfaces (Schick et al. 1999). This may cause a general decline in the water table and a deterioration in groundwater quality with urbanization (Jat et al. 2009).

4.5 Effects of other pressures

Other than hydromorphological pressures are beyond the scope of this review. However, there are several hydromorphological processes which in parallel also determine physico-chemical properties of the water. Thus, HYMO pressures affecting such processes will definitely also affect the related physico-chemical variables as well as potential feedbacks to hydromorphology and / or biota. Relevant other processes and potential effects have been indicated in the conceptual figures and are briefly listed here without further detailed explanation and discussion.

4.5.1 Water temperature modification cold

Cooler water released by stratified reservoirs will have greater viscosity and therefore its capacity to erode channels will be reduced because it will reach lower flow velocities.

4.5.2 Water temperature modification warm

Shainberg et al. (1996) concluded that high water content and high temperature (which induces high Brownian motion) during aging enhance clay-to-clay contacts and cementation of soil particles into a cohesive structure that resists rill erosion. Sidorchuk (1999), through field and laboratory experiments, found that water temperature became the main factor of gully erosion in frozen soil or in soil with the permafrost (so called thermoerosion).

4.5.3 Toxic substances – pollution

The impacts of toxics on aquatic biological organisms may be increased or hidden depending on HYMO processes. Channel and bank erosion may unearth contaminants and promote their dissolution in water increasing their toxicity. On the contrary, sedimentation processes can bury pollutants at the channel bed and thereby reduce their toxicity.

4.5.4 Eutrophication – nutrient enrichment

Vegetation encroachment will have a high demand on dissolved nutrients and thus, reducing eutrophication impacts on aquatic biota. Also, riparian vegetation with an extended canopy has a dense root system that filters nutrients from phreatic waters.

4.5.5 Organic pollution

Excessive growth of macrophytes in eutrophic conditions and the leaf fall of riparian species in autumn, accumulate organic matter in the water. Hydraulic turbulent conditions favoring reaeration of the water column and hence the oxygen entrance which promotes the decomposition of this organic matter, reducing the impact of anoxic conditions due to organic contamination.

5 Identification of gaps

Published studies on field observations and experiences usually deal with the consequences of pressures on HYMO variables or, more frequently, on biological quality elements. Though widely predicted by models, field observations of the mechanistic routes through which these effects operate have been seldom reported. Therefore, there is a lack of observational reports on the mechanisms through which pressures influence processes, and how process alterations affect HYMO variables, and finally how these disturbed HYMO variables modify biological metrics. Further, target-specific experimental work is needed to characterize and document observable effects of HYMO pressures on HYMO variables.

From our review of literature on field observations and experiences, this is especially noticeable for the following HYMO effects of pressures:

- Water abstraction: the effects on lowering phreatic levels
- Increased flows: effects on hydrological and riparian variables
- Flow regime alteration: the effects on bank stability, channel and riparian width, woody debris and particulate organic matter deposition
- Hydropeaking effects on drought frequency and duration, and on riparian corridor
- Effects of river fragmentation due to other causes than large dams
- Effects of impoundments on water velocity and bottom siltation
- Effects of large dams on large woody debris (LWD) dynamics
- Effects of Cross Section channelization on channel depth decrease, drought duration, POM, LWD; phreatic level; riparian mortality and disconnection
- Effects of meander realignment on flood duration, thalweg variability, phreatic level, riparian mortality and disconnection
- Effects of riparian vegetation alteration on channel width and depth; and on nude zones available for vegetation colonization
- Effects of alteration of instream habitat on interstitial capacity, sand and gravel quantity, thalweg and bank structure variability and LWD
- Effects of bottom rigidifying on HYMO variables
- Effects of embankments, levees or dikes on shear stress, thalweg altitude, riparian vegetation aging and mortality, phreatic level, POM
- Effects of sediment input on thalweg altitude, flood frequency, riparian corridor width and oxbow filling
- Effects of loss of vertical connectivity on nude zones available for vegetation colonization, and riparian vegetation aging
- Effects of other physico-chemical pressures such as water cooling, toxics and pollutants, eutrophication and nutrient enrichment, organic and inorganic pollution

6 Meta-analysis of effect sizes of hydromorphological response variables and processes

6.1 Identification of the most relevant hydromorphological processes and variables using fuzzy logic cognitive maps

We further analyzed the conceptual schemes of the interactions between the HYMO pressures, the main processes affected and the resulting quantified changes on HYMO variables to identify the most relevant hydromorphological processes and variables in altered river systems across spatial and temporal scales. Therefore, we treated the conceptual schemes as Fuzzy Logic Cognitive Maps (FCM) obtained by extraction from scientific literature (according to Özesmi & Özesmi 2004). FCMs are based on graph theory models of the causal relationships between defined variables and are helpful to understand the dynamic of systems that are not yet fully understood. According to Kosko (1992a), FCMs can be viewed as a combination of fuzzy logic and artificial neural networks (ANN) and qualitatively incorporate expert knowledge to explore implications for ecosystem management (Hobbs et al. 2002). A detailed description of methodology, construction and application of FCMs is provided in Hobbs et al. (2002), Özesmi & Özesmi (2004), and Papageorgiou & Kontogianni (2012). Recently, applications of FCMs have been used to understand the ecological relationship between biotic and abiotic ecosystem variables (e.g. Özesmi & Özesmi 1999, Hobbs et al. 2002, Tan & Özesmi 2006).

6.1.1 Transforming conceptual schemes to adjacency matrices

The conceptual schemes used for FCM analysis contained three different types of variables: (1) hydromorphological impacts (pressures), (2) flux variables (processes), and (3) altered ecosystem variables (HYMO state variables). In the FCMs, these variables can take certain fuzzy values in the range between [0, 1]. The variables are linked by causal relationships that represent the response of the latter variable to the former (visualized by the arrows of different size). These arrows take a certain weight according to the causal relationship between variables in the range of [-1, 1], where a value of -1 indicates a negative relationship and a value of +1 a positive. The causality between the variables needs to be either positive or negative which excludes cases where the relationships would exhibit both causalities (Hobbs et al. 2002). The conceptual schemes were then transformed into adjacency matrices in the form $A(D) = [a_{ij}]$ (Harary et al. 1965). Thereby, the HYMO processes v_i (such as sedimentation) are listed on the vertical axis and the HYMO variables v_j (such as drought duration) on the horizontal axis, which produces a square matrix. The causal link between the variables is then coded by the value of the arrow weight into the square matrix. We treated each pressure's conceptual scheme separately to build an adjacency matrix and subsequently combined all adjacency matrices by matrix addition to construct an overall adjacency matrix of the total system including all pressures. Conflicting connections with opposite signs (that would decrease total causal relationship during matrix addition) that resulted from different logical structure of few conceptual schemes (Zhang & Chen 1988) were corrected by switching signs, an operation that does not change system behavior (Kim & Lee 1998). After total matrix addition, each element in the summed overall adjacency matrix was normalized by the number of conceptual schemes included (Kosko 1992b).

6.1.2 Calculation of graph theory indices

FCMs are complex systems as they incorporate a large number of variables that might interact with each other by feedback loops. Based on this structure, the overall behavior of the total system differs from that of the single compartments of which it is constructed (Özesmi & Özesmi 2004). As FCMs are based on graph theory models they can be analyzed using matrix algebra provided by the graph theory to calculate structural indices. To understand the structure of the system and to identify the most relevant hydromorphological processes and variables we calculated the centrality (Harary et al. 1965) of the HYMO processes and HYMO variables. According to Özesmi & Özesmi (2004) the centrality of a variable shows its contribution to the total system. Centrality of a variable is calculated as the summation of its outdegree and indegree. The outdegree is calculated as the row sum of absolute values of the respective variable (the cumulative weight of the connections exciting the variable) in the adjacency matrix. The indegree is calculated as the column sum of absolute values of the respective variable (the cumulative weight of the connections entering the variable) in the adjacency matrix. The calculation of indegree and outdegree enables the definition of three different variable types in the system (Bougon et al. 1977): transmitter, receiver, and ordinary variables.

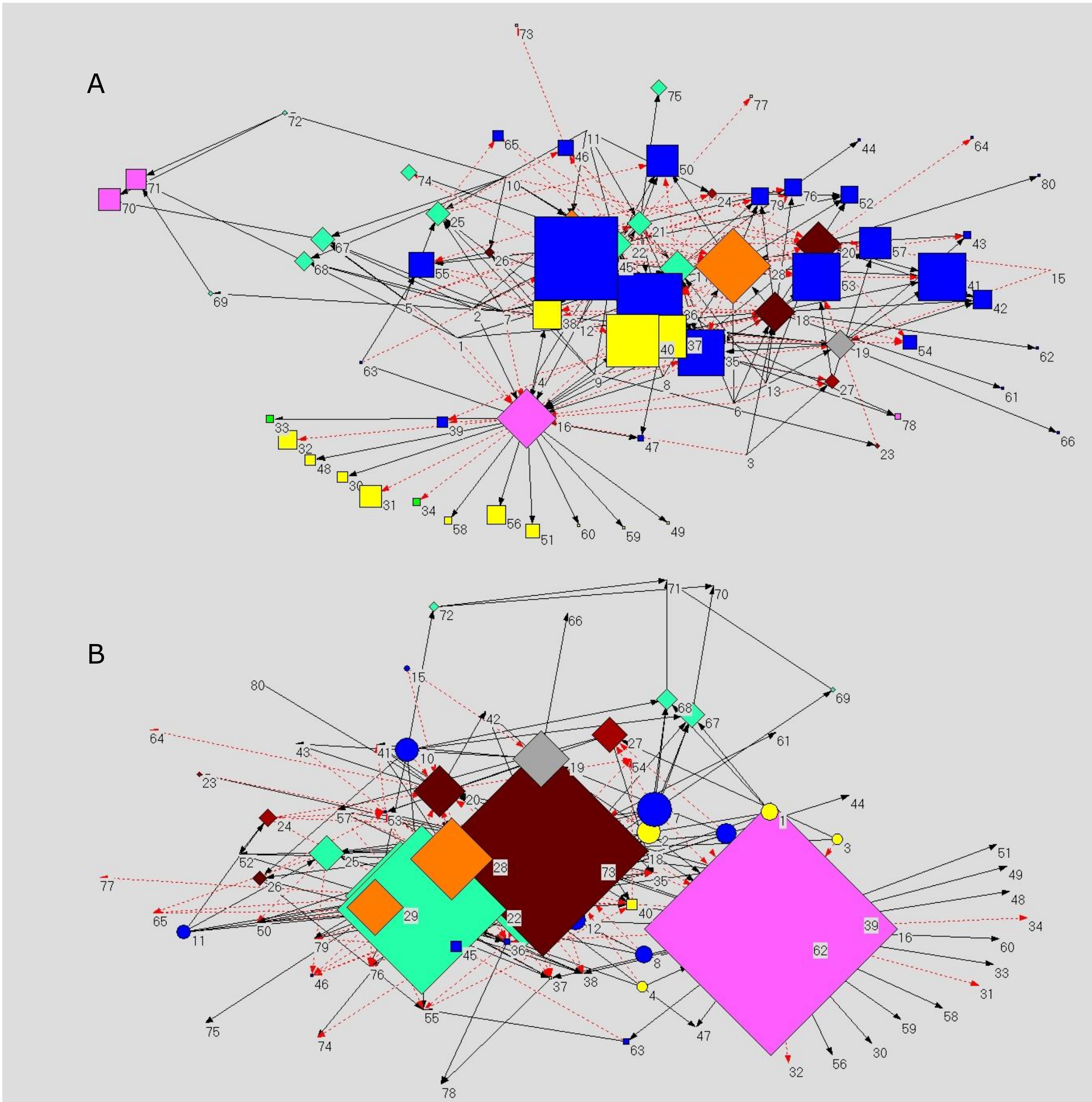
Transmitter variables are the forcing functions of the system and have positive outdegree and zero indegree. Receiver variables (representing the ends of the system) have a positive indegree and, consequently, zero outdegree. Variables that have both non-zero indegree and outdegree are called ordinary variables and can be either transmitter or receiver (Bougon et al. 1977). To better depict the effect size of ordinary variables we calculated the outdegree/indegree ratio (*O/I ratio*). A large outdegree/indegree ratio indicates transmitter variables that are important in the system as they affect a higher number of variables than the number of variables they are affected by. Complexity of the overall system was calculated by the ratio of receiver to transmitter variables (*R/T*, number of receiver variables divided by the number of transmitter variables) (Özesmi & Özesmi 2004). Density (*D*) of the overall system was calculated by dividing the number of connections (*c*) by the maximum number of connections possible between N variables ($D = c / (N*(N-1))$, Hage & Harary 1983). The density (clustering coefficient) of a FCM is an index of connectivity, which shows how connected or sparse the maps are. The hierarchy index *h* was calculated according to MacDonald (1983). When *h* is equal to 1 then the system is fully hierarchical and when *h* is equal to 0, the system is fully democratic. Systems with low hierarchy index values are much more adaptable to changes due to their high level of integration and dependence compared to hierarchical systems (Sandell 1996).

6.1.3 Visualization of the HYMO pressure/impact system

To analyze the total HYMO pressure/impact system in more depth, we visualized the adjacency matrix in terms of the variables strengths in a two-dimensional manner. Therefore, we grouped the variables in different categories. The groups (1) hydrological regime, (2) river continuity, and (3) morphological conditions comprise the HYMO pressures, the groups (4) water flow dynamics, (5) sediment dynamics, (6) bank dynamics, (7) vegetation dynamics, (8) large wood dynamics, (9) aquifer dynamics, and (10) other dynamics comprise the HYMO processes as they were analyzed in the conceptual schemes. The groups (11) hydrological regime variables, (12) river continuity variables, (13) morphological condition variables, and (14) other variables comprise the HYMO variables as they were analyzed in the conceptual schemes. For the variable strengths, we visualized centrality, outdegree, and indegree separately. We used the Kamada-Kawai algorithm as layout algorithm (Kamada & Kawai 1989). This algorithm produces regularly spaced results (especially for connected networks that are not very large) that are more stable than results of comparable algorithms as the Fruchterman-Reingold algorithm (Fruchterman & Reingold 1991). The Kamada-Kawai algorithm is a force-directed layout algorithm and moves the FCM variables to locations that minimize the variation in line length (de Nooy et al. 2005). Visualization was done using Pajek (Batagelj & Mrvar 1998).

6.1.4 HYMO pressure/impact system

The investigated overall HYMO pressure/impact system shows a high level of complexity (complexity = 2.6), meaning that the system results in many outcomes and responses in relation to relatively few forcing pressures. The density of the overall system is relatively low (density = 0.036) indicating that the causal relationships are distributed equally and not in a clustered form. Further, variables and processes do not show a large number of causal relationships within the different types of variables but from one type of variable to another. The hierarchy index expresses how adaptable the system is to changes if certain variables would change. Thus, the calculated very low hierarchy index value of 0.0002 indicates that the system is very flexible to changes. We visualized the overall HYMO pressure/impact system in Figure 20 in terms of the variables strengths (a) indegree, (b) outdegree, and (c) centrality. The assignment of the variable names to the presented numbers in Figure 20 is given in Appendix A.


A
B

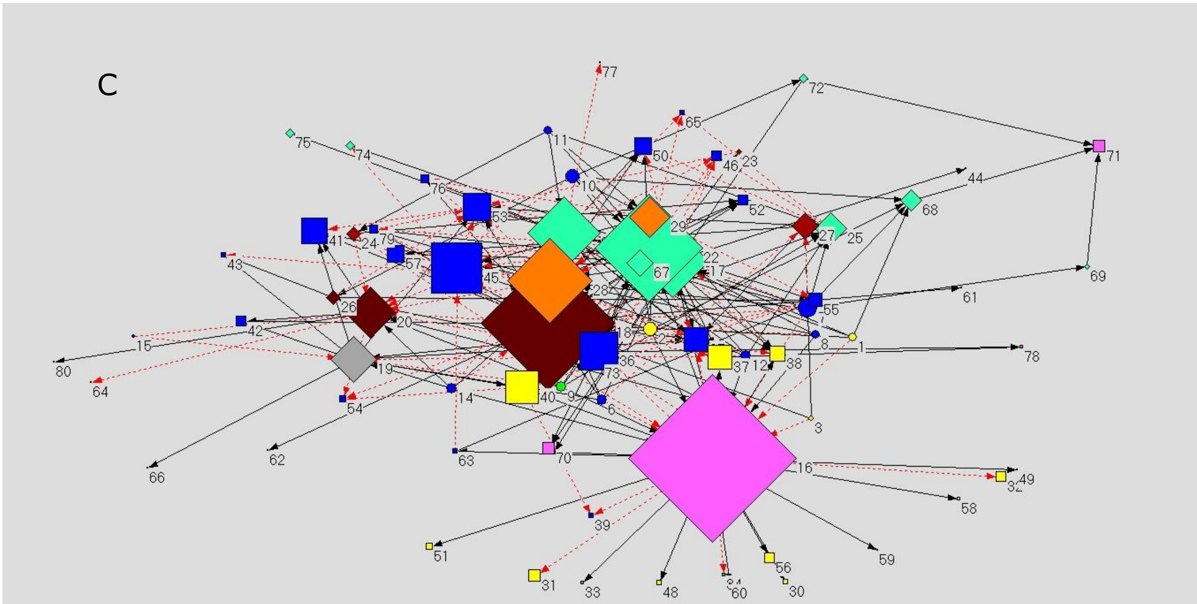


Figure 20: HYMO pressure/impact system according to the variable strengths (A) indegree, (B) outdegree, and (C) centrality. Yellow circles= hydrological regime pressures, blue circles= morphological condition pressures, green circles= river continuity pressures. Pink diamonds= water flowing dynamics, turquoise diamonds= sediment dynamics, orange diamonds= bank dynamics, dark brown diamonds= vegetation dynamics, light brown diamonds= large wood dynamics, gray diamonds= aquifer dynamics, aquamarine diamonds= other dynamics. Yellow boxes= hydrological regime variables, blue boxes= morphological condition variables, green boxes= river continuity variables, pink boxes= other variables. Black solid arrows= positive effect, red dashed arrows= negative effect. For numbers see Appendix A.

6.1.5 Most relevant hydromorphological processes

The centrality of variables in FCMs shows how connected they are to other variables depending on the cumulative strengths of the causal relationships entering and exciting the variables. The most central process in the HYMO pressure/impact system is ***water flowing***, followed by ***vegetation encroachment***, ***sediment entrainment***, ***bank stabilization***, ***sedimentation***, and ***sediment transport*** (Figure 21). All of the analyzed processes except *large wood entrainment* have higher effects on other variables than they are affected by others, as shown by higher outdegree than indegree values. For *large wood entrainment*, outdegree and indegree are similar. The five variables showing highest centralities also show highest outdegrees by almost the same order and thus, these processes are most relevant to other variables in the system (Figure 22).

Analyses of HYMO processes indegree (Figure 23) showed that *bank stabilization* and *water flowing* are most affected by the hydromorphological pressures influencing the system. Considering the ratio of outdegree to indegree ratio (O/I ratio) gives a slightly different picture about the order of the five most relevant hydromorphological processes in the system (Figure 24). A high O/I ratio indicates variables that have more effect on other variables relatively to their own affection compared to variables with low O/I ratios. *Sediment entrainment* shows the highest O/I ratio followed by *vegetation encroachment*, *sediment transport*, *water flowing*, *bank erosion and failure*, and *sedimentation*.

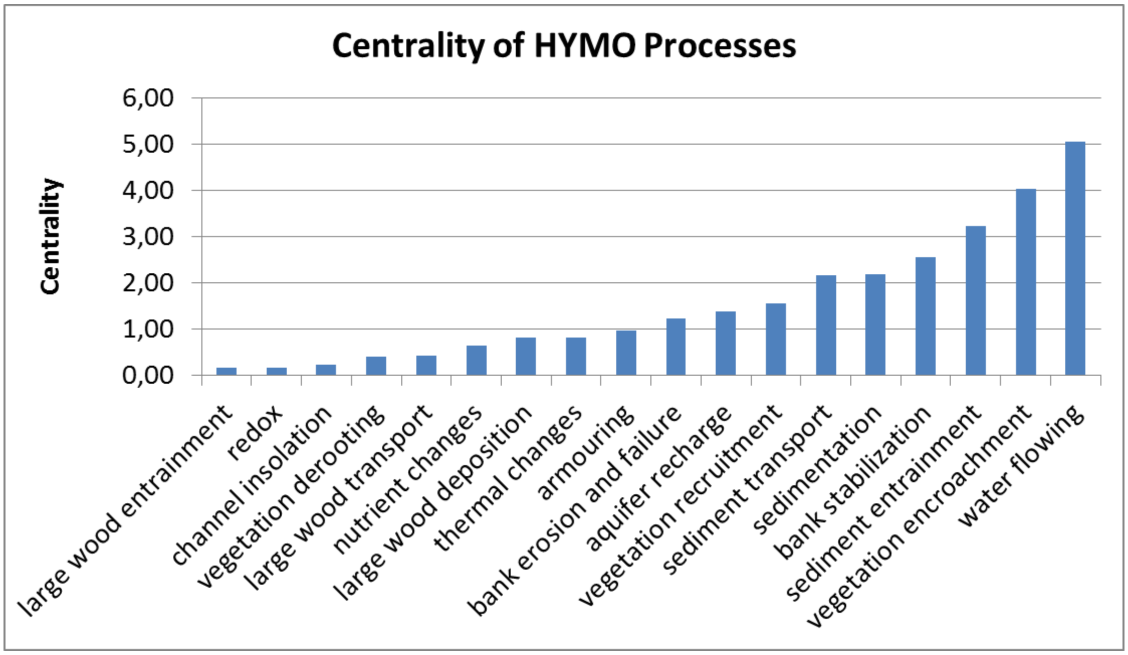


Figure 21: Centrality of the processes caused by pressures according to the pressure typology developed in the FORECASTER project.

6.1.6 Most relevant hydromorphological variables

The most central variable in the HYMO pressure/impact system is *thalweg altitude*, followed by *channel width*, *phreatic level*, *large woody debris*, *riparian cover area*, *depth water column*, and *% fines* (Appendix B). These variables showing largest centralities that are minimum 50% larger than those of the other variables analyzed. From the HYMO variables analyzed only eight affect other variables in the system and, thus, show outdegrees. These variables are *channel width*, *depth water column*, *phreatic level*, *thalweg altitude*, *interstitial capacity*, *large woody debris*, *channel depth*, and *shear stress*.

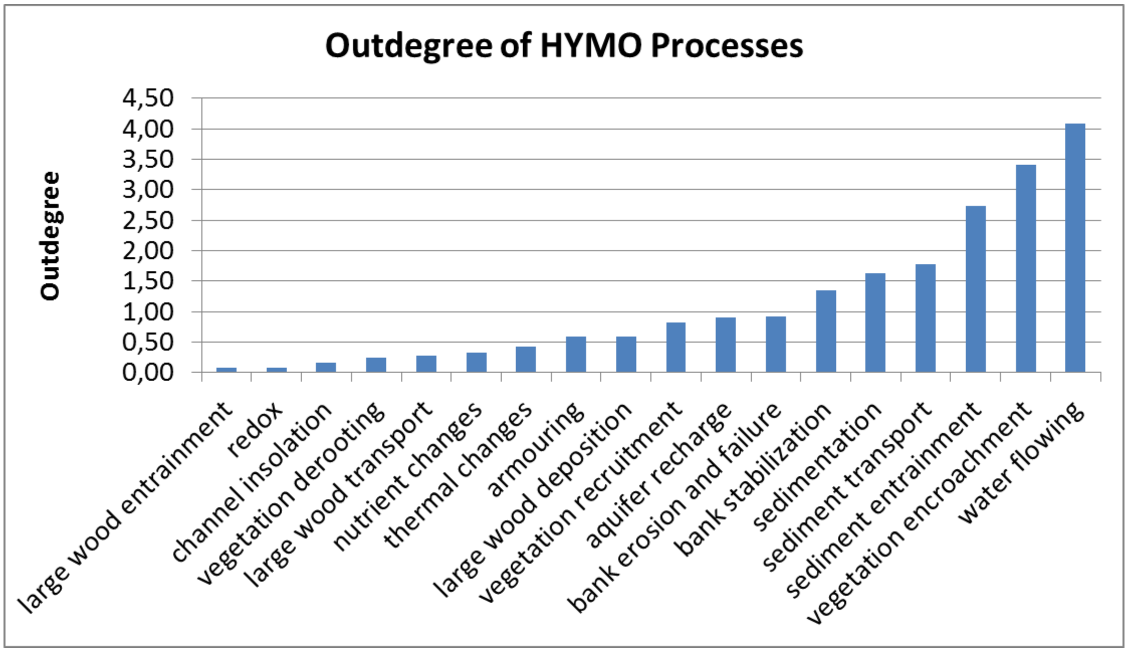


Figure 22: Outdegree of the processes caused by pressures according to the pressure typology developed in the FORECASTER project.

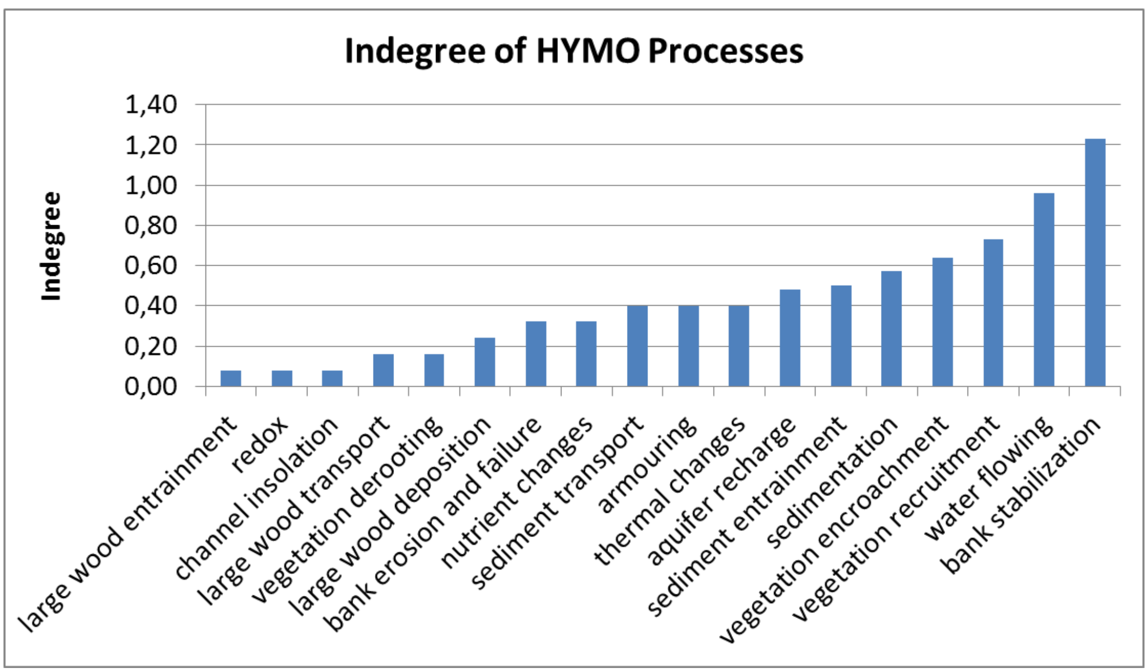


Figure 23: Indegree of the processes caused by pressures according to the pressure typology developed in the FORECASTER project.

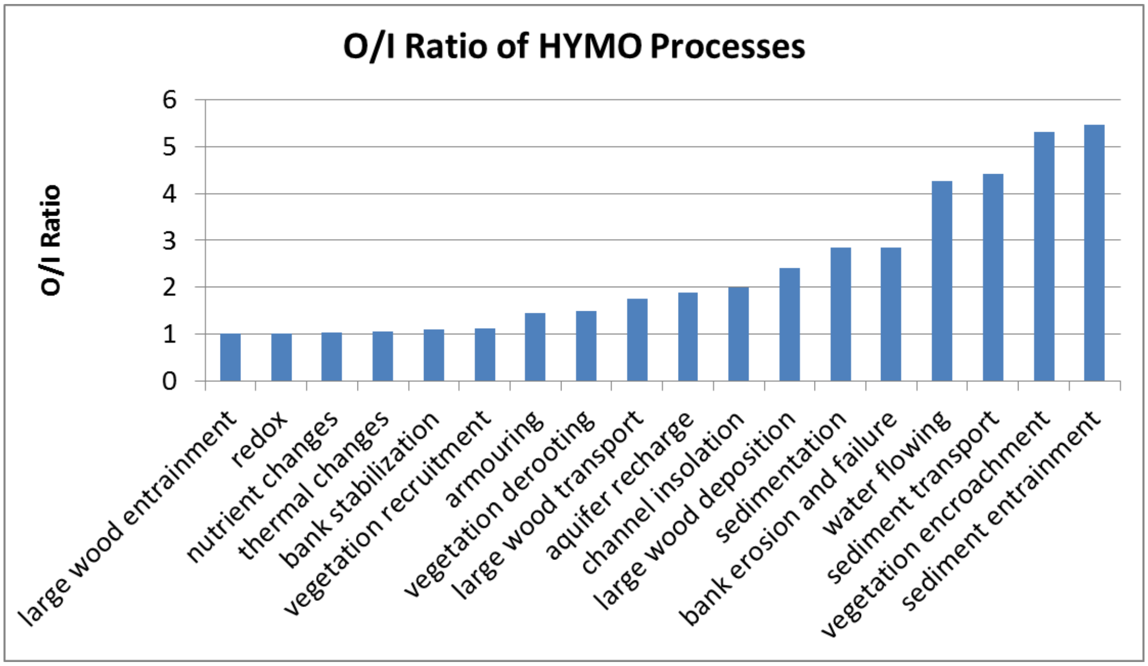


Figure 24: O/I ratio of the processes caused by pressures according to the pressure typology developed in the FORECASTER project.

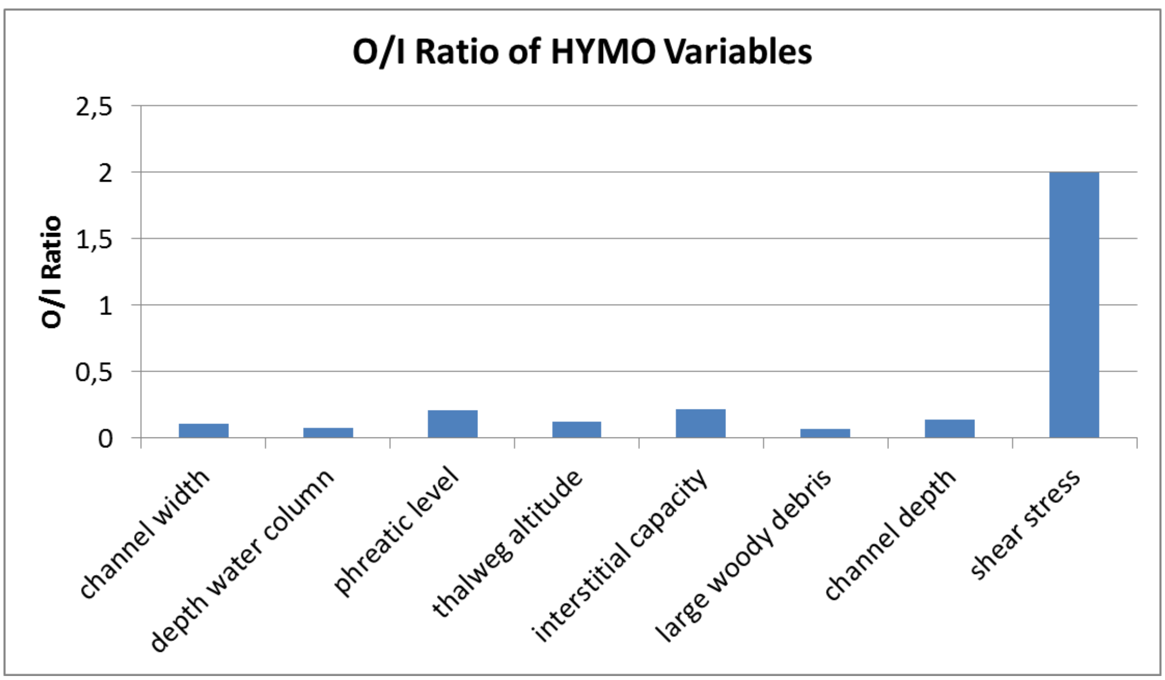


Figure 25: O/I ratio of the variables affected by HYMO processes that affect other HYMO variables.

Considering the ratio of outdegree to indegree (O/I ratio) of these variables indicates that ***shear stress*** has highest effect on other variables relatively to its own affection compared to the other variables with low O/I ratios (Figure 25). All of those variables except *shear stress* show considerably low outdegree and high indegree; thus, the high O/I ratio of *shear stress* is only related to its extremely low indegree (*shear stress* was only found to be affected by *water flowing*).

6.2 Implications for river management

The coded overall adjacency matrix was used in simulating the system behavior and to run management simulations. First of all, we used the auto-associative neural network method (Reimann 1998) to calculate the systems steady state. In a first step the vector of initial states of variables (I^n) is multiplied with the adjacency matrix. Then, within this steady state vector a value of 1 is placed for each variable. The result of the matrix multiplication was then transformed into the interval [0, 1] using a logistic function $(1 + e^{-x})^{-1}$ (Gray et al. 2011, Tan & Özesmi 2006). The new vector was then again applied to matrix multiplication with the adjacency matrix and the result was again subjected to the logistic function. We repeated this process until the system converged to a fixed point. According to Kosko (1986), the resulting values of this multiplication process can either go into steady state, into a limit cycle, or into chaotic pattern. All of our calculations reached a stable steady state with less than 20 iterations. The steady state conditions are given in Appendix C.

6.2.1 Effects of single pressure removals

The matrix calculations described above can be used to ask “what if” questions in various management option scenarios (Kosko 1987). Therefore, the specific variables belonging to each management option simulation are clamped in the initial state vector at the desired value (between 0 and 1) at each step of the matrix multiplication process. The final result of the management option simulation process can then be compared to the steady state without any management scenario. To describe the effect of single pressure removal from the total HYMO pressure/impact system, we clamped the respective variables to 0 and run the system until it converged to a fixed point. Here we briefly report on the most pronounced increases and decreases only, while the complete set of results of all HYMO process and variable changes can be found in the Appendices D-E. An overview over the percentages of variables changed by single pressure removals is given in Figure 26 and more detailed explained in the following.

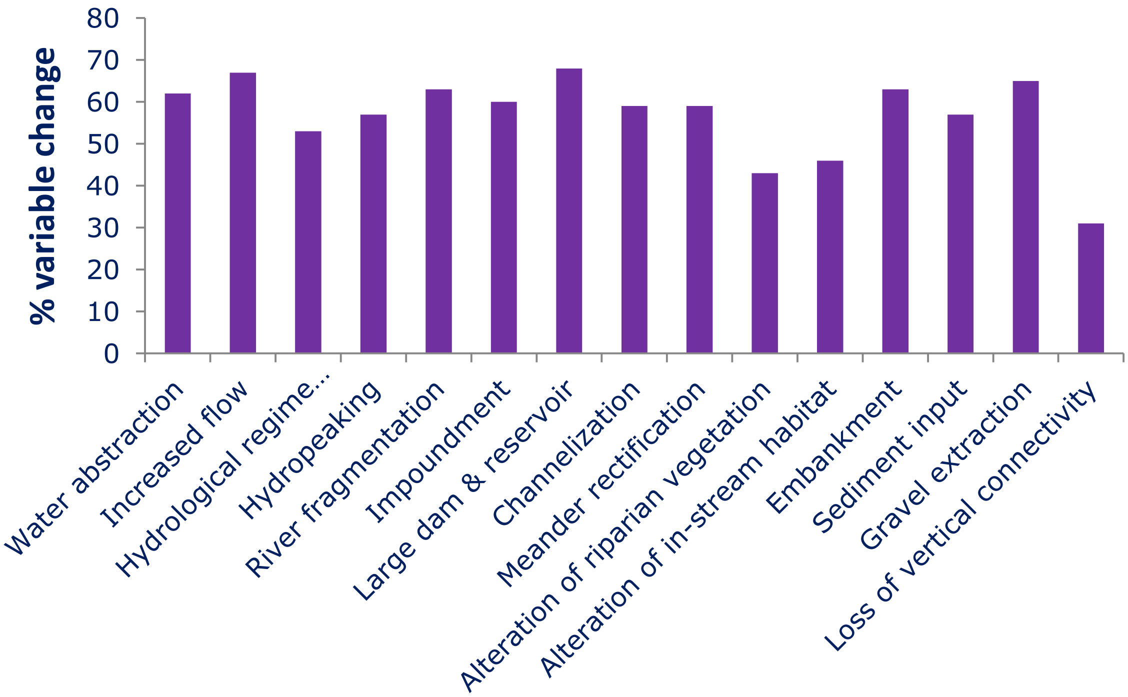


Figure 26: Percentages of variables changed by single pressure removals.

Water abstraction. When water abstraction was removed from the system, 62% of the variables changed. The main changes comprised a strong increase in the process *water flowing* and the variables *depth water column* and *flood magnitude*, while the processes *sedimentation*, *vegetation encroachment* and *bank stabilization* strongly decreased. Associated to this, the variables *drought duration*, *drought frequency* and *% fines* also strongly decreased.

Increased flow. When increased flow was removed from the system, 67% of the variables changed. The main changes comprised a strong increase in the variables *drought duration* and *drought frequency*. The processes *water flowing*, *aquifer recharge*, *sediment transport*, *bank erosion and failure*, and the variables *phreatic level*, *thalweg altitude*, and *flood magnitude* strongly decreased.

Hydrological regime modification. When hydrological regime modifications were removed from the system, 53% of the variables changed. The main changes comprised a strong increase in the process *water flowing* and the variable *flood magnitude*, while processes *vegetation encroachment* and *large wood deposition* and variables *drought duration*, *drought frequency*, *large woody debris*, and *particulate organic matter* strongly decreased.

Hydropeaking. When hydropeaking was removed from the system, 57% of the variables changed. The main changes comprised a strong increase in the processes *vegetation encroachment*, *bank stabilization*, and the variables *drought duration*, *drought frequency*, and *riparian cover area*. The processes *water flowing* and *sediment entrainment* strongly decreased, as well as the variables *channel width*, *depth water column*, *water velocity*, and *flood magnitude*.

River fragmentation. When river fragmentation was removed from the system, 63% of the variables changed. The main changes comprised an increase in the processes *water flowing*, *sediment transport*, and *large wood transport* that lead to strong increase in the variables *substrate size* and *flood magnitude*. The process *armouring* strongly decreased, as well as the variables *drought duration* and *drought frequency*.

Impoundment. When impoundments were removed from the system, 60% of the variables changed. The main changes comprised a strong increase in the processes *water flowing* and *large wood deposition* and the variables *depth water column* and *flood magnitude*, while the process *bank stabilization* extremely decreased. A strong decrease was also observed in the variables *drought duration*, *drought frequency*, *% fines*, and *riparian cover area*.

Large dam & reservoir. When large dams and reservoirs were removed from the system, 68% of the variables changed. The main changes comprised a strong increase in the processes *water flowing*, *vegetation encroachment*, *sediment entrainment*, and *large wood deposition* and in the variables *depth water column*, *phreatic level*, *substrate size*, *large woody debris*, *flood magnitude*, and *particulate organic matter*. The processes *sedimentation*, *armouring*, and *bank stabilization* strongly decreased, as well as the variables *drought duration*, dr*ought frequency*, and *thalweg altitude*.

Channelization. When channelization was removed from the system, 59% of the variables changed. The main changes comprised a strong increase in the processes *sedimentation* and *vegetation encroachment*. The processes *water flowing*, *sediment entrainment*, *bank stabilization*, and the variables *channel width*, *depth water column*, *water velocity* and *flood magnitude strongly decreased*.

Meander rectification. When meander rectification was removed from the system, 59% of the variables changed. The main changes comprised a strong increase in the process *aquifer recharge* and the variables *drought duration*, *drought frequency*, and *thalweg altitude*, while in total five processes (*water flowing*, *sediment entrainment*, *large wood entrainment*, *armouring*, and *vegetation derooting*) but only two variables (*depth water column*, *flood magnitude*) strongly decreased.

Alteration of riparian vegetation. When alteration of riparian vegetation was removed from the system, 43% of the variables changed. The main changes comprised a strong increase in the processes *vegetation recruitment* and *bank stabilization*; while processes *sediment entrainment*, *vegetation derooting*, and *bank erosion and failure* strongly decreased. The variables *channel width* and *depth water column* also strongly decreased.

Alteration of in-stream habitat. When alteration of in-stream habitat was removed from the system, 46% of the variables changed. The main changes comprised a slight increase in the processes *vegetation recruitment* and *bank stabilization*, as well as in the variables *phreatic level*, *thalweg altitude*, *interstitial capacity*, *substrate size*, *large woody debris*, *sand & gravel quantity*, and *infiltration rate*. The processes *sediment transport* and *sediment entrainment* strongly decreased.

Embankment. When sediment input was removed from the system, 63% of the variables changed. The main changes comprised a strong increase in the process *aquifer recharge* and the variables *drought duration*, *drought frequency*, and *thalweg altitude*. Processes *water flowing*, *sediment transport*, *sediment entrainment*, *armouring*, and *bank stabilization* strongly decreased, as well as variables *depth water column*, *water velocity*, and floo*d magnitude*.

Sediment input. When sediment input was removed from the system, 57% of the variables changed. The main changes comprised a strong increase in the process *water flowing* and the variables *depth water column* and *flood magnitude*, while processes *sedimentation*, *vegetation encroachment*, *vegetation recruitment*, *bank stabilization*, and variables *drought duration* and *drought frequency* strongly decreased.

Gravel extraction. When gravel extraction was removed from the system, 65% of the variables changed. The main changes comprised a strong increase in the processes *vegetation encroachment* and *sediment transport* and the variables *drought duration* and *drought frequency*, while the process *vegetation recruitment* extremely decreased.

Loss of vertical connectivity. When loss of vertical connectivity was removed from the system, 31% of the variables changed. The main changes comprised a strong increase in the processes *aquifer recharge* and *vegetation recruitment* and the variable *phreatic level*. Only the variables *channel width*, *riparian mortality*, and *riparian fragmentation* decreased slightly.

6.2.2 Management option simulations

Following the determination of the systems steady state and the effects of single pressure removal, scenarios have been developed which involved multiple interacting HYMO pressures. These scenarios should represent hydromorphological impacts in a more precisely as multiple HYMO pressures are commonly found in river systems simultaneously acting on HYMO variables. The effect sizes of these management option simulations are presented in Table 3.

Scenario 1 simulates the simultaneously occurring effects of meander rectification. Thus, we clamped *meander rectification*, *increased flow*, *channelization*, *alteration of riparian vegetation*, *alteration of in-stream habitat*, and *embankment* in the management option simulations at a high level (1).

Scenario 2 simulates the simultaneously occurring effects of large dam construction. Thus, we clamped *hydrological regime modification*, *river fragmentation, large dam & reservoir*, *alteration of riparian vegetation*, *alteration of in-stream habitat*, and *loss of vertical connectivity* in the management option simulations at a high level (1).

Scenario 3 simulates the simultaneously occurring effects of water abstraction from a river system. Thus, we clamped *water abstraction* and *hydrological regime modifications* in the management option simulations at a high level (1), but *hydropeaking* at a low level (0).

Table 3: Effects of hydromorphological pressure removal on the HYMO variables identified in the conceptual schemes.

	Scenario 1	Scenario 2	Scenario 3
flow variables			
base flow	+++	---	---
flow magnitude	++	--	--
water lev rise rate	++	--	--
water lev recession rate	++	--	--
flood duration	+++	---	---
flood frequency	+++	---	---
flood magnitude	+++	---	---
drought duration	---	+++	+++
drought frequency	---	+++	+++
hydraulic variables			
water column detph	+++	---	---
flow velocity	+++	--	---
shear stress	++	--	--
connection to groundwater			
infiltration rate	--	0	0
phreatic level	+++	---	---
river continuity			
isolated segment size	+++	---	---
no. isolated segments	---	+++	+++
channel dimensions			
channel depth	+++	--	--
channel width	+++	+++	---
thalweg variables			
thalweg altitude	+++	++	--
channel slope	+++	++	++
substrates			
substrate size	---	--	--
interstitial capacity	---	--	+
% fines	---	++	+++
sand & gravel quantity	---	--	++
large woody debris	---	--	+++
part. organic matter	---	-	+++
bank variables			
bank size	--	--	++
bank stability	--	++	+++

	Scenario 1	Scenario 2	Scenario 3
area of new vegetation	---	---	+++
structure of the riparian zone			
riparian canopy area	--	--	-
riparian mortality	++	++	--
riparian fragmentation	++	++	+
rip. vegetation aging	--	--	-
vegetation growth	--	0	++
rip. corridor continuity	--	0	++
rip. cover area	---	--	+++
structure of the floodplain			
oxbow drought	---	+++	+++
artificial oxbows	--	--	0
height of the floodplain	++	--	--
other variables			
nutrient concentration	+++	+++	++
water temperature	+++	+++	+++
channel insolation	+++	+++	0
pollutant burial	+	+	-
toxic sediments	++	+	--

6.3 Interpretation of results

We used a multi-step fuzzy cognitive mapping approach (Özesmi & Özesmi 2004) to run a hydromorphological pressure/impact simulation model that was created from conceptual schemes. This approach enabled us to run the model with steady state conditions (without any management) and also to run management option simulations by manipulating relevant variables in the system. As a result, the impact of any management option simulation can be assessed by the deviation of the HYMO variables from the steady state conditions. As stated by Tan & Özesmi (2006) results obtained from such modeling approach have to be interpreted with caution. The effect sizes of variables changed reflect only increases or decreases relatively to the variables steady state or to other variables affected at the same time. Thus, results have to be qualitatively interpreted rather than as quantitative measure (Tan & Özesmi 2006).

In its steady state, the overall hydromorphological pressure/impact model depicted the situation of the HYMO processes and variables according to the conditions commonly found in hydromorphologically altered large river systems (Appendix C). Drought duration, drought frequency, and thalweg altitude are relatively low due to channelization and water regulation. Furthermore, nutrient concentration, water temperature, % fines, and phreatic level are enhanced. Thus, as the steady state of the model results in reliable output, the management option simulations described above should yield reliable outputs as well. In addition to these management options, a simulation excluding all hydromorphological pressures should reliably depict the steady state of large natural river systems without alteration. This scenario massively positively affects the processes *large wood deposition* and *vegetation recruitment*, while banks destabilize and sediment processes return to natural dynamics. Subsequently, substrate size, sand and gravel quantity, the amounts of particulate organic matter and large woody debris are improved. Exploring these simulation results in detail revealed that the model captured the conditions of natural river ecosystems. Thus, the model is able to predict the responses of the complex interactions of hydromorphological pressures, processes, variable, and biota in a reliable and realistic way.

Channel width, riparian cover, thalweg altitude, phreatic level, and large woody debris were the most central variables in the overall pressure/impact model. All of these variables vary considerably between river types, e.g. mid-sized vs. large rivers, lowland vs. highland rivers, or gravel vs. sand dominated rivers. Thus, depending on the river region, the model should yield discriminative effects of pressures on biota when variables are adjusted according to their relative importance and weight. Adjusting processes and variables to the effect size within certain river types in the initial state vector during the simulation process might therefore enhance accuracy when predicting biota response to pressure removal in specific river types. Hence, the developed model might be applied to a broad range of river systems.

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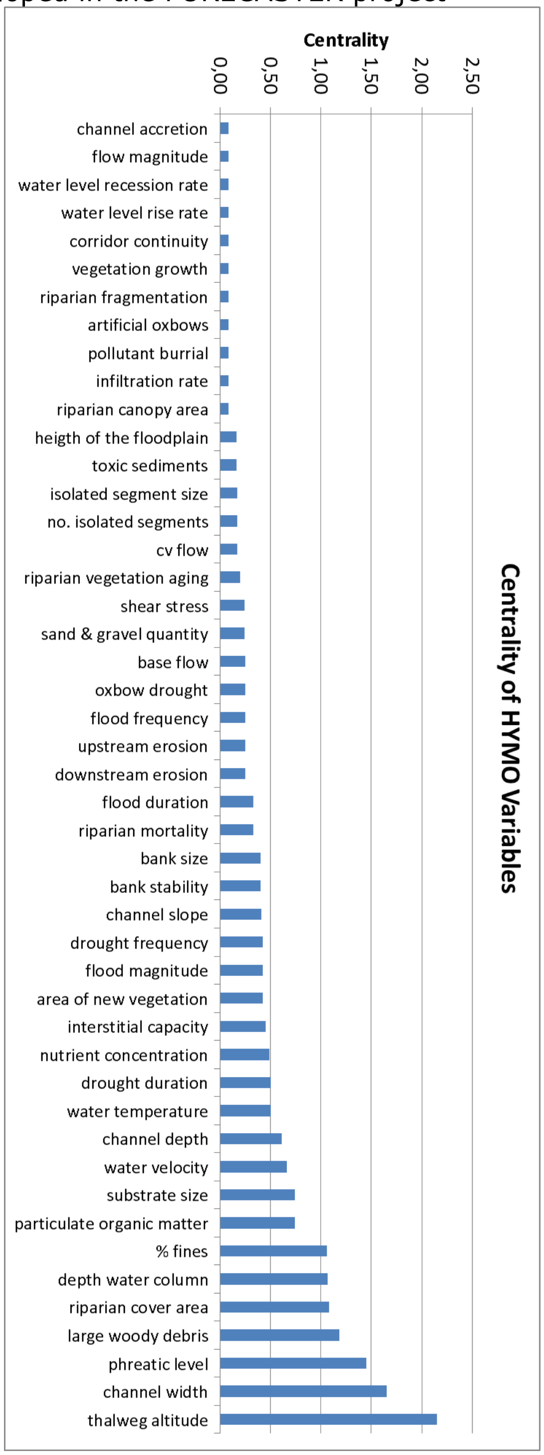
Appendices

Appendix A: Assignment of the variable names to the numbers presented in Figure 20.

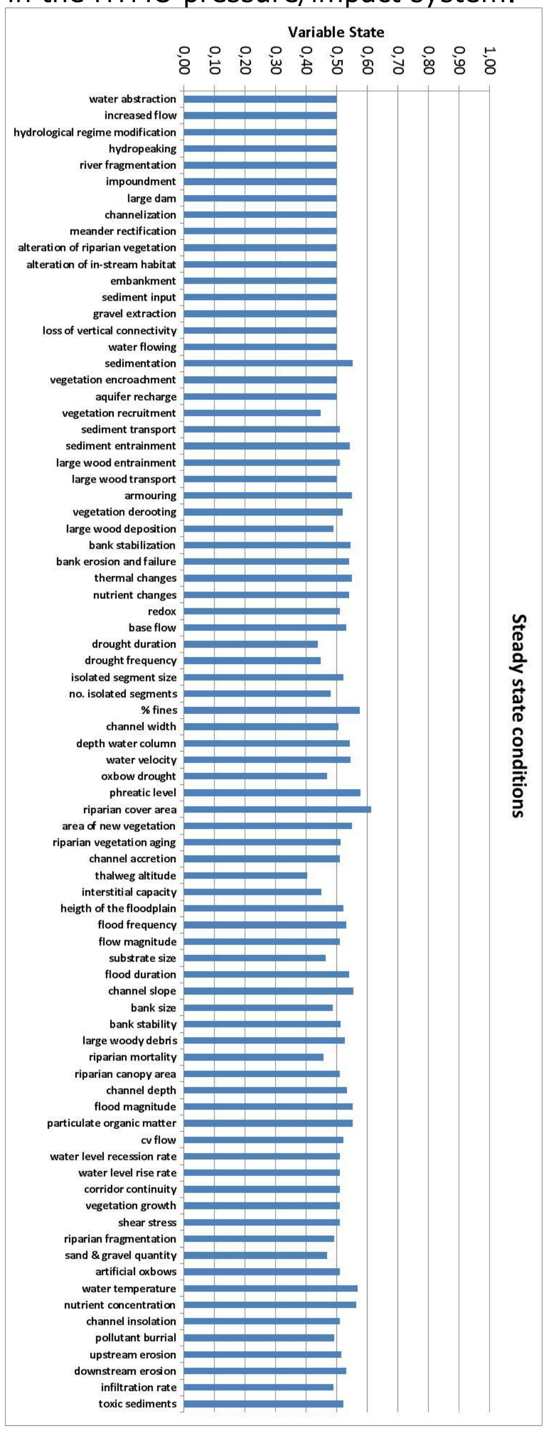
Variable Name	Number	Variable Name	Number
HYMO Pressures		depth water column	37
water abstraction	1	water velocity	38
increased flow	2	oxbow drought	39
hydrological regime modification	3	phreatic level	40
		riparian cover area	41
hydropeaking	4	area of new vegetation	42
river fragmentation	5	riparian vegetation aging	43
impoundment	6	channel accretion	44
large dam	7	thalweg altitude	45
channelization	8	interstitial capacity	46
meander rectification	9	floodplain accretion	47
alteration of riparian vegetation	10	flood frequency	48
		flow magnitude	49
alteration of in-stream habitat	11	substrate size	50
		flood duration	51
embankment	12	channel slope	52
sediment input	13	large woody debris	53
gravel extraction	14	riparian mortality	54
loss of vertical connectivity	15	channel depth	55
		flood magnitude	56
		particulate organic matter	57
HYMO Processes			
water flowing	16	cv flow	58
sedimentation	17	water level recession rate	59
vegetation encroachment	18	water level rise rate	60
aquifer recharge	19	corridor continuity	61
vegetation recruitment	20	vegetation growth	62
sediment transport	21	shear stress	63
sediment entrainment	22	riparian fragmentation	64
large wood entrainment	23	sand & gravel quantity	65
large wood transport	24	artificial oxbows	66
armouring	25	water temperature	70
vegetation derooting	26	nutrient concentration	71
large wood deposition	27	channel insolation	72
bank stabilization	28	pollutant burial	73
bank erosion and failure	29	bank size	76
thermal changes	67	infiltration rate	77
nutrient changes	68	toxic sediments	78
redox	69	bank stability	79
upstream erosion	74	riparian canopy area	80
downstream erosion	75		

Variable Name	Number	Variable Name	Number
HYMO Variables			
base flow	30		
drought duration	31		
drought frequency	32		
isolated segment size	33		
no. isolated segments	34		
channel siltation	35		
channel width	36		

Appendix B: Centrality of the HYMO variables affected by pressures according to the pressure typology developed in the FORECASTER project



Appendix C: Steady state conditions of the HYMO pressures, processes variables, and the biological elements in the HYMO pressure/impact system.



Appendix D: Effects of hydromorphological pressure removal on HYMO processes identified in the conceptual schemes.

	Effect of hydromorphological pressure removal														
	Water abstraction	Increased flow	Hydrological regime modification	Hydropeaking	River fragmentation	Impoundment	Large dam & reservoir	Channelization	Meander rectification	Alteration of riparian vegetation.	Alteration of in-stream habtat	Embankment	Sediment input	Gravel extraction	Loss of vertical connectivity
Hydrological regime															
water flowing	---	+++	---	+++	---	---	---	+++	+++	0	0	+++	---	+++	0
aquifer recharge	0	+++	0	0	0	+++	0	0	---	0	0	---	0	+++	---
Morphological conditions															
sediment entrainment	0	0	0	+++	0	0	---	+++	+++	+++	+++	+++	0	0	0
sediment transport	0	+++	0	0	---	0	0	0	0	0	+++	+++	0	---	0
sedimentation	+++	++	0	0	0	+++	+++	---	0	0	++	++	+++	--	0
bank erosion and failure	0	+++	0	0	0	0	0	0	0	+++	+++	0	0	+++	0
bank stabilization	+++	--	++	---	++	++++	+++	+++	---	---	--	+++	+++	--	--
armouring	0	0	0	0	+++	0	+++	0	+++	0	+++	+++	0	0	0
vegetation encroachment	+++	0	+++	---	0	+++	---	---	0	0	0	0	+++	---	0
vegetation recruitment	--	--	--	++	++	--	++	++	+	---	--	--	+++	++++	---
vegetation derooting	0	0	0	0	0	0	0	0	+++	+++	0	0	0	0	0
large wood entrainment	0	0	0	0	0	0	0	0	+++	0	0	0	0	0	0
large wood transport	0	0	0	0	---	0	0	0	0	0	+++	0	0	0	0
large wood deposition	0	0	+++	0	0	---	---	0	0	0	0	0	0	0	0
Other															
thermal changes	+++	+++	0	0	+++	0	0	+++	0	+++	0	0	0	0	0
nutrient changes	+++	+++	0	0	0	0	0	+++	0	+++	0	0	0	0	0
redox	0	0	0	0	0	0	0	+++	0	0	0	0	0	0	0

Appendix E: Effects of hydromorphological pressure removal on HYMO variables identified in the conceptual schemes.

	Effect of hydromorphological pressure removal														
	Water abstraction	Increased flow	Hydrological regime mod.	Hydropeaking	River fragmentation	Impoundment	Large dam & reservoir	Channelization	Meander rectification	Alteration of riparian veget.ation	Alteration of in-stream habitat	Embankment	Sediment input	Gravel extraction	Loss of vertical connectivity
Hydrological regime															
base flow	--	++	--	++	--	--	--	++	++	0	0	++	--	++	0
flow magnitude	--	++	--	++	--	--	--	++	++	0	0	++	--	++	0
cvflow	--	++	--	++	--	--	--	++	++	0	0	++	--	++	0
water level recession rate	--	++	--	++	--	--	--	++	++	0	0	++	--	++	0
water level rise rate	--	++	--	++	--	--	--	++	++	0	0	++	--	++	0
flood frequency	--	++	--	++	--	--	--	++	++	0	0	++	--	++	0
floodduration	--	++	--	++	--	--	--	++	++	0	0	++	--	++	0
flood magnitude	---	+++	---	+++	---	---	---	+++	+++	0	0	+++	---	+++	0
drought duration	+++	---	+++	---	+++	+++	+++	---	---	0	0	---	+++	---	0
drought frequency	+++	---	+++	---	+++	+++	+++	---	---	0	0	---	+++	---	0
oxbow drought	++	--	++	--	++	++	++	--	--	-	+	--	++	--	+
depth water column	---	++	--	+++	--	---	---	+++	+++	+++	++	+++	---	++	+
water velocity	--	++	--	+++	-	--	--	+++	++	++	++	+++	--	++	0
shearstress	--	++	--	++	--	--	--	++	++	0	0	++	--	++	0
phreatic level	--	+++	--	++	-	++	---	++	--	++	--	--	--	+++	---
River continuity															
isolated segment size	--	++	--	++	--	--	--	++	++	0	0	++	--	++	0
no. isolated segments	++	--	++	--	++	++	++	--	--	0	0	--	++	--	0
corridor continuity	++	0	++	--	0	++	--	--	0	0	0	0	++	--	0
riparian fragmentation	+	+	+	-	-	+	-	-	0	++	+	+	--	--	++
artificial oxbows	0	++	0	0	0	++	0	0	--	0	0	--	0	++	--
Morphological conditions															
channel width	--	++	--	+++	++	--	--	+++	++	+++	++	++	--	+	++
channeldepth	+	--	+	++	-	+	--	++	++	++	-	++	+	--	-

	Effect of hydromorphological pressure removal														
	Water abstraction	Increased flow	Hydrological regime mod.	Hydropeaking	River fragmentation	Impoundment	Large dam & reservoir	Channelization	Meander rectification	Alteration of riparian veget.ation	Alteration of in-stream habitat	Embankment	Sediment input	Gravel extraction	Loss of vertical connectivity
channelslope	++	-	++	++	--	++	--	++	++	++	++	++	++	--	-
bank size	-	+	++	--	--	--	--	--	+	--	+	+	-	--	+
bankstability	++	--	++	--	-	++	++	--	--	--	--	+	++	--	-
thalweg altitude	-	+++	--	--	++	--	+++	---	---	--	--	---	-	+++	+
infiltration rate	0	-	0	0	++	0	0	0	0	0	--	--	0	++	0
% fines	+++	++	++	--	-	+++	++	---	--	--	++	--	+++	--	---
interstitial capacity	--	--	0	--	++	--	--	+	--	--	--	--	--	++	0
substrate size	--	++	+	++	---	+	---	++	--	++	--	--	--	--	-
sand & gravel quantity	0	--	0	--	+	0	+	--	--	--	--	--	0	++	0
channel accretion	++	+	0	0	-	++	++	--	0	0	+	+	++	-	0
floodplain accretion	-	++	--	++	--	-	-	+	++	0	+	++	-	++	0
riparian cover area	+++	++	+++	---	+	+++	--	---	--	--	-	++	+++	--	--
area of new vegetation	++	++	++	--	+	++	--	--	--	--	-	--	++	++	--
riparian vegetation aging	-	++	-	+	+	+	-	-	--	--	-	--	++	++	--
vegetation growth	++	0	++	--	0	++	--	--	0	0	0	0	++	--	0
riparian mortality	--	-	-	++	+	--	++	++	+	++	+	+	--	-	++
riparian canopy area	-	-	-	+	+	-	+	+	+	--	-	-	++	++	--
large woody debris	++	+	+++	--	+	++	---	---	--	--	--	--	++	--	--
particulate org. matter	++	+	+++	--	-	-	---	---	--	--	-	--	++	--	++
Other															
water temperature	+++	+++	0	0	+++	0	+++	0	0	+++	0	0	0	0	0
nutrient concentration	++	++	0	0	0	0	+++	0	0	+++	0	0	0	0	0
pollutant burial	+	+	0	+	-	+	+	-	+	+	+	+	+	-	0
toxic sediments	-	+	-	+	-	-	-	+	+	+	+	+	-	+	+