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WISER

Water bodies in Europe: Integrative Systems to assess Ecological status and Recovery

DELIVERABLE

Deliverable D5.1-1: Conceptual models of the impact of degradation and restoration on riverine aquatic organisms

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Content

Non-technical summary

Anthropogenic degradation of aquatic ecosystems—rivers, lakes, estuaries and coastal waters—is manifold, pervasive and dates back for centuries in Europe. The ecosystems are affected by physical, chemical, hydrological and morphological modifications, all of which impose environmental pressures on the structure and function of aquatic communities. Human impacts on aquatic ecology have frequently been studies and numerous indicators for assessment and monitoring of various environmental impacts on aquatic ecosystems were developed.

In response, the knowledge about the linkages between environmental pressures and aquatic communities was used to derive appropriate measures to rehabilitate and restore aquatic ecosystems. Restoration ecology is often assuming that communities are beginning to recover as soon as the pressures are reduced or removed. However, the simple reversal of degradation equally often does not show the desired and anticipated ecological effect and the biota continue to stay 'degraded'. Firstly, the small spatial scale of many restoration measures does not fit the often very broad-scale degradation at the catchment level; secondly monitoring activities are rather short-term and do not sufficiently account for long time periods required for restoration; and thirdly, the knowledge about a catchment's potential for recovery is sparse.

Module 5 of the WISER project will model relationships between restoration measures, their effect on environmental pressures and finally their ecological effect on aquatic communities. This report on Conceptual Models of degradation and recovery aims at providing a conceptual framework for guiding such studies within the WISER project. The models transfer the relationships between environmental pressures and biological impact and between restoration measures and biological recovery into cause-effect chains, while the linkages are based on an evaluation of the peer-reviewed literature. Hypotheses can be derived from well-referenced chains and can be tested with causative data analyses. Moreover, the results will be used to set up predictive models on the community's recovery after restoration. Finally, knowledge gaps can be identified and summarised to guide future research.

This draft version aims at outlining the general approach to develop the Conceptual Models. General examples are derived from the existing restoration literature and are illustrated. More examples will be provided with the final version due in May 2010. The final version will also address the quantification of cause-effect chains and the identification of important knowledge gaps.

Terms and definitions

- *Adaptive (ecosystem) management*: paradigm for river basin (restoration) management that is adaptive in its behaviour. Adaptive ecosystem management is an iterative, stepwise approach that involves synthesis of available information in an ecosystem context to define the problem, public participation in goal setting (e.g. protection and restoration of native biodiversity), research and peer review to define science-based management actions (e.g., reregulation), effective monitoring and evaluation of management actions and adaptive revision of actions based on new information from scientific research (Stanford et al. 1996).
- *Conceptual Model*: a map of entities (concepts) and their relationships. Here, this map is used to structure and illustrate the relationships of the components of degradation and restoration and their qualitative and quantitative linkages.
- *Degradation*: deterioration or impairment of the quality of a water body.
- *DPSIR*: the causal framework for describing the interactions between society and the environment adopted by the European Environment Agency (EEA): Driving forces, Pressures, States, Impacts, Responses (http://glossary.eea.europa.eu).
- *DPSIR**R***: DPSIR scheme extended by the *Recovery* components, i.e. the return of the structural and functional characteristics of the organism groups due to restoration.
- *Impact groups*: the groups of characteristics used in the WFD (Annex V, Table 1.2) to describe the ecological status using the biological quality elements: composition and abundance, diversity, sensitive/tolerant species, biomass (only phytoplankton) and age structure (only fish).
- *Mechanistic relationship*: relation between two or more objects (variables) that can be fully expressed as a formula.
- *Recovery*: The recovery of the biota of an ecosystem or water body from the adverse impacts of environmental pressures. Recovery is expected in consequence of appropriate response measures and activities (e.g., physical *Restoration*, waste water treatment).
- *Rehabilitation*: Activity to improve the (ecological) status of degraded waters. Unlike *Restoration*, rehabilitation does only aim to partially restore or to artificially simulate the natural processes or structures in a water body. As rehabilitation does not aim to restore the natural pre-disturbance conditions, it should not be confounded with restoration (Lenders et al. 1998 in Jungwirth et al. 2002).
- *Restoration*: Activity to improve the (ecological) status of degraded waters. The goal of this process is to emulate the structure, functioning, diversity, and dynamics of the specified ecosystem. One of the most useful definitions in practice seems to be that of Henry & Amoros (1995): ‘restoration should be defined as returning an ecosystem to its conditions prior to disturbance (if known and possible), or, as in most cases, to a state as similar as possible to that which prevailed prior to disturbance, according to the changes that have occurred in the watershed’ (see also NRC 1992).
- *Statistical relationship*: relation between two or more objects (variables) that cannot be fully expressed as a formula. Instead, the relationship can be expressed as correlation or regression using a series of statistical measures to express the strength of the relationship.
- *Stressor*: used here synonymous for pressure.

Introduction

The degradation of the aquatic environment, freshwater as well as marine ecosystems, dates back for centuries and is pervasive at present in Europe (Tockner et al. 2009). Almost all river basins suffer from the impact of multiple environmental pressures: organic pollution (e.g., industrial and domestic effluents), eutrophication (e.g., due to the application of fertilisers and manure in agricultural landscapes), physical habitat and flow modification (e.g., water regulation and flood protection), and extensive water uses (e.g., cooling water, hydropower generation and irrigation). Lake ecosystems are mainly being affected by eutrophication (agricultural land use) and physical habitat modification of their shoreline, while estuaries and wetlands are mostly affected as they constitute the ultimate sink for nutrients and other sources of pollution and contaminants originating from entire river basins (Cloern 2001; Diaz and Rosenberg 2008). In addition, transitional and coastal waters are being physically modified, for instance, for flood protection purposes (e.g., Pollard and Hannan 1994) or navigation (e.g., van der Wal et al. 2002). These and other pressures might occur individually, but more often do act in combination and pose a serious threat on the ecological status of aquatic ecosystems.

As a consequence, the ecosystems lose biodiversity and functionality. Many sensitive species quickly disappear, while basic ecosystem functions (such as self purification, biomass production and decomposition) are believed to change significantly as soon as degradation becomes severe and exceeds a threshold. Biodiversity, ecosystem functions, and community characteristics (e.g., feedings types, habitat preferences, reproduction traits), are often known to react more or less specific along different pressure gradients and are, therefore, being frequently used as bioindicators within assessment and monitoring schemes (Huryn et al. 2002; Hering et al. 2004; Feld and Hering 2007; Feld et al. in press; Borja at al. 2009a, b). The assessment of aquatic ecosystems, therefore, requires knowledge of the different impacts of numerous environmental stressors on the evenly numerous characteristics of aquatic communities: fish, benthic macroinvertebrates, macrophytes, angiosperms, macroalgae, phytobenthos and phytoplankton. Their relation to the components of ecosystem degradation can be based on ecological theory (e.g., Lake et al. 2007) and has often been tested and discussed, in particular in the huge body of literature on the Water Framework Directive (WFD) since 2000.

If the assessment reveals that a quality target (‘good ecological status’ with respect to the WFD) is not met for a specific lake or a river stretch, and that the target is unlikely to be met without further action, society’s response to degradation is required. Degraded water bodies are being, for instance, rehabilitated to improve the physical habitat quality and to support the recovery of the biota, so that the quality targets will be met in the future. In other cases, waste water is being treated to reduce pollution of river, lake and coastal water effluents. Restoration, in its strict sense, goes one step further and aims at converting a water body back to its conditions before degradation occurred, i.e. the natural conditions without human impact (NRC 1992). Typically, restoration ecology is based on the same ecological theory, as was used before to identify and describe the relation between degradation and ecological quality (e.g., King and Hobbs 2006).

With regard to rivers, however, studies on monitoring the effects of restoration frequently reveal that the riverine communities do not show the anticipated and desired signs of recovery (e.g., Palmer et al. 1997; Jähnig et al. 2009). Similar results have been reported from lakes (e.g., Jeppesen et al. 2005) and transitional/coastal waters (Duarte et al. 2009). The relationships of restoration and its ecological impacts seem to (at least partly) differ from the relationships identified for degradation. In other words: restoration is often not 'simply' the opposite of degradation. Some restoration studies already imply that our knowledge about the time needed for a freshwater or marine ecosystem to recover from degradation is still limited (e.g., Moerke et al. 2004; Nilsson et al. 2005). One important gap addresses the endpoint of restoration and its possible deviance from the ecological status prior to degradation (reference). Another knowledge gap refers to the time scale needed for an ecosystem to recover from degradation. The salient endeavour of restoration ecology still is to identify and test the relationships between degradation and ecology and to transfer the findings to practical restoration (King and Hobbs 2006).

One means to identify and structure general relationships is Conceptual Modelling. In a broader sense, Conceptual Models constitute an ecological framework and can be used, for example, to structure the impact of environmental pressures on the aquatic flora and fauna. Well-documented and statistically proven, but also rather vague relationships can be identified and knowledge gaps become obvious. The linkages can be structured, for instance, based on the knowledge of rather qualitative or quantitative relationships between causes and effects, or the knowledge of empirical or mechanistic relationships. Such models are potentially helpful to define hypotheses on the effects of ecosystem restoration and possible recovery of aquatic communities. Finally, these hypotheses can be tested with real data and used to develop predictive models to forecast the spatial and temporal implications of restoration.

Such predictive models are considered extremely useful for river basin managers to identify and prioritise restoration measures based on existing quantifiable knowledge and the required information on the uncertainty of the predictions. At present, the decisions are—at best—based on adaptive management, a paradigm that has been advocated for many ecological restoration situations explicitly because of the lack of predictive ecological models (e.g., Clark 2002). Adaptive management should be derived from a learning experience and be based on the assessment of the outcome of restoration measures (Downs and Kondolf 2002; Woolsey et al. 2007). Thus, it requires a post-project appraisal of restoration measures in order to allow of this learning experience. Very often, however, monitoring and assessment of the progress and success of restoration measures are replaced by a rather inefficient learning experience: trial and error (Downs and Kondolf 2002).

This document drafts the rationale, development and application of Conceptual Models and thereby, to form the basis for the development of predictive (empirical and statistical) models of the effect of river restoration measures. The report exemplifies how hypotheses on the effect of restoration can be derived from the Conceptual Models and how they might be tested using existing data. Although it is planned to extend the scope of the Conceptual Models also to lake and transitional/coastal ecosystems, this draft, and also the final version of Deliverable 5.1-1 due in May 2010, will focus on rivers, as does the entire Workpackage 5.1. This draft has the following objectives:

- to summarise the ground on which Conceptual Models can be built
- to outline and test the approach to develop the Conceptual Models
- to review the scientific literature and to justify the components of the models
- to document and prove the linkages with references
- to provide examples for both ecosystem degradation and restoration (limited to benthic macroinvertebrates in this draft)

The following objectives will be included until the submission of the final version in May 2010:

- to provide further examples of the impact of ecosystem degradation and restoration on riverine fish, benthic invertebrates, macrophytes and phytobenthos
- to identify promising (well-documented and quantitative) relationships between pressures and their biological impacts and between restoration measures and their effect on biological recovery
- to identify existing knowledge gaps
- to evaluate the usefulness of the approach to develop Conceptual Models

The impacts of degradation and restoration in the literature

Overview of the reviewed restoration literature

A first review focused on an overview of the recent literature published between 1998 and 2009 and revealed 38 peer-reviewed papers on the analysis of the effects of restoration studies. Altogether, 17 scientific journals were cited (Figure 1). The most papers were published in Freshwater Biology (8 papers), followed by the Journal of Applied Ecology (5) and Restoration Ecology (5). Eleven articles were reviews on the restoration literature, and often focussing on one specific restoration aspect, e.g. dam removal (Bednarek 2001).

Ten out of 38 papers lacked a clear geographic focus, or focussed on the global perspective. Another two papers analysed the situation in Europe, while the remaining 26 papers presented research done in nine OECD-countries (Figure 2). Only one study was conducted in Asia (Japan), all others originated in Northern America or Europe.

Most studies aimed at restoring the riverine morphology/physical habitat (22 papers) and/or hydrology/flow conditions (16). Measures to reconstitute the longitudinal connectivity or changing water use/resource exploitation were evaluated by only a few papers, while land use was not considered by any paper (Figure 3). Indicator groups used to measure progress and success (Figure 4) were macrozoobenthos (17) followed by abiotic indicators (16). Frequently-used abiotic indicators were, for instance, differences in flow regime, sediment transport, nutrient uptake, pool formation or retention of coarse particular organic matter (CPOM). Fish metrics played a role in seven studies, while macrophyte response was considered in five papers. Only one paper analysed the effect of restoration on phytobenthos (Hering et al. 2006).

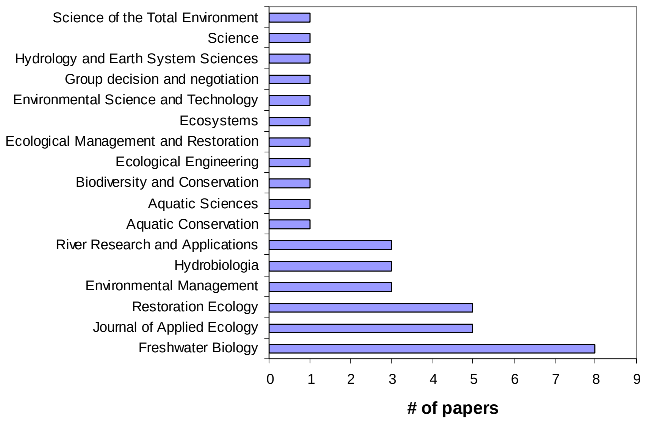

Figure 1: Number of articles reviewed and source journals (N = 38).

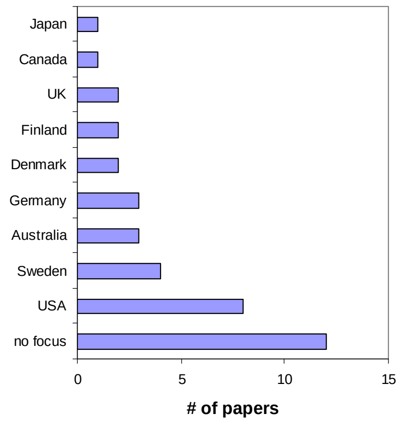

Figure 2: Number of reviewed articles per country.

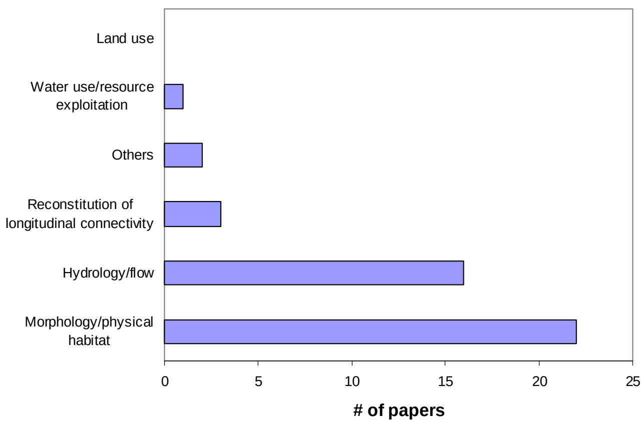

Figure 3: Number of reviewed articles per group of restoration measures.

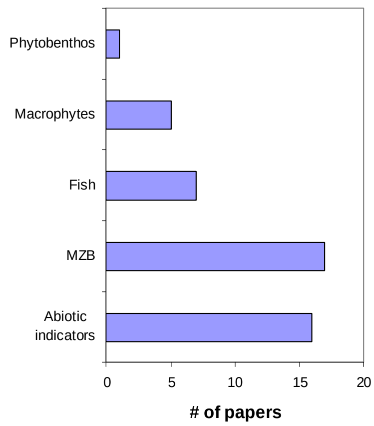

Figure 4: Number of reviewed articles per indicator group.

A major finding is that information essential to compare and analyze study results are often lacking in the scientific literature. Only 20 papers specify the time period of sampling and only 16 inform about length of the time period between end of restoration measures and their sampling. The length of this period is crucial information, as many organism groups are known to need longer periods of time to recover to a near-natural status. The same can be said about information to classify the size of the researched stream, with stream order given by only seven papers and catchment size by only five.

Example: The impact of land use on riverine fish, benthic macroinvertebrates and benthic algae

According to Allan (2004) **agricultural land use** degrades river ecosystems by increasing non-point inputs of pollutants, pesticides and fine sediments, by impacting riparian and stream channel habitat and altering flows. Enhanced nutrient levels and solar radiation (loss of riparian shading) lead to an increase in algal biomass, which affects the aquatic food web (e.g., increase of macroinvertebrate grazers). Major changes associated with increased urban land area include the increases of the amounts and variety of pollutants in runoff, more erratic hydrology owing to increased impervious area and runoff conveyance, increased water temperatures owing to the loss of riparian vegetation, reduction in channel and habitat structure owing to sediment inputs, bank destabilisation, scouring, channelisation and restricted interactions between the river and its land margin (and floodplain).

The manifold pressures and impacts of **urbanisation** on rivers have been reviewed by Paul and Meyer (2001). The authors stress the role of 'impervious surface cover', which has been identified as the main *Pressure* caused by urbanisation with severe implications for the riverine hydrology and morphology (Dunne and Leopold 1978; Arnold and Gibbons 1996; Booth and Jackson 1997). McMahon and Cuffney (2000) reported the catchment's cover of impervious area to be the major predictor of urbanisation and urban impacts on streams. Furthermore, Paul and Meyer (2001) refer to three groups of *State* variables (hydrology, geomorphology, temperature) and their *Impact* on two organism groups (fish, benthic macroinvertebrates).

The implications of urbanisation include the increase in surface runoff and peak discharge (Arnold and Gibbons 1996; Booth and Jackson 1997). As runoff is enhanced, channel dimensions enlarge, which in turn causes an increase in water temperature (Galli 1991). This hydromorphological and physical degradation affects the diversity and integrity of riverine fish communities (Klein 1979; Steedman 1988, Wang et al. 1997; Yoder et al. 1999) and of benthic macroinvertebrates (Horner et al. 1997; Yoder et al. 1999). This example of the impact of catchment urbanisation is partly illustrated in Annex 2; however, the Figure does not include 'biotic integrity' as a separate impact group. Biotic integrity is considered redundant here, as it is expressed as multimetric 'Index of Biotic Integrity' (IBI, e.g., Karr 1999) and, thus, amalgamates the individual impact groups used here in a (redundant) combined metric.

A more general review of the principle mechanisms by which land use influences stream ecosystems, has been compiled by Allan (2004). The author summarizes seven groups of pressures: 'sedimentation', 'nutrient enrichment', 'contaminant pollution', 'hydrologic alteration', 'riparian degradation' and 'loss of large woody debris'. Sediment entry from adjacent crop land and sedimentation increases turbidity (Henley et al. 2000) and impairs habitat conditions for benthic algae, crevice-occupying invertebrates and gravel-spawning fish (Wood and Armitage 1997). Nutrient enrichment affects the autotroph's production and biomass and results in a shift of algal composition. Decomposition processes lead to a decline of dissolved oxygen and sensitive taxa will be replaced by tolerant, often non-native species. In particular invertebrates and fish are affected by contaminant pollution (Woodward et al. 1997; Schulz 2004). Growth may be depressed, reproduction may fail and the endocrine systems may be disrupted. The hydrological alterations listed by Allan (2004) are similar to those reviewed by Paul and Meyer (2001) and are already mentioned above. Besides the loss of shading and the increase in water temperature due to the loss of riparian woody vegetation, Allan (2004) also mentions the increase in channel erosion and the decrease in sediment and nutrient trapping from surface runoff. Finally, the loss of large woody debris causes a loss of habitat and organic matter storage, all of which have an adverse effect on the diversity and community functions of fish and benthic macroinvertebrates (Gurnell et al. 1995, 2002; Stauffer et al. 2000).

Example: The ecological impact of dam removal in rivers

The removal of dams and its possible ecological impacts on riverine organisms has been reviewed by Bednarek (2001), who also presented a series of case studies to underpin the review with real data. Accordingly, several important river characteristics are positively affected by the removal of dams and other transverse structure that cause impoundment. An unregulated flow regime allows of a natural flow, i.e. the return of lotic and dynamic flow conditions to formerly impounded sections. Bunn and Arthington (2002) stressed the role of flow as a major determinant of physical habitat in streams, which in turn is a major determinant of biotic composition. More recently, Acreman and Dunbar (2004) referred to the flow regime required in a river to achieve desired ecological objectives, i.e. the ‘environmental flow’. Environmental flow does include floods, medium and low flow, as all elements of a flow regime are considered important (Poff et al. 1997). Low flows provide a minimum habitat for species and prevent invasives, medium flows sort river sediments and stimulate fish migration and spawning, and floods maintain channel structure and allow movement onto floodplain habitats (Acreman and Dunbar 2004).

Occasional floods reconnect the aquatic and riparian habitat (Shuman 1995; but see also Jähnig et al. 2009 for a more recent study), and backwaters are refilled. Fine materials (e.g., sand, silt, mud) erode and uncover coarser substrata (e.g., gravel, pebble and cobbles), which enhances the overall habitat diversity (Kanehl et al. 1997; Born et al. 1998). The sediment transport also affects habitat diversity further downstream. Dissolved oxygen and water quality improve (Hill et al. 1993); the temperature regime changes (less warming of stagnant water). Bednarek (2001), however, also refers to some negative effects, such as contamination further downstream due to the transport of contaminated sediments or the overall abrasive effect of fine sediment transport. But these adverse effects are considered rather short-term, while improvement will occur in the long-term.

Overall, the changing abiotic conditions improve biodiversity and reproduction of fish. The spawning grounds for salmonid species increase (Iversen et al. 1993), while fish passage is now possible for migrating species because of the restored longitudinal connectivity. Hence, typical riverine (migrating) fish benefit, while lentic and reservoir-specific species decrease. The maintenance of the longitudinal, but also of the lateral connectivity with the floodplain, is essential to the viability of populations of many riverine species (Bunn and Arthington 2002).

Development of conceptual models

Both ecosystem degradation and restoration involve socio-economic and ecological components. With regard to degradation, socio-economic drivers (e.g., society's food and energy demand or industrial production) impose various pressures on all kinds of aquatic ecosystems, which in turn have adverse effects on their biological communities. In brief, this is frequently addressed with pressure-impact analysis. In contrast, ecosystem rehabilitation and restoration require society's response to reduce the pressures, to inverse degradation and to ultimately improve the ecological status of ecosystems. The DPSIR scheme (EEA 2007) does already provide a framework to link socio-economy with ecology and is, therefore, considered useful to develop the Conceptual Models of degradation and restoration presented in the following. The DPSIR scheme has been applied in previous similar studies (Elliott 2002; Karageorgis et al. 2005), whereas a main advantage of the scheme is its simplicity that renders the communication with non-scientists feasible (Stanners et al. 2007). To illustrate the scheme and its components, an example is presented in the following.

Society's food demand, for instance, implies agricultural land use (*Driver*). The intensive application of fertilisers and pesticides in agricultural crops is often linked with pollution and eutrophication (*Pressure*) and causes water quality deterioration of adjacent rivers and lakes. Nutrients (N, P) and contaminants are being transferred with surface runoff from agricultural areas and through nutrient leaching from the soils. This inevitably has a stimulating effect on the growth of macrophytes and algae, but will also negatively affect the aquatic fauna (fish, benthic invertebrates) as soon as decomposers start depleting oxygen and causing water quality deterioration (*State*). In parallel to eutrophication and contamination, rivers in agricultural landscapes are morphologically modified and hydrologically regulated (*Pressure*). As a result, microhabitats and flow regimes may change (*State*).

As a result of high population density and its demand for food (*Driver*) weirs and dams (*Pressure*) are built to control the ground water levels (*State*), but also disrupt the longitudinal connectivity of the system (*State*). Land use is often extended to the river banks and inhibits the development of a natural (vegetated) riparian buffer. As a consequence, the riverine fauna and flora is being disrupted, sensitive taxa disappear (*Impact*), and a few tolerant taxa become dominant in the system (*Impact*). Rivers and estuaries are easily being invaded by alien species (*Impact*).

To reverse degradation and to improve the ecological status, measures of restoration and mitigation are required. Best-practice agriculture (*Response*), for instance might reduce the amount of fertilisers applied per area to the amount that is equivalent to the plant biomass produced per area. Hydromorphological conditions might be restored (*Response*) to a more diverse habitat and flow regime. Land use in the riparian zone might be abandoned (*Response*) to promote the natural development of a diverse riparian buffer strip with grasses, shrubs and trees. This example of a simple DPSIR scheme can be illustrated with a Conceptual Model for degradation (Figure 5) and restoration' (Figure 6) due to agricultural land use.

The community's change, i.e. the altering community characteristics towards the conditions equal to the quality targets (pre-degradation conditions), is referred to as *Recovery* in the following. In its strict sense, however, *Recovery* means the full recovery of both community structure and function accompanied by all physical and chemical conditions prior to degradation (Henry and Amoros 1995). The extension of the DPSIR scheme with *Recovery* eventually results in the DPSIRR scheme, i.e. the *Driver-Pressure-State-Impact-Response-Recovery* chain.

Limitation of the model components

Conceptual Models can be developed almost arbitrarily complex. One driver, for instance, might control several or numerous pressures and, thus, might reveal a complex network of states and impacts on the targeted organisms. In turn, a single restoration measure might affect several pressures in parallel and thus have various effects on water quality and physical habitat status, which ultimately control the community's change. More complex examples will result, if multiple pressures and their ecological impacts are to be considered in parallel and will finally end up in useless illustrations. In order to limit this complexity on beforehand, a selection of major drivers of ecosystem change, related pressures and major biological impact groups were pre-defined. For the Conceptual Models of degradation, the selection includes:

- *Driver*: 'urbanisation', 'agriculture', 'water withdrawal and regulation', 'navigation', 'flood protection' and 'Climate Change'. This selection includes the most important direct drivers of ecological change in freshwater and marine ecosystems during the past 50 years (MEA 2005).
- *Pressure*: the general focus for Workpackage 5.1 (management of rivers) was laid on hydromorphological degradation and the combined effects of eutrophication, land use and hydromorphological degradation.
- *State*: the specific environmental condition(s) (variables) affecting the biota and controlled by the pressure(s).
- *Impact*: 'taxonomic composition and abundance', (biological) 'diversity', 'sensitive/tolerant taxa', 'age structure' (reproductive status) and 'biomass'. This selection of impact is equivalent to the biotic characteristics listed in Annex V of the WFD to describe ecological status (2000/60/EC, Table 1.2, p. 38 ff).

For the restoration models, the following criteria were pre-defined:

- *Response*: major group of restoration/rehabilitation measures: flow regime, water quality, connectivity, channel physical structure, riparian/floodplain structure, channel management, and resource use (see also Acreman and Dunbar 2004). This selection is assumed to cover the major fields of restoration according to the review of existing literature presented above.
- *State*: effect(s) of restoration on the riverine abiotic conditions, i.e. the change of the 'States'. The State component is the same in both degradation and restoration Conceptual Models and, hence, provides the option to link both models.
- *Recovery*: the impact of the change of state(s) due to restoration/rehabilitation on the biota. These impact groups are the same as listed above for the degradation models.

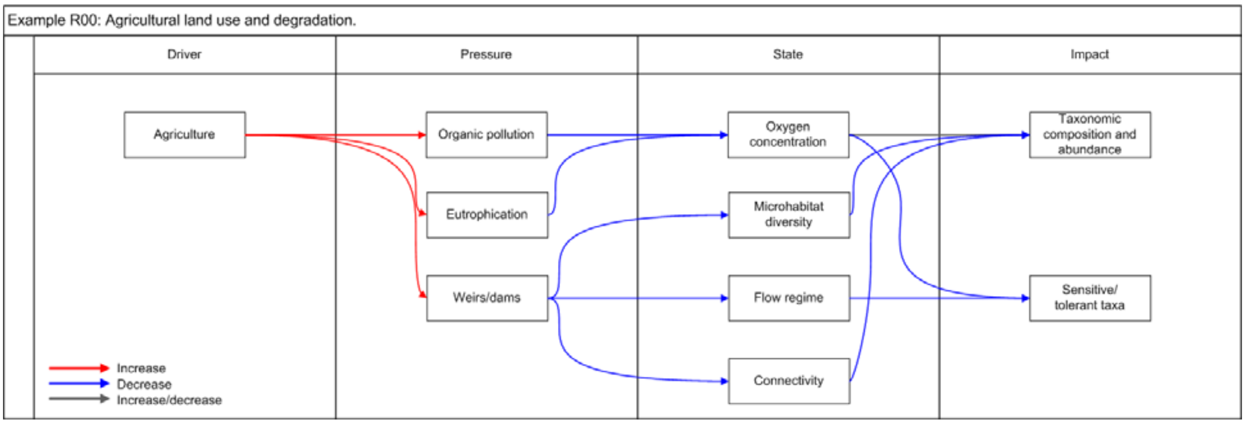

Figure 5: Example of a simple Conceptual Model of the impact of degradation due to agricultural land use.

The degree of complexity of the models is in addition determined by the number of linkages (arrows) between the DPSIR components. State variables, for instance, may affect all impact groups if based on ecological theory. For instance, the decrease in oxygen concentration due to organic pollution (Figure 7) is known to affect the taxonomic composition and abundance, in particular the number and density of pollution-sensitive taxa like salmonid fish species. If not balanced by additional tolerant fish taxa, this loss in community richness will reduce biological diversity, too. If reproduction of other fish species fails to occur, this has inevitably an effect on the age structure of the species' population, and most likely also on the total biomass. Hence, multiple impacts may easily result in complex models, too.

A potential combination of both models is provided with the 'State' component, which is included in both degradation (DP**S**I) and restoration (R**S**R) models. The State might be considered the key component of both chains, as it is likely referring to the (abiotic) habitat conditions that ultimately impact the structure and function of the organism groups. However, this linkage is not being included in the illustrations provided with this draft for two reasons. Firstly, restoration is often not simply the reversal of degradation (e.g., Moerke et al. 2004), which would, however, be implied by such a linkage. Secondly, for clarity reasons, this draft version of D5.1-1 aims at outlining the basic principles and possible application of Conceptual Models. As this issue deserves further discussion, it will be further elaborated and discussed in the final version.

Linkage of the components

The linkages are represented by arrows, while red arrows in the models indicate increase, and blue ones decrease in the variable the arrow is pointing at. In order to limit the degree of complexity of the linkages between the components, only those linkages were considered for the final Conceptual Models (see Case Studies below) that can be concluded from the scientific degradation and restoration literature.

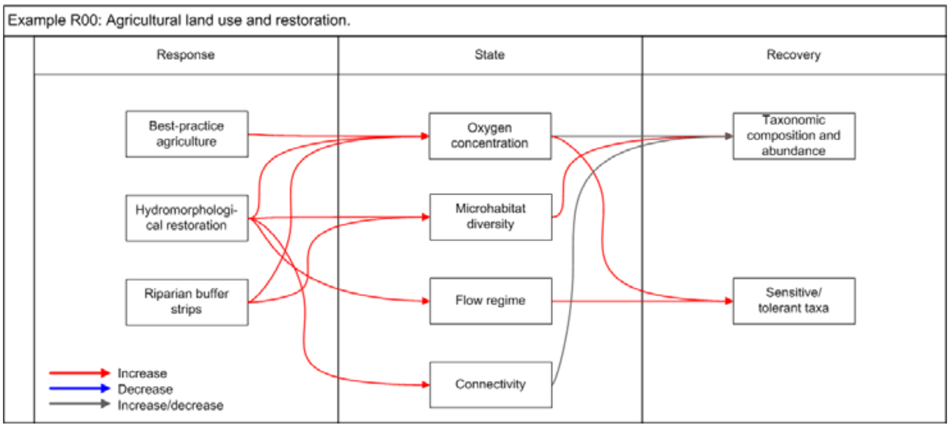

Figure 6: Example of a simple Conceptual Model of the effect of restoration.

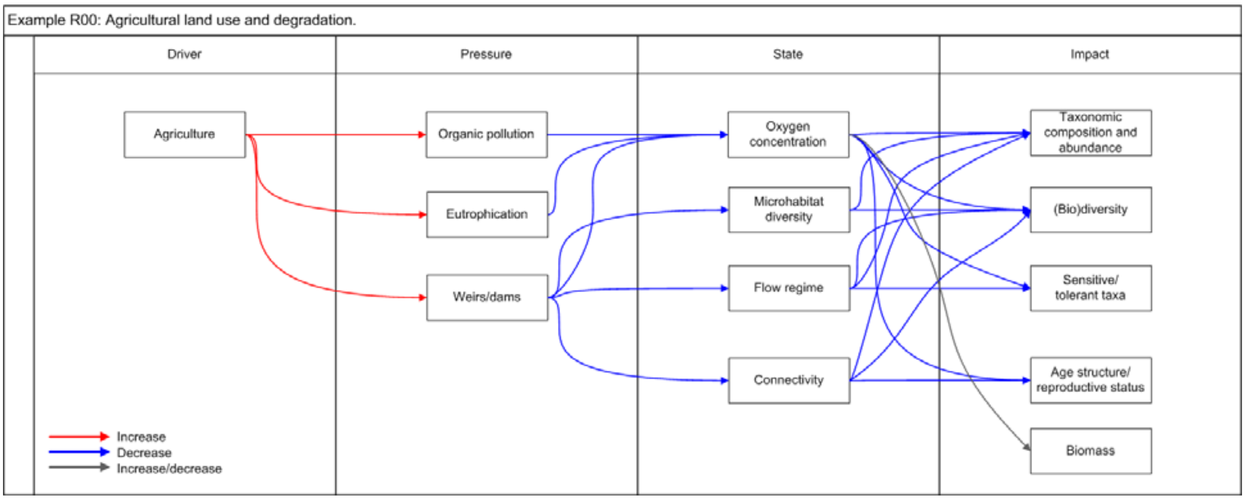

Figure 7: Example of a Conceptual Model with a complex array of impacts due to agricultural land use.

The linkages were further distinguished according to their quantitative or qualitative nature.

- A quantitative linkage refers to relationships with information on the degree of change (e.g., an increase of *x* by 10% causes an increase of *y* by 20%). Linkages that are based on either empirical (e.g., x and y are correlated with an $R^2 = 0.79$) or mechanistic relationships (e.g., *y* is *a* times *x*) were also considered quantitative. Quantitative relationships are preferred over qualitative.
- A qualitative linkage was given, if only the direction of a trend was reported (e.g., an increase of *x* causes a decrease of *y*). Though not likely to be useful for subsequent quantitative analysis and modelling, such information is considered important for the development of hypothesis and thus included here.

Each linkage was, therefore, numbered and referred to in a table with information on the quantitative or qualitative nature of the linkage and the appropriate reference(s).

Examples of Conceptual Models of degradation and restoration

The impact of urban and agricultural organic pollution on river benthic macroinvertebrates

The degree of urbanisation (area covered by houses, roads, industries, etc.) and agricultural land use is linked to point source and non-point source pollution. This example focuses on organic pollution originating from domestic and industrial waste water, and from agriculture. The DPSI chain is illustrated in Annex 1 and referenced in Table 1.

The degree of pollution, for instance, has been quantified by Paxéus (1996) for domestic waste water and by Foy and Kirk (1995) for organic pollution because of dairy cow farming. The resulting oxygen depletion due to decomposition and degradation of organic compounds adversely impacts the invertebrate community, namely the presence of sensitive taxa (e.g., Zelinka and Marvan 1961; Rolauffs et al. 2004) and the overall diversity (e.g., Brabec et al. 2004)

Table 1: References to the DPSI chain for the impact of organic pollution on riverine benthic macroinvertebrates (see Annex 1 for an illustration).

Connector No.	Description	Quantitative	Qualitative
1	Domestic and industrial (organic) waste water	Domestic waste waters contain numerous organic compounds, which contribute up to 80 % of COD to the total discharge to a Swedish waste water treatment plant (Paxéus 1996). Specific organic compounds ranged 5-50 µg/l.	
2	Agricultural pollution (manure, silage effluent)	A decrease in water quality of one class was associated with an increase in the combined grazing/stocking rate of cattle and sheep of 0.6 dairy cow equivalents/ha in 42 Northern Irish lowland streams. The worst pollution events, with BOD concentrations in excess of 100 mg/l, occurred at the end of May and were caused by discharges of silage effluent (Foy and Kirk 1995; Hooda et al. 2000).	
3	Oxygen depletion due to decomposition of organic compounds	Increase of BOD5 along a gradient of increasing pollution (e.g., Brabec et al. 2004)	Decreasing O_2 concentrations with increasing urbanisation (Jones and Clark 1987)
4	Changing composition, richness may increase or (more likely) decrease, abundance may increase or decrease	Linear decrease of EPT taxa and Margalef diversity along a pollution gradient (e.g., Brabec et al 2004; Ofenböck et al. 2004; Pinto et al. 2004)	
5	Loss of pollution-senstive taxa, increase/increasing dominance of tolerant taxa	Increase of saprobic indices and other metrics along a pollution gradient (Dahl et al. 2004; Rolauffs et al. 2004); change of saprobic valences (Zelinka and Marvan 1961; Moog 1995)	

The impact of hydromorphological degradation (due to urbanisation) on river benthic invertebrates

The degree (area) of urbanisation in a watershed is linked to the degree of physical modification and flow regulation of its streams and rivers. The flow regimes are significantly impacted by the surface runoff from impervious areas (e.g., industrial and private buildings, parking lots, streets, see Paul and Meyer 2001 for a review). This in turn requires the regulation of flow, for instance by means of flood protection, which very often is not restricted to the urban areas but extends to the river segments up and downstream. As a result, the river courses, i.e. the bed and bank structures and the riparian zones, are being physically degraded and severely modified. Hydromorphological degradation results in reduced benthic macroinvertebrate diversity (e.g., Minshall 1984), the loss of sensitive taxa such as stoneflies (e.g., Hynes 1976) and a change in community composition. The example is illustrated in Annex 2.

Table 2: References to the DPSI chain for the impact of hydromorphological degradation on riverine benthic macroinvertebrates (see Annex 2 for an illustration).

<table>
<tr><th>Connector No.</th><th>Description</th><th>Quantitative</th><th>Qualitative</th></tr>
<tr><td>1</td><td>Rivers are being regulated and hydrologically and physically modified in urban areas</td><td>Major pressure is % of impervious area, which is correlated with stormwater discharge (power function!) and hence with channel geomorphology and habitat structure (review by Paul and Meyer 2001)</td><td>% Urban land use (and % impervious surface area) in the catchment are good predictors of biotic integrity (Wang 2001, in Allan 2004)</td></tr>
<tr><td>2</td><td>Physical modification includes sealing and paving of the river bed</td><td></td><td>Various personal observations</td></tr>
<tr><td>3</td><td rowspan="4">Bed and bank modification reduces the overall diversity of habitats (flow conditions and substrata) and the availability of key substrata, such as gravel</td><td rowspan="4">% Bed and bank fixation determines a hydromorphological gradient and negatively influences habitat (substrata) diversity (Feld 2004).</td><td rowspan="4">Channelization leads to the homogenisation of flow and loss of habitat diversity (Boët et al 1999; Paul & Meyer 2001)</td></tr>
<tr><td>4</td></tr>
<tr><td>5</td></tr>
<tr><td>6</td></tr>
<tr><td>7</td><td rowspan="2">Urbanisation increases hydraulic stress (channelization, storm water) with adverse flow conditions</td><td rowspan="2">% Impervious Surface Cover (ISC) is a good predictor of the impacts of urbanisation on abiotic and biotic characteristics of a river (Paul & Meyer 2001); values > 10% ISC indicate severe impact on riverine fishes and macroinvertebrates; compared with runoff in forested catchments, 10-20% increase of ISC cause twofold runoff, and 75-100% ISC cause a fivefold increase of runoff.</td><td rowspan="2">Increasing stormwater runoff leads to altered stream channel form, accelerated channel erosion and bed form (Klein 1979)</td></tr>
<tr><td>8</td></tr>
<tr><td>9</td><td rowspan="4">Taxonomic composition and abundance decrease due to the less diverse habitat structure and uniform flow conditions</td><td>Positive correlation between bed particle size and richness/density (Minshall 1984)</td><td></td></tr>
<tr><td>10</td><td></td><td>Flow variation is a predictor of macroinvertebrate community (composition) (Wood et al. 2000)</td></tr>
<tr><td>11</td><td>Relative roughness of bed was positively correlates with B-IBI and EPT richness (Moorley and Karr 2002); bed particle size was positively correlated with IBIs (Roy et al 2003);</td><td></td></tr>
<tr><td>12</td><td></td><td>% Gravel is correlated with occurrence of some species of Plecoptera (e.g., Hynes 1976)</td></tr>
</table>

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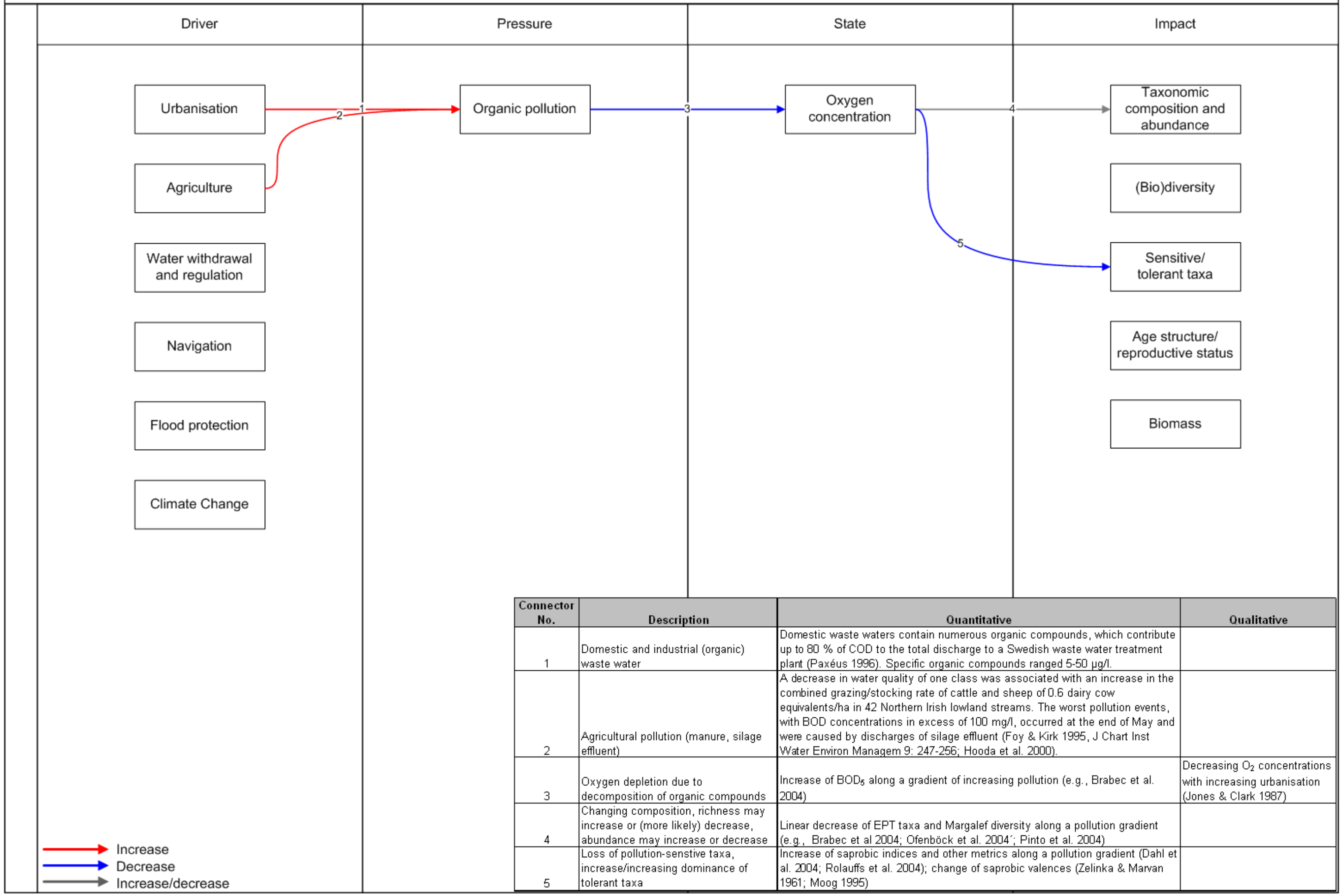
Annex

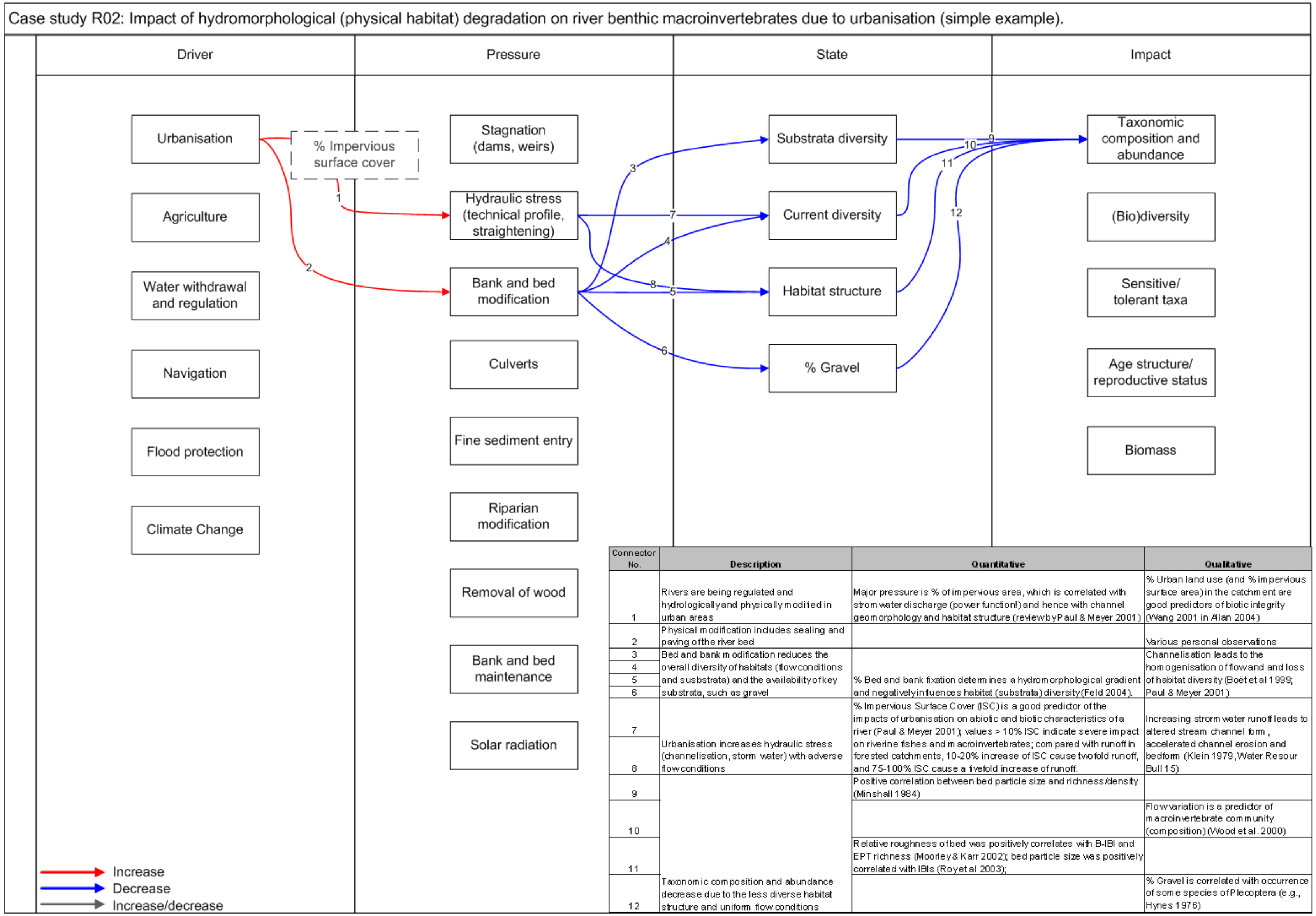
Annex 1

Case study R01: Impact of organic pollution on river benthic macroinvertebrates due to urbanisation



Connector No.	Description	Quantitative	Qualitative
1	Domestic and industrial (organic) waste water	Domestic waste waters contain numerous organic compounds, which contribute up to 80 % of COD to the total discharge to a Swedish waste water treatment plant (Paxéus 1996). Specific organic compounds ranged 5-50 µg/l.	
2	Agricultural pollution (manure, silage effluent)	A decrease in water quality of one class was associated with an increase in the combined grazing/stocking rate of cattle and sheep of 0.6 dairy cow equivalents/ha in 42 Northern Irish lowland streams. The worst pollution events, with BOD concentrations in excess of 100 mg/l, occurred at the end of May and were caused by discharges of silage effluent (Foy & Kirk 1995, J Chart Inst Water Environ Managem 9: 247-256; Hooda et al. 2000).	
3	Oxygen depletion due to decomposition of organic compounds	Increase of BOD_5 along a gradient of increasing pollution (e.g., Brabec et al. 2004)	Decreasing O_2 concentrations with increasing urbanisation (Jones & Clark 1987)
4	Changing composition, richness may increase or (more likely) decrease, abundance may increase or decrease	Linear decrease of EPT taxa and Margalef diversity along a pollution gradient (e.g., Brabec et al 2004; Ofenböck et al. 2004´; Pinto et al. 2004)	
5	Loss of pollution-senstive taxa, increase/increasing dominance of tolerant taxa	Increase of saprobic indices and other metrics along a pollution gradient (Dahl et al. 2004; Rolauffs et al. 2004); change of saprobic valences (Zelinka & Marvan 1961; Moog 1995)	

Annex 2



Connector No.	Description	Quantitative	Qualitative
1	Rivers are being regulated and hydrologically and physically modified in urban areas	Major pressure is % of impervious area, which is correlated with strom water discharge (power function!) and hence with channel geomorphology and habitat structure (review by Paul & Meyer 2001)	% Urban land use (and % impervious surface area) in the catchment are good predictors of biotic integrity (Wang 2001 in Allan 2004)
2	Physical modification includes sealing and paving of the river bed		Various personal observations
3, 4, 5, 6	Bed and bank modification reduces the overall diversity of habitats (flow conditions and susbstrata) and the availability of key substrata, such as gravel	% Bed and bank fixation determines a hydromorphological gradient and negatively influences habitat (substrata) diversity (Feld 2004).	Channelisation leads to the homogenisation of flow and and loss of habitat diversity (Boët et al 1999; Paul & Meyer 2001)
7, 8	Urbanisation increases hydraulic stress (channelisation, storm water) with adverse flow conditions	% Impervious Surface Cover (ISC) is a good predictor of the impacts of urbanisation on abiotic and biotic characteristics of a river (Paul & Meyer 2001); values > 10% ISC indicate severe impact on riverine fishes and macroinvertebrates; compared with runoff in forested catchments, 10-20% increase of ISC cause twofold runoff, and 75-100% ISC cause a fivefold increase of runoff.	Increasing strorm water runoff leads to altered stream channel form, accelerated channel erosion and bedform (Klein 1979, Water Resour Bull 15)
9		Positive correlation between bed particle size and richness/density (Minshall 1984)	
10			Flow variation is a predictor of macroinvertebrate community (composition) (Wood et al. 2000)
11		Relative roughness of bed was positively correlates with B-IBI and EPT richness (Moorley & Karr 2002); bed particle size was positively correlated with IBIs (Roy et al 2003);	
12	Taxonomic composition and abundance decrease due to the less diverse habitat structure and uniform flow conditions		% Gravel is correlated with occurrence of some species of Plecoptera (e.g., Hynes 1976)

Annex 3: Restoration literature considered and selected characteristics of the references.

Author	Year	Title	Journal	Vol	Iss	Review paper	Start of sampling	End of sampling	Time period (days)	Catchment size	Stream order	No of study sites	Geographic region: Continent	Geographic region: Water Body	Geographic region: Country
Acreman	2004	Defining environmental river flow requirements – a review	Hydrology and Earth System Sciences	8	5	yes	-	-	-	-	-	-	global	-	-
Aldridge	2009	Rehabilitation of stream ecosystem functions through the reintroduction of coarse particulate organic matter	Restoration Ecology	17	1	no	2004	2004	8	-	-	1	Australia	Torrens river catchment	Australia
Anand	2004	Quantification of restoration success using complex systems concepts and models	Restoration Ecology	12	1	yes	-	-	-	-	-	-	global	-	-
Arthington	2003	Flow restoration and protection in Australian rivers	River Research and Applications	19		yes	-	-	-	-	-	-	Australia	-	Australia
Bednarek	2001	Undamming rivers: a review of the ecological impacts of dam removal	Environmental Management	27	6	yes	-	-	-	-	-	-	global	-	-
Bernhardt	2005	Synthesizing U.S. river restoration efforts	Science	308	5722	yes	-	-	-	-	-	-	North America	-	USA

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Acreman	2004	yes	no	no	no	no	no	no	no	no	no	no
Aldridge	2009	no	no	no	no	no	yes	no	no	no	no	no
Anand	2004	no	no	no	no	no	no	no	no	no	no	no
Arthington	2003	yes	no	no	no	no	no	no	no	no	no	no
Bednarek	2001	yes	yes	no	no	no	no	no	no	no	no	yes
Bernhardt	2005	no	yes	no	no	no	no	no	no	no	no	no

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Bond	2003	Local habitat restoration in streams: constraints on the effectiveness of restoration for stream biota	Ecological Management and Restoration	4	3	yes	-	-	-	-	-	-	-	-	-
Boulton	2007	Hyporheis rehabilitation in rivers: restoring vertical connectivity	Freshwater Biology	52	4	yes	-	-	-	-	-	-	-	-	-
Brooks	2002	Assessing stream ecosystem rehabilitation: limitations of community structure data	Restoration Ecology	10	1	no	1998	1998	19	-	-	1	North America	Milltown Creek	USA
Bukaveckas	2007	Effects of channel restoration on water velocity, transient storage, and nutrient uptake in a channelized stream	Environmental Science and Technology	41	5	no	2002	2005	730	-	-	-	North America	Wilson Creek	USA
Bunn	2002	Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity	Environmental Management	30	4	yes	-	-	-	-	-	-	global	-	-

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Bond	2003	no	no	no	no	no	no	no	no	no	no	no
Boulton	2007	no	no	no	no	no	no	no	no	no	no	no
Brooks	2002	no	yes	no	no	no	no	no	yes	no	no	no
Bukaveckas	2007	yes	yes	no	no	yes	no	no	no	no	no	yes
Bunn	2002	yes	no	no	no	no	no	yes	yes	yes	no	no

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Chen	2008	Effects of large woody debris on surface structure and aquatic habitat in forested streams, southern interior British Columbia, Canada	River Research and Applications	24	6	no	2003	2004	-	-	1-5	35	North America	-	Canada
Corsair	2009	Multicriteria decision analysis of stream restoration: potential and examples	Group decision and negotiation			no	-	-	-	-	-	-	-	-	-
Dahlström	2004	Influence of woody debris on channel structure in old growth and managed forest streams in central Sweden	Environmental Management	33	3	no	1999	2001	-	-	-	20	Europe	-	Sweden
Engström	2009	Effects of stream restoration on dispersal of plant propagules	Journal of Applied Ecology	46	2	no	2005	2006	365+	-	2-3	9	Europe	-	Sweden
Friberg	1998	Long-term, habitat-specific response of a macroinvertebrate community to river restoration	Aquatic Conservation	8	1	no	1989	1995	1825	-	-	4	Europe	Gelsa	Denmark

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Chen	2008	yes	yes	no	no	no	no	no	no	no	no	yes
Corsair	2009	no	no	no	no	no	no	no	no	no	no	no
Dahlström	2004	yes	yes	no	no	no	no	no	no	no	no	yes
Engström	2009	yes	yes	no	no	no	no	no	no	no	no	yes
Friberg	1998	no	yes	no	no	no	no	no	yes	no	no	yes

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Günther	2005	Restoration ecology meets carabidology: effects of floodplain restitution on ground beetles	Biodiversity and Conservation	14	7	no	1999	2002	365	-	-	6	Europe	Hase	Germany
Harrison	2004	The effect of instream rehabilitation structures on macroinvertebrates in lowland rivers	Journal of Applied Ecology	41	6	no	1999	1999	1095	-	-	26	Europe	-	UK
Hering	2006	Assessment of European streams with diatoms, macrophytes, macroinvertebrates and fish: a comparative metric-based analysis of organism response to stress	Freshwater Biology	51	9	no	2002	2003	-	-	-	185	Europe	-	-
Huxel	1999	Habitat loss, fragmentation, and restoration	Restoration Ecology	7	3	no	-	-	-	-	-	-	-	-	-

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Günther	2005	no	yes	no	no	yes	no	no	no	no	no	no
Harrison	2004	no	yes	no	no	no	no	no	yes	no	no	no
Hering	2006	no	no	no	no	no	no	yes	yes	yes	yes	no
Huxel	1999	no	no	no	no	no	no	no	no	no	no	no

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Jähnig	2009	Effects of re-braiding measures on hydromorphology, floodplain vegetation, ground beetles and benthic invertebrates in mountain rivers	Journal of Applied Ecology	46	2	no	2004	2005	-	180-650	-	7	Europe	-	Germany
Jähnig	2008	Substrate-specific macroinvertebrate diversity patterns following stream restoration	Aquatic Sciences	70	3	no	2004	2005	-	180-650	-	7	Europe	-	Germany
Jansson	2007	Restoring freshwater ecosystems in riverine landscapes: the roles of connectivity and recovery processes	Freshwater Biology	52	4	yes	-	-	-	-	-	-	global	-	-
Kail	2007	The use of large wood in stream restoration: experiences from 50 projects in Germany and Austria	Journal of Applied Ecology	44	6	no	-	-	-	-	-	-	Europe	-	-

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Jähnig	2009	no	no	no	no	no	no	no	yes	no	no	no
Jähnig	2008	no	no	no	no	no	no	no	yes	no	no	no
Jansson	2007	no	no	no	no	no	no	no	no	no	no	no
Kail	2007	no	yes	no	no	no	no	no	no	no	no	no

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Korsu	2004	Response of benthic invertebrates to disturbance from stream restoration: The importance of bryophytes	Hydrobiologia	523	1	no	2001	2001	70	-	-	25	Europe	Kokemäenjoki river	Finland
Lake	2001	Linking ecological theory with stream restoration	Freshwater Biology	52	4	yes	-	-	-	-	-	-	-	-	-
Larson	2001	Effectiveness of large woody debris in stream rehabilitation projects in urban basins	Ecological Engineering	18	2	no	-	-	730+	-	-	6	North America	-	USA
Lemly	2000	Influence of large woody debris on stream insect communities and benthic detritus	Hydrobiologia	421	1	no	-	-	365	-	3	1	North America	North Fork Stony Creek	USA
Lepori	2005	Effects of stream restoration on ecosystem functioning: detritus retentiveness and decomposition	Journal of Applied Ecology	42		no	-	-	1095+	-	2-4	7	Europe	Ume River system	Sweden

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Korsu	2004	yes	yes	no	no	no	no	no	yes	no	no	no
Lake	2001	no	no	no	no	no	no	no	no	no	no	no
Larson	2001	yes	yes	no	no	no	no	no	yes	no	no	yes
Lemly	2000	yes	yes	no	no	no	no	no	yes	no	no	yes
Lepori	2005	yes	yes	no	no	no	no	no	yes	no	no	yes

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Lind	2006	The influence of reduced flow during a drought on patterns of variation in macroinvertebrate assemblages across a spatial hierarchy in two lowland rivers	Freshwater Biology	51		no	1997	2000	-	12660-24010	-	2	Australia	-	Australia
Mainstone	2002	Phosphorus in rivers - Ecology and management	Science of the Total Environment	282-283		yes	-	-	-	-	-	-	Europe	-	UK
Maloney	2008	Changes in macroinvertebrate and fish assemblages in a medium-sized river following a breach of a low-head dam	Freshwater Biology	53	5	no	2002	2005	1095+	6888	-	1	North America	Fox River	USA
Moerke	2004	Restoring stream ecosystems: Lessons from a midwestern state	Restoration Ecology	12	3	no	-	-	-	-	-	-	North America	-	USA

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Lind	2006	no	no	no	no	no	no	no	yes	no	no	no
Mainstone	2002	no	no	no	no	no	no	no	no	yes	no	no
Maloney	2008	yes	yes	no	no	no	no	yes	yes	no	no	yes
Moerke	2004	yes	yes	no	no	no	no	yes	yes	no	no	yes

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Muotka	2007	Changes in habitat structure, benthic invertebrate diversity, trout populations and ecosystem processes in restored forest streams: A boreal perspective	Freshwater Biology	52	4	no	multiple	multiple	multiple	-	multiple	multiple	Europe	-	Finland
Nakano	2006	Responses of macroinvertebrate communities to river restoration in a channelized segment of the Shibetsu River, northern Japan	River Research and Applications	22		no	2003	2003	>365	671		1 restored, 2 controls	Asia	Shibetsu River	Japan
Nielsson	2005	Forecasting environmental responses to restoration of rivers used as log floatways: an interdisciplinary challenge	Ecosystems	8		no							Europe	e.g., Ume River	Sweden

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Muotka	2007	yes	yes	no	no	no	no	yes	yes	no	no	yes
Nakano	2006	no	yes	no	no	no	no	no	yes	no	no	yes
Nielsson	2005	yes	yes	no	yes	yes	no	yes	yes	yes	no	yes

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Pedersen	2006	Effects of stream restoration and management on plant communities in lowland streams	Freshwater Biology	51		no	2002	2002	<60		6 m wide channels	10 restored, 20 controls	Europe	misc rivers in jutland	Denmark
Shields	2003	Response of fishes and aquatic habitats to sand-bed stream restoration using large woody debris	Hydrobiologia	494		no	1999	2001	365	-	4	5	North America	Little Topashaw Creek	USA

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Pedersen	2006	no	yes	no	no	no	yes	no	no	yes	no	yes
Shields	2003	no	yes	no	no	no	no	yes	no	no	no	yes