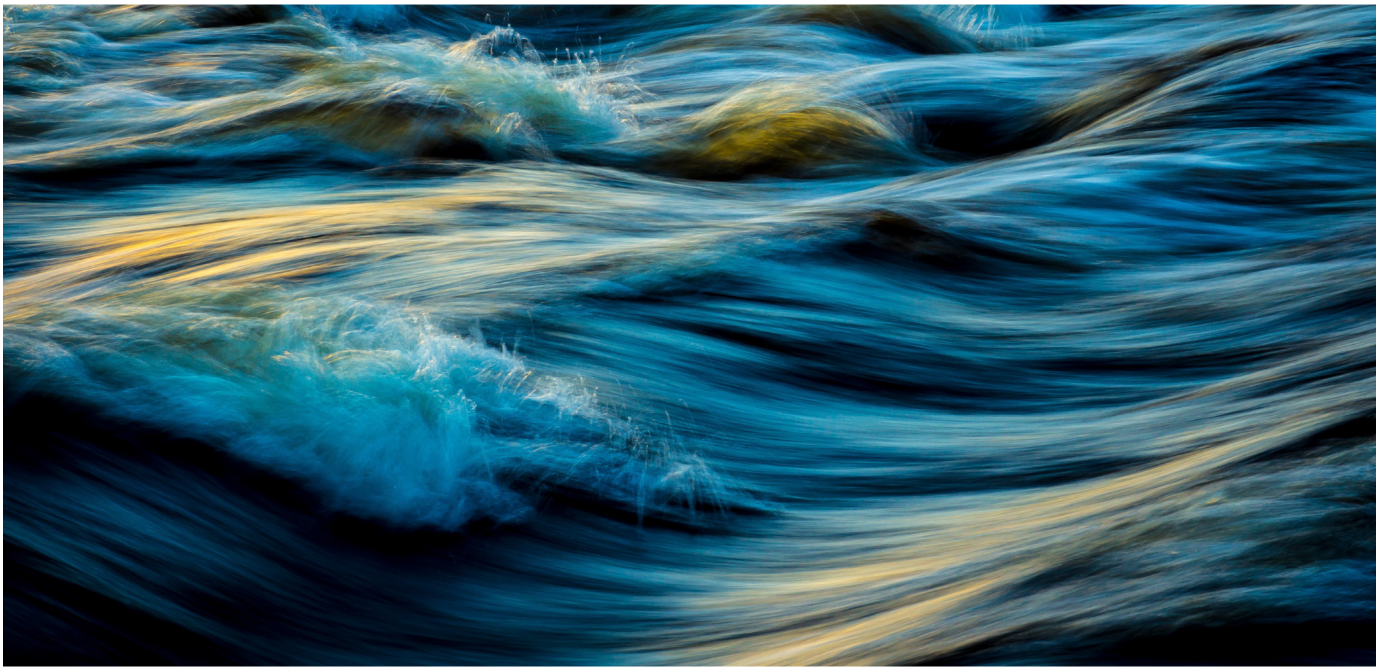

MARS RECOMMENDATIONS

on how to best assess and mitigate impacts of multiple stressors in aquatic ecosystems

MARS project funded by the European Union within the 7th Framework Programme, Grant Agreement 603378, Duration: February 1st, 2014 – January 31th, 2018
www.mars-project.eu

MARS PROJECT
Managing Aquatic ecosystems and water Resources under multiple Stress

MARS Recommendations

on how to best assess and mitigate impacts of multiple stressors in aquatic ecosystems

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Legal notes

This document is based on the MARS project deliverable D8.2, resulting from Task 8.2. "Advising river basin managers and sectors for the 3rd RBMPs" of the EU research project "Managing Aquatic ecosystems and water Resources under multiple Stress (MARS)" funded by the European Union under the 7th Framework Programme, Theme ENV.2013.6.2-1 (Water resources management under complex, multi-stressor conditions), grant agreement no: 603378, *http://mars-project.eu*.

Acknowledgements

We would like to thank all MARS partners for their contribution to this document. Further, we are grateful for the invaluable comments and suggestions of our applied partners and collaborators of the Austrian Federal Ministry of Sustainability and Tourism (Veronika Koller-Kreimel, Helena Mühlmann); Environment Agency UK (Jo-Anne Pitt, Sian Davies); Environmental Administration Finland and Finnish Environment Institute (Marko Järvinen); International Commission for the Protection of the Danube River (Edith Hödl, Adam Kovacs); National Administration Romanian Waters (Corina Boscornea, Elena Tuchiu, Graziella Jula) and Umweltbundesamt Germany (Ursula Schmedtje). We also would like to thank all partners, River Basin Managers and other stakeholders who attended the ***Stakeholder Workshop*** in Vienna 2016, which was an important foundation for this document.

Vienna, Essen and Oslo, November 2018

Content

Preface

The EU FP 7 project MARS – "Managing Aquatic ecosystems and water Resources under multiple Stress" (duration 01.02.2014 – 31.01.2018) investigated how multiple human stressors affect rivers, lakes, groundwater, transitional and coastal waters. Outcomes of this research project are more than *200 scientific publications*, more than *4000 pages of deliverables*, various *tools* and background information about multiple stressors; all available in the *Freshwater Information System*.

This document provides recommendations and highlights relevant outcomes of the MARS project aiming to inform River Basin Managers and stakeholders in other sectors (energy, water industry, agriculture) on how to best assess and mitigate impacts of multiple stressors acting on Europe's aquatic ecosystems. The document aims at supporting those who implement the EU Water Framework Directive (WFD) and who have to make recommendations or take decisions based on existing monitoring data. MARS mainly addressed pressures regarding hydromorphology, nutrients and climate change, while the focus of this document is on the most common and typical stressor combinations of European waters. The FP 7 "sister projects" *SOLUTIONS* and *GLOBAQUA* specifically addressed multi-stressor issues related to toxic contamination and water scarcity.

For convenience and better readability, this document uses hyperlinks to relevant MARS *results*, *models* and *tools* to enable readers to directly access the respective websites. In regards to terminology and definitions, the *Freshwater Information Platform* contains a collection of terms from previous EU projects in the *Freshwater Glossary*, which should be used for further information.

Executive Summary

According to a recent EEA report (EEA 2018), about ***40% of Europe's water bodies are impacted by two or more pressures***. Ignoring this fact may lead to wrong decisions within River Basin Management (RBM), and further to ineffective measures and stranded investments.

MARS has analysed data from various spatial scales, i.e. local water body, single river basin and European scale, in order to better understand and disentangle complex ***interactions between pressures, resulting stressors*** and their effects on aquatic biota. Several stressors from one or more pressure categories often occur in combination (multiple stressors) and can have a variety of outcomes: ***Additive*** effects equal the sum of single stressor effects, while ***synergistic*** effects are larger than the sum of single stressor effects and ***antagonistic*** effects are smaller than the sum of single stressor effects. When ***various stressors*** are active in a water body, their combined effects pose various challenges to River Basin Managers. Multi-stressor situations thus require knowledge on the relative importance of different stressors (stressor hierarchy, including dominating stressors) and their impacts in order to find the best combination of mitigation or restoration measures.

MARS has generated a ***general framework supported by MARS tools*** for tackling multi-stressor conditions in River Basin Management and to select appropriate management strategies concerning the level and type of necessary mitigation measures. Guided by key questions, the proposed framework supports decision making by identifying dominating and interacting stressors to prioritise measures. Depending on the multi-stressor situation, most effective restoration is expected by prioritising dominating stressors in case of prevailing stressors, non-antagonistic stressors in case of antagonistic interactions and stressor combinations in case of synergistic interactions. Some general patterns on interactions between pairs of stressors have been found in MARS, e.g. waterbody type-specific synergistic and antagonistic interactions for combinations of nutrient and temperature stressors in lakes. However, the assessment of the relative importance of stressors and their impacts, as well as the concrete planning of measures requires case-specific approaches.

The ***MARS Tools*** support the analytical process at various levels: The tremendous amount of EU water-related information has been integrated and synthesized within the ***MARS Geodatabase*** and the ***Freshwater Information System,*** now helping to identify important stressors, their spatial distribution and combinations as well as their effects on the ecological status of lakes and rivers. In data limited environments ***Conceptual Models*** provide an overview of the cause-effect relations between pressures, stressors, status and measures. A ***Cookbook*** has been compiled for multiple stressor analysis, consisting of an analytical framework to deal with environmental and stressor data, accompanied by a procedure for statistical analysis and interpretation.

The ***Model Selection Tool*** provides an overview on the applicability of widely used models for River Basin Management. ***Heat Maps*** are visualisation tools to identify how two stressors interact along each of the two gradients for a certain biological quality element, leading to potential combinations of mitigation efforts needed to reach good ecological status. The ***Diagnostic Tool*** calculates the probability for causes of deterioration based on selected biological metrics. Finally, the ***Scenario Analysis Tool*** allows visualising and analysing current and future multi-stressor conditions and impacts on ecological status in European rivers and lakes. MARS tools may be supplemented by ***experimental settings*** that can serve as an effective method to tackle case specific multi-stressor situations. Within MARS a number of meso-scale lake- and river experiments provided detailed answers for case specific multi-stressor situations covering hydromorphological and water quality stressor combinations.

MARS ***has demonstrated*** how the large amount of data generated in context of the WFD throughout Europe can be used to improve RMB and ***how science can contribute to achieve WFD objectives***. The outcomes of MARS support River Basin Managers and others faced with WFD implementation in their efforts to plan and implement effective restoration measures, by enhancing the understanding of multiple stressors, their hierarchy and interactions, as well as on the impacts they cause on the aquatic ecosystem.

1. Introduction

Many European water bodies are subject to multiple human pressures as pollution, morphological alteration, or hydrological changes, which counteract with achieving the good ecological status demanded by the WFD (EEA 2018). The WFD requires EU member states to collect and update information on the type and magnitude of significant pressures and related impacts affecting their water bodies. Based on WFD data reported by 25 member states to EEA in 2016-2017, 60% of EU's water bodies are still not in a good ecological status (EEA 2018). Overall, about 40% of Europe's water bodies are impacted by two or more pressures (Figure 1; Lakes: 18%, Rivers: 43%, Transitional waters: 53%, Coastal waters: 36%).

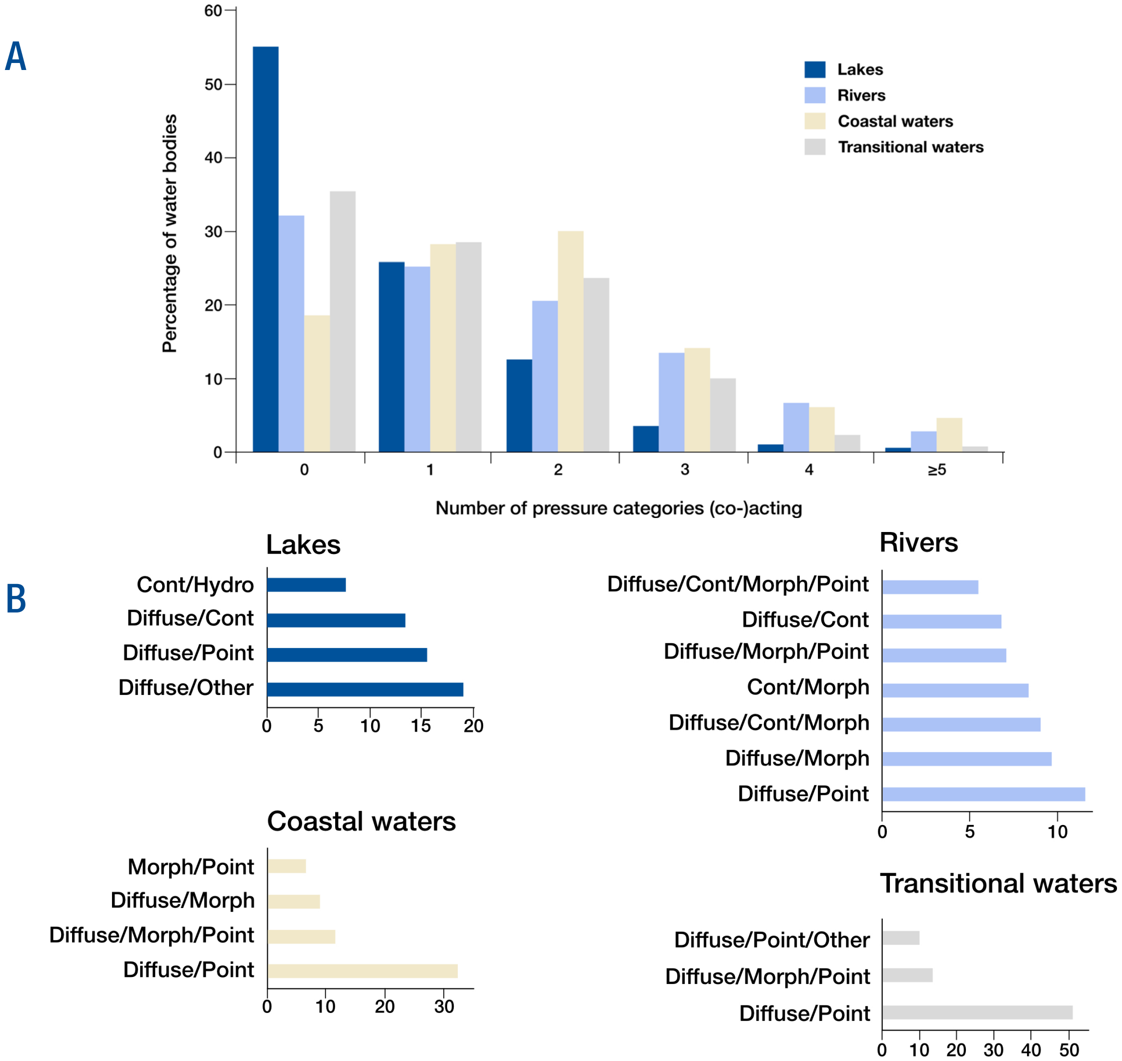


Figure 1: (A) Percentage of water bodies at lakes, rivers, transitional and coastal waters affected by no, one or several significant pressures[1]. (B) Most frequent multi-pressure combinations across water categories (expressed as percentages of water bodies with ≥ 2 co-acting pressures). Data-source: EEA WISE Database, March 2018.

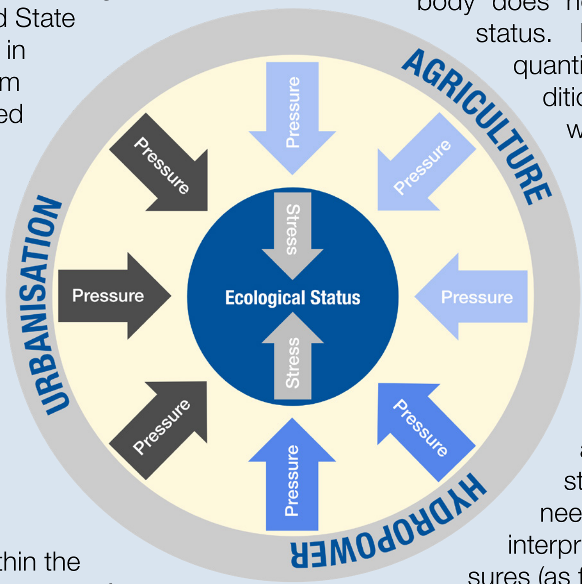
[1] Data reported for 103,130 water bodies by 25 EU member states (excl. IE, GR, LT) within the 2nd WFD RBM cycle 2009-2015. Pressure categories cover point source pollution (Point), diffuse pollution (Diffuse; excluding atmospheric deposition), water abstraction, physical alteration (Morph), hydrological alteration (Hydro), continuity disruption (Cont) and other pressures (Other; including introduced species and diseases = 1.6%; exploitation or removal of animals or plants = 0.6%; groundwater recharges or alteration = 0.2%; litter or fly tipping < 0.1%).

The outcomes of MARS should support River Basin Managers and others faced with WFD implementation in their efforts to plan and implement effective restoration measures, by enhancing the understanding of multiple stressors, their hierarchy and interactions, as well as on the impacts they cause on the aquatic ecosystem.

In the next chapters of this document, a step-wise approach of MARS on how to handle multiple stressors in River Basin Management is described. This is followed by examples of consistent multi-stressor interaction effects on different biological quality elements (BQEs), including implications for mitigation measures.

FACTBOX: What is the difference between stressors and pressures?

The **driver-pressure-state-impact-response (DPSIR)** causal framework defines pressures as the direct effects of a **Driver** (= anthropogenic activity like agriculture, hydropower etc.). **Pressures** affect the ecosystem's **State** (= its physical, chemical and biological characteristics). And State changes may result in effects on ecosystem characteristics valued by man (**Impact**). The term 'stressor' is not used in the DPSIR framework, and this often promotes confusion among managers and scientists. **Stressors are (putative) causes in a cause-and-effect chain**. This places stressors within the Pressure or State category of the DPSIR framework, depending on which causal parameters are investigated.



A stressor represents the immediate cause for moderate or worse ecological status (e.g. oxygen depletion causing suffocation of fish), or it is a preceding factor in a causal chain conditioning moderate or worse status (e.g. river flow variation [causing changes in near-bottom flow] causing benthic invertebrates to indicate poor ecological status).

Introducing the term 'stressor' allows for more specific analysis of the reasons why a water body does not reach good ecological status. Knowing about stressor quantity and combination is additionally important to inform water management under multi-stressor conditions. Moreover, **a single pressure** (e.g. the broad pressure category of diffuse source pollution) **can exert different stressors** (e.g. increased concentrations of nutrients, pesticides and fine sediment accumulation), affecting the state of the ecosystem. We need to keep this in mind when interpreting reported WFD pressures (as for Figure 2).

Further details and definitions of the stressor term can be found in the ***Freshwater Information System***.

Figure 2: Stressors (light grey) are inking pressures to ecological status.

Web link
What is the difference between stressors and pressures
read more

The various analytical approaches (models and tools) and their benefits in disentangling complex interactions between stressors and their effects on aquatic biota are briefly presented with links to further information. Examples from single studies are also given for various spatial scales (water bodies, single river basins, large-scale patterns across Europe). The selected examples are taken from ***MARS publications***, highlighting their practical implementation and include links to references and to the more detailed ***MARS deliverables*** (Chapter 6).

In multi-stressed systems, River Basin Managers can take various pathways to achieve good ecological status. Besides the vast amount of environmental- and stressor data gathered by WFD monitoring and assessment for each European River Basin, MARS has generated useful outcomes and developed various tools to support RBM under multi-stress conditions:

➔ The ***MARS Geodatabase*** and the ***Freshwater Information System***, developed to define and identify important pressures/stressors on European waters, their spatial distribution and combinations as well as their effects on the ecological status of lakes and rivers (Chapter 3.3). This Europe-wide information can be used to put the regional conditions encountered in RBM into context.

➔ The ***Cookbook for multiple stressor analysis***, an analytical framework to deal with environmental and stressor data, accompanied by guidance on the statistical analysis and the interpretation of results (Chapter 4.4).

➔ The ***Model Selection Tool***, to provide an overview on the applicability of widely used models for RBM (Chapter 5.1).

➔ ***Conceptual Models*** based on expert knowledge, helping to provide an overview of the cause-effect relations between pressures, status and measures in a structured way (Chapter 6.2).

➔ Heat Maps, to be used to identify how two stressors interact along each of the two gradients for a certain biological quality element, leading to potential combinations of mitigation efforts needed to reach good ecological status (Chapter 5.2).

➔ The ***MARS Diagnostic Tool***, to calculate the probability for causes of deterioration of good ecological status (e.g. share of urban land use) on catchment- or water body scale based on selected biological metrics (Chapter 5.3).

➔ The ***MARS Scenario Analysis Tool***, an online tool allowing visualising and analysing current and future multi-stressor conditions and impacts on ecological status in European rivers and lakes (Chapter 5.4).

The tools are further described in Chapter 2, their benefits and applications are outlined in Chapter 5.

2. How to handle a multi-stressor situation?

Several stressors from one or more pressure categories often occur in combination (multiple stressors) and can have a variety of outcomes:

Additive: Multi-stressor effects equal the sum of single stressor effects.

Synergistic**:** Multi-stressor effects are larger than the sum of single stressor effects.

Antagonistic**:** Multi-stressor effects are smaller than the sum of single stressor effects.

When various stressors are active in a water body, their combined effects make the selection of best measures difficult and pose a challenge to River Basin Managers. Multi-stressor situations thus require knowledge on the relative importance of different stressors (stressor hierarchy, including dominating stressors)[2] and their impacts in order to find the best combination of mitigation or restoration measures. The biological assessment used in water body classification, related structural and functional biological metrics as well as supporting (abiotic) elements and reported pressures can help to inform River Basin Managers about the existence of dominant stressors or stressor interactions.

The flow chart in Figure 3 provides guidance for handling multi-stressor situations in River Basin Management, focusing on three steps, illustrated in red, blue and yellow boxes:

1. Knowledge about stressor hierarchy and interactions is key to effective management (light blue box).
2. MARS approaches and tools to inform about these characteristics (dark blue box) are available and are addressed in the subsequent chapters of this document.
3. Based on the specific situation identified for a water body, different management strategies are recommended (including various options for prioritising mitigation measures and to consider whether they would be sufficient to achieve the objectives; yellow boxes).

[2] Stressors showing the strongest effect on ecological status (and its biological elements) relative to other stressors acting are called “dominant stressors”.

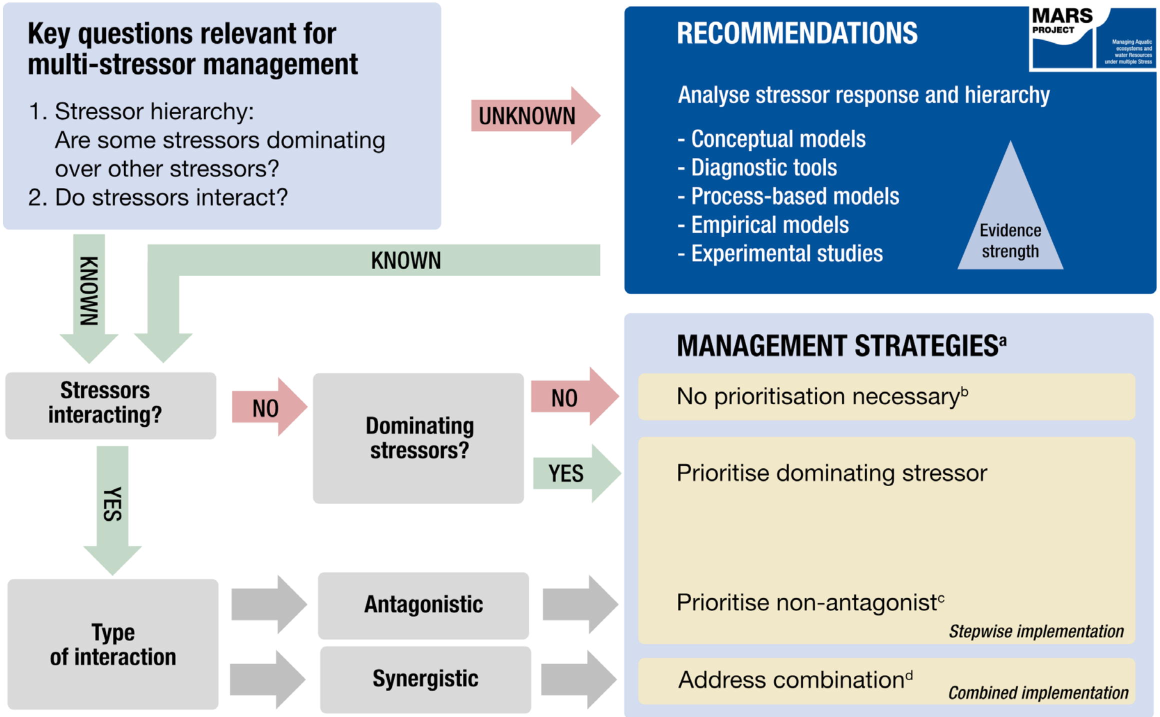


Figure 3: Key questions relevant for tackling multi-stressor conditions in River Basin Management (involving supportive MARS tools addressed in these recommendations), leading to appropriate management strategies concerning the level and type of necessary mitigation and adaptation measures.

[a] Any management strategy needs to consider criteria of cost-effectiveness in selecting mitigation measures. [b] Alternative prioritisation option: Which measures additionally ensure the provision of relevant ecosystem services? [c] Antagonists are stressors that dampen the effects of other co-acting stressors (e.g. high flow pulses dampen effects of nutrient enrichment). Reducing the antagonist without prior mitigation of the other stressors (non-antagonists) would result in aggravated stressor effects. [d] In synergistic settings the combined implementation may require increasing the mitigation efforts (e.g. putting additional measures in place).

If a water body fails to achieve good ecological status, the results of the preceding pressure analysis can already provide first clues on the presence and importance of significant pressures co-acting on the water body. This allows for evaluating the relevance of multiple stressors, which need to be mitigated depending on their dominance/hierarchy and interaction (as shown in Figure 3):

➔ If a ***dominant*** stressor can be identified, this one should be prioritized. For ***additively*** acting stressors, no prioritization is required (yet taking into account the measures' cost-effectiveness), or ranking measures according to their benefits for ecosystem services. Water pollution (e.g. from untreated waste water) often represents a dominant stressor whose mitigation would need to be addressed first before tackling other stressors.

➔ If stressors ***interact***, the type of interaction needs to be taken into account for selecting the appropriate measures and the adequate level of measures (intensity and quantity). Stressor interaction can be determined using the ***analytical approaches of MARS presented in this document***.

- ⇨ If stressors interact in an ***antagonistic*** way, the effect of one stressor (non-antagonist) is reduced by the presence of another stressor (antagonist), because they act in different directions. For example, if regular flow pulses occur in combination with nutrient enrichment, the nutrients are reduced due to flushing these downstream. If the flow pulses (antagonist) would be mitigated first, the nutrient enrichment (non-antagonist) could increase in the water body and cause undesirable effects of the mitigation. Targeting first the "non-antagonist" (in this case nutrients) helps to avoid undesirable effects. The quantity of measures to achieve good status generally cannot be reduced when stressors interact antagonistically, only in case that interaction effects and their influence on all biological and supporting quality elements are evaluated before, in order to avoid undesirable effects. Additionally, adverse effects downstream water bodies need to be considered.

- ⇨ When stressors interact ***synergistically***, as it is, for instance, often observed for nutrients and temperature increase, the level of measures may have to be increased to achieve the WFD objectives. If possible, both stressors should be targeted simultaneously (e.g. by riparian shading to mitigate temperature increase) to achieve more effective mitigation than stepwise implementation of single measures. But if temperature increase cannot be managed effectively, greater reduction in nutrients may be the only option.

➔ In cases of three or more stressors co-acting, stressor hierarchies should be identified and the mitigation of the two most dominant stressors has to be prioritised, considering their possible interactions. With more stressors involved, interaction patterns may become more complex. Such settings require phased mitigation approaches based on an adaptive management strategy.

If a stressor hierarchy is unknown, there are several ways offered by MARS to analyse the effects of stressors on ecological status using different sources of information (described in Chapter 4). Although some general patterns on interactions between pairs of stressors have been found in MARS (Chapter 2.2), the assessment of the relative importance of stressors and their impacts, as well as the concrete planning of measures have to be adapted to the local conditions. Thus, MARS can assist here with input, but River Basin Managers have to decide on the best way of action using monitoring data and available tools.

The MARS methodologies and tools to evaluate stressor hierarchies and interactions are summarized below. The choice of adequate tools mainly depends on the case-specific objectives, process understanding and data availability (described in detail in Chapters 4 & 5):

➔ **Conceptual Models** are based on expert knowledge but help to formulate a problem in a structured way. Conceptual models support the identification of key system elements and interrelations as well as system boundaries. They often make the problem more explicit and enable the formulation of clear hypotheses for more detailed analyses. The level of expertise available limits the level of evidence achievable by conceptual models.

  Objective: to overview multi-stressor conditions in a DPSIR context

  Relevant spatial scale: (large) river basins

  Required data: expert knowledge

  Implementation efforts: low

➔ The **Diagnostic Tool** developed in MARS employs Bayesian models enabling a linkage between expert knowledge and data driven analyses. By that, it represents a link between conceptual and empirical models and is very useful in data-limited situations to provide evidence of stressor hierarchies on a semi-quantitative basis.

  Objective: to identify cause of failing good ecological status in water bodies

  Relevant spatial scale: (groups of) water bodies

  Required data: WFD monitoring data, research data, expert knowledge

  Implementation efforts: high

➔ MARS also provides a number of **methodologies and tools for empirical- and process-based approaches** applicable at multiple spatial and temporal scales. These approaches require comprehensive process understanding and adequate field data. They are able to quantify stressor effects by identifying dominating stressors and interactions and, hence, provide strong evidence on stressor hierarchies.

  Empirical models

  Objective: to evidence multi-stressor - impact relationships in specific water bodies

  Relevant spatial scale: (groups of) water bodies (up to water body types)

  Required data: WFD monitoring data

  Implementation efforts: intermediate

  Process-based models

  Objective: to extrapolate and predict multi-stressor conditions and their effects

  Relevant spatial scale: (groups of) water bodies to (large) river basins

  Required data: model-specific input data and WFD monitoring data (for model validation)

  Implementation efforts: high

➔ The **Scenario Analysis Tool** developed in MARS is an online tool allowing visualising and analysing multi-stressor conditions in European rivers. It considers six stressor indicators and their effects on the ecological status of different European river types, including a prognosis of future developments based on two different scenarios.

➔ In cooperation with scientists, **experiments** can be used as a tool for specific cases where process understanding is still low and/or empirical field data are not available. Experiments give deep insights into selected stressor interactions, however, the evidence gained is limited by the transferability of the results to the real world.

Objective: to unravel the processes of biological effects caused by multiple stressors

Relevant spatial scale: results transferable to water body type

Required data: none (generates own data)

Implementation efforts: high (requires specific facilities)

➔ Depending on the level of expertise available for River Basin Management planning, and the data availability and questions to be answered, there are trade-offs among MARS tools and methodologies.

Case-specific selection and combination of approaches guarantees the most effective analytical procedure with the highest possible level of evidence and relevance.

2.1 MARS step-wise approach to assess and mitigate impacts of multiple stressors

MARS proposes a step-wise approach to assess and mitigate impacts of multiple stressors in River Basin Management. This enables case-specific and data-driven management solutions to tackle multi-stressor situations in Europe's water bodies. It is achieved by combining case-specific data with existing knowledge, analytical approaches and tools from MARS:

0. Starting point for River Basin Managers

The water body fails to achieve good ecological status, and multiple stressors are the putative causes.

1. Identify the hierarchy of stressors (i.e. the magnitude and relative importance of stressors):

Urging question: What are the most relevant stressors in your river basin/water body? Can a hierarchy of stressors be identified?

➔ Find information on the integration of stressors into the DPSIR concept in the ***Freshwater Information System***.

➔ Use simple boxplots paired with statistical tests or more sophisticated modelling approaches (see ***MARS Cookbook***) to assess significant responses of BQEs to multiple stressors.

➔ Combine analyses with the ***MARS Diagnostic tool***.

2. Understand the interactions of multiple stressors:

Urging question: Do stressors in your river basin/water body interact and if yes, in which way?

➔ Use the ***MARS Diagnostic Tool*** and ***synthesis results*** (MARS Deliverable 6.2) to identify the impacts of stressor combinations on different BQEs or ecosystem functions.

➔ Have a look at the consistent interactions found by MARS, described in Chapter 2.2.

Relevant links in this document

Chapter 6.1: Mapping and analysing the configuration of multiple stressors

Chapter 6.4: Identification of stressor hierarchies

➔ Interactions can be assessed and estimated based on analytical approaches (Figure 3/ Chapter 6), e.g. conceptual models, diagnostic tools, process-based models, empirical models, experimental studies.

➔ Modelling advice can be found in the *MARS Cookbook*.

3. Prioritize mitigation/restoration options:

Urging question: What are the consequences for prioritization and implementation of measures?

➔ Dominating stressors should be prioritized.

➔ For additive stressors (not influencing each other), no prioritization is required, or the measures could be ranked according to their benefits for ecosystem services.

➔ If stressors interact, the type of interaction needs to be taken into account for selecting the right measures and the right quantity of measures to achieve good ecological status/potential, as described on Page 9.

Relevant links in this document:

Chapter 2.2: Consistent interactions

Chapter 4: Analytical procedure

Chapter 6: Examples and evidence from MARS studies

2.2 Consistent stressor-interaction effects found in the MARS project

A question to be considered by managers when planning the programme of measures is whether synergistic interactions call for additional measures to achieve good ecological status or potential. Another question is whether antagonistic interactions mean that less measures are needed to achieve good ecological status or potential, or that the same level of measures still should be implemented for one or both stressors.

As ecological status is assessed in River Basin Management Plans by using intercalibrated biological quality elements (BQEs), we have selected the MARS results which have used relevant BQE metrics as response indicators for different types of rivers and lakes, and where paired stressor combinations show consistent interactions. These are presented in Table 1 and afterwards in a text, along with underlying ecological explanations, as well as possible implications for mitigation measures, compared to situations without such interactions.

FACTBOX: Consistent interactions of stressors found by MARS studies

Out of 150 single results of pair-wise stressor combinations analysed within studies of MARS (i.e. experiments, catchment analyses and pan-European analyses), two-thirds were additive (had no significant interactions), while one-third showed significant interactions. For most of those studies, the response variables applied are not directly comparable to the intercalibrated WFD metrics for different BQEs. Some of the studies are not published yet but are in preparation. Further information also can be found in the ***MARS synthesis*** and the ***respective deliverables***.

MARS Final Report

Table 1 Consistent interactions of stressor pairs and related effects on different BQEs in various types of water bodies.*

No.	Stressor 1	Stressor 2	BQE	Water Cat.	Type of water body	Type of interaction
1	Nutrients	Temperature	Phytoplankton	Lakes Rivers	Nutrient limited lakes & rivers	Synergistic
2	Nutrients	Temperature	Phytoplankton	Lakes	Nutrient-saturated lakes	Antagonistic
3	Nutrients	Browning	Phyto-plankton Cyanobacteria	Lakes	Nutrient limited Northern, stratified lakes	Antagonistic
4	Nutrients	High flow	Phytoplankton	Lakes Rivers	Large stratified lakes with long retention time (incl. large rivers, impounded)	Synergistic, but see addendum in text
5	Nutrients	High flow/ Hydropeaking	Phytobenthos	Rivers	Nutrient limited upland rivers	Antagonistic (up to dominating 2nd stressor)
6	Nutrients	Channel-isation	Benthic invertebrates and Fish	Rivers	Any type of river	Antagonistic, but small interaction effect

*No other consistent interactions were found for other stressor pairs, other WFD relevant BQE metrics and other types of water bodies within MARS.

Interaction no. 1: Nutrients and temperature effects on phytoplankton in nutrient-limited lakes and rivers

Nutrient enrichment combined with temperature increase has a synergistic interaction effect on phytoplankton biomass and species composition in nutrient-limited lakes and rivers due to accelerated primary production of opportunistic phytoplankton species. This effect calls for increased nutrient reduction (or making the nutrient concentration targets more stringent) to achieve and maintain good ecological status for phytoplankton. The interaction effect varies from 25% (Danish mesocosms, analysed by T. Bucak) to 100% (Finnish rivers, analysed by K. Rankinen in Stefanidis et al., 2018) and is supported by other MARS studies of impacts on phytoplankton taxonomic composition, using large-scale spatial datasets, e.g. J. Moe., ***poster at final MARS conference*** as well as by published papers on impacts of warming on cyanobacterial blooms (***Jöhnk et al., 2008***).

Interaction no. 2: Nutrients and temperature effects on phytoplankton in highly eutrophic lakes

Nutrient enrichment combined with temperature increase has an antagonistic interaction effect on phytoplankton biomass in highly eutrophic (nutrient-saturated) lakes. This antagonistic interaction is due to light-limitation caused by self-shading, leading to lower net primary production (higher respiration than primary production). To achieve good ecological status for phytoplankton, nutrient reduction measures should be kept at the needed level regardless of the interaction, as reduced nutrient input will cause a switch from light-limitation to nutrient limitation and thus reduce the antagonistic effect. This interaction effect was found in three different single studies in MARS, all showing an interaction effect of > 60%: UK mesocosm experiment (analysed by H. Feuchtmeyer and J. Richardson), Võrtsjärv case study in Estonia (analysed by T. Nõges and P. Nõges), European large-scale dataset focusing on eutrophic lakes (analysed by S. Thackeray).

Interaction no. 3: Nutrients and browning effects on phytoplankton (Cyanobacteria) in stratified lakes

Nutrient enrichment combined with browning (increase of humic substances) has an antagonistic interaction effect on cyanobacteria in stratified, Northern lakes, probably due to changes in the light quality (lack of blue light) and/or adsorption of phosphorus to humic substances. The level of nutrient reduction measures can be decreased if browning continues, as the risk of cyanobacterial blooms is less in humic lakes. However, potential risk for blooms of other harmful algae (e.g. *Gonyostomum semen*), as well as the need to counteract increased oxygen depletion in the hypolimnion of humic lakes and to protect downstream water bodies should also be taken into account. This interaction effect ranges from 4%-42% based on three different spatial scales: MARS experiment in large, deep mesocosms in lake Stechlin in Germany, the ***Vansjø case study in Norway*** and a large-scale spatial dataset from 500 Northern lakes (analysed by A. Lyche Solheim and H. Gundersen).

Interaction no. 4: Nutrients and high flow effects on phytoplankton in large lakes and rivers

Nutrient enrichment combined with high flow (increasing discharge of water from the catchment to the lake) has a synergistic interaction effect on phytoplankton in large, stratified lakes with long retention time, and in large impounded rivers, due to more nutrients being flushed in. Compared to a situation without such interactions, this effect calls for increased nutrient reduction and/or combined with measures to reduce high flow episodes, such as restoring wetlands and floodplains. This interaction effect ranges from 14% to 69% found in three MARS studies: The ***Vansjø case study in Norway***, the ***Thames case study in the UK*** and in a large scale European dataset (analysed by S. Thackeray). Addendum: in small, shallow lakes with short retention time, and smaller, fast-flowing rivers, the interaction will be antagonistic due to insufficient time for nutrient uptake, causing a flushing of the phytoplankton and nutrients downstream.

Interaction no. 5: Nutrients and high flow/hydropeaking effects on phytobenthos in rivers

Nutrient enrichment combined with frequent high flow pulses (hydropeaking) has an antagonistic effect on phytobenthos in nutrient limited upland rivers, due to the high flow ripping off especially filamentous algae from the substrate. Hydropeaking proved to be very dominating, overriding all other stressor effects. Nutrient-reduction measures to achieve good ecological status or potential can be decreased if hydropeaking is not reduced, taking into account potentially negative impacts of the nutrients on downstream water bodies. If hydropeaking is reduced, the other effects become more important, so that nutrient reduction measures will be needed.

This interaction effect ranges from 18% to 62% and is based on two different MARS studies: MARS river flume experiments in Norway (*Bækkelie et al., 2017*; *Schneider et al., 2018*) and Austria (*Bondar-Kunze et al., 2016*).

Interaction no. 6: Nutrients and morphological alteration (channelisation, riparian vegetation alteration) effects on benthic invertebrates and fish in rivers

Nutrient enrichment combined with channelisation and riparian vegetation alteration has a small antagonistic effect on benthic invertebrates and fish in rivers, due to faster current velocity and better oxygen exchange. The level of nutrient reduction measures to achieve good ecological status or potential can be decreased, but taking the potentially negative impacts of nutrients on downstream water bodies into account. If morphological restoration measures are applied, e.g. increasing habitat availability, nutrient reduction measures still are needed, as the antagonistic effect is reduced. The interaction effect is small (4-23%) and was found in five single studies in MARS, based on the intercalibration exercises for benthic invertebrates and fish in very large rivers (Birk et al., 2017; *Birk et al., 2019*).

3. Data available/required for multi-stressor analyses

3.1 Ecological status data and supporting quality elements

The EU Member States have assessed the ecological status of their water bodies according to the WFD (EEA 2018). The assessment of ecological status is based on the WFD definitions, taking into account biological quality elements as well as physico-chemical and hydromorphological quality elements. The use of biological quality elements has increased since the 1st RBMPs, due to the availability of a much larger number of intercalibrated biological assessment methods (*EEA 2018*). This has also increased the confidence in the assessments. The percentage of water bodies classified with one or more biological quality elements has reached 65% for rivers, 50% for lakes and 80% for transitional and coastal waters (EEA 2018, Figure 2).

The biological status is based on the assessment of the worst result of the BQEs: phytoplankton, aquatic flora, benthic invertebrates and fish. The abiotic conditions are described by the hydromorphological and the physico-chemical quality elements. Hydromorphological quality elements are river continuity, hydrological and morphological alterations and tidal regime. The physico-chemical quality elements include temperature, transparency, salinity, nutrients, acidification, oxygen conditions and basin-specific pollutants, e.g. coblackmagicpper, zinc and various organic pollutants. Data were reported by EU Member States to ***WISE - Water Information System for Europe***, ***Central Data Repository (CDR)*** based on 1st and 2nd River Basin Management

Plans (RBMPs). The WFD reference spatial data sets include information about European River Basin Districts, their sub-units, surface water bodies, groundwater bodies and monitoring sites of the RBMPs. The data sets are part of WISE and compile information reported by the EU Member States and Norway to the European Commission (EC) and to the European Environment Agency (EEA) since 2010. These data sets can be used to disentangle the complex interlinks between multiple pressures and the ecological situation in a river basin or water body of concern.

3.2 Pressure data

Understanding relations between multiple stressors and ecological status is a prerequisite to plan effective management measures (***Hering et al., 2015***; ***Teichert et al., 2016***). The above mentioned "supporting quality elements" (hydromorphological and physico-chemical) can be used to describe the present stressors at water body or catchment scale and can provide information on the pressures. Furthermore, the WFD requires significant pressures to be identified. Significant in this context means that the pressure contributes to an impact that may result in failing to achieve the good ecological status. The combination of biological and abiotic data then serves to identify the relation between ecological status and abiotic state, e.g. by a pressure-impact analysis.

FACTBOX: Significant pressures

The WFD requires that Member States collect and maintain information on the type and magnitude of significant pressures and impacts affecting water bodies. The common understanding of a "significant pressure" is that it is any pressure that on its own, or in combination with other pressures, may lead to a failure to achieve one of the WFD objectives of good status.

"Significance" of pressures should be based on empirical pressure-impact analysis. ***Mühlmann (2013)*** have developed thresholds for hydromorphological alterations in Austria based on scientific evidence that define the significance of a pressure (see Table 1 in ***Schinegger et al., 2018***). Thresholds for nutrient pollution should also be based on relationships with sensitive biological quality elements (***Poikane et al., 2018***). For estuaries and coasts also see also ***Borja et al. (2006)***.

Table 2: Important and useful data sources for multi-stressor analysis recommended by MARS. These contain metadata, spatial data and the pdf-files of the RBMPs. However, there are limitations in terms of accessibility to some of the data (they might need to be requested at related institutions for individual studies).

Data sources	Description	Weblink
WISE WFD visualisation tool (2nd RBMPs)	The WISE visualisation tool displays tables, graphs and maps based on the data reported by EU Member States for the 2nd River Basin Management Plans.	Surface water bodies: a) *Ecological status or potential and chemical status, by country* b) *Failing to achieve good status, by RBD* c) *QE status, by category* d) *Number of quality elements used, by country*
WISE WFD database (1st RBMPs)	WISE-WFD database contains data from the 1st River Basin Management Plans: E.g. ecological and chemical status of surface water bodies, significant pressures affecting surface water bodies, impacts on surface water bodies etc.	*https://bit.ly/2z3BdDz*
EEA - Downloadable data and maps about Europe's environment	Data about Europe's environment: Air pollution, Biodiversity – Ecosystems, Climate change, Energy, Environment and health, Industry, Land use, Marine, Policy instruments, Resource efficiency and waste, Soil, Specific regions, Sustainability transitions, Transport, Water	*https://bit.ly/2DcK1tS*
Status of implementation of the WFD in the EU Member States	Detailed information about the River Basin Management Plans available in each River Basin District	*https://bit.ly/2RFr078*
Map on Multiple Pressures on European Rivers in the Global Freshwater Biodiversity Atlas	Represents the number of pressure indicators (hydrological, morphological and nutrient) exceeding the threshold value for good ecological status in each Functional Elementary Catchment (FEC) as derived by the EU MARS project	*https://bit.ly/2Qv4sG8*
Map on Multiple Human Pressures and Their Spatial Patterns in European Running Waters in the Global Freshwater Biodiversity Atlas	High-resolution data analysis of human pressures at the European scale, where important pressure criteria for 9,330 sampling sites in 14 European countries were analysed (stemming from the EU EFI+ project)	*https://bit.ly/2zEgntP*
RESTORE database	Database on river restoration projects	*https://restorerivers.eu*
REFORM rivers catalogue	Catalogue of hydromorphological restoration measures for rivers, streams and floodplains resulting from the EU REFORM project.	*https://bit.ly/2Qvq6d8*
Natural water retention measures (NRWM) platform	Gathering of information on NWRM (green infrastructures applied to the water sector, permitting to achieve and maintain healthy water ecosystems) at EU level	*http://nwrm.eu*

3.3 Data from the MARS Geodatabase

Many European institutions collect data on the state of the water environment and environmental pressures. MARS integrated all readily available datasets and created an integrative ***MARS Geodatabase*** (MARSgeoDB).

The MARSgeoDB is developed in accordance with the WISE concept and builds on the EEA ECRINS database (***European Catchments and Rivers Network System***), consisting of river segments, lakes and about 100,000 sub-catchments (FECs) covering Europe, EFTA states and further, hydrologically connected areas to the east. The MARSgeoDB includes various spatial layers of information, which can be of use for River Basin Management:

- Meteorological and hydrological data (***WorldClim - Global Climate Data***; ***Waterbase - Water Quantity***)
- Land use and land cover data for catchments (Copernicus CORINE) and floodplains (***Copernicus Riparian Zone***)
- Population density data (***SEDAC, Gridded Population of the World***; ***EEA, Population density***)
- Agricultural data from ***EUROSTAT***
- Data from ***WATERBASE – Rivers*** and ***WATERBASE - UWWTD***: Urban Waste Water Treatment Directive – reported data
- The European Pollutant Release and Transfer Register (***E-PRTR***)
- Information of WFD water body codes, national water body types and European broad water types (***Lyche Solheim et al., 2015***)

The MARSgeoDB also enables exploratory analyses, e.g. to identify the most influential (important) pressures for each water body and related thresholds probably causing deterioration of the ecological status. For that purpose, a list of proxy variables was developed (along with the establishment of the MARS Scenario Analysis Tool - SAT): Morphological alteration (from floodplain land use and land cover data), indicators of hydrological pressures for hydrological alteration parameters (a ratio between current and semi-natural hydrological conditions modelled with PCR-GLOBWB (***Van Beek et al., 2011***) and diffuse pollution of nutrients modelled in ***MONERIS*** (***Venohr et al., 2011***; Gericke & Venohr, 2015). With machine learning techniques the MARS SAT then classifies pressures in relation to ecological status of rivers as reported in the 1st RBMPs. The result is the first set of multi-pressure maps of European rivers (Figure 4).

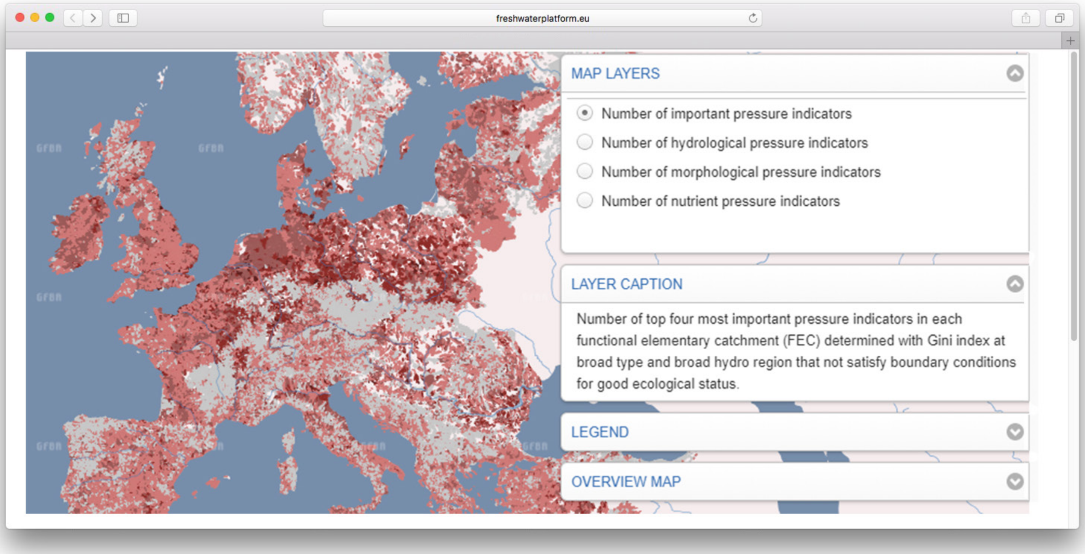


Figure 4: Screenshot of the multi-pressure map derived from the MARSgeoDB. Shades of red show the intensity (number) of pressures acting in FECs, the darker the colors, the more pressures prevail.

Web link
MARS SAT tool
MARSgeoDB

Two most important pressure indicators from each group are finally displayed in Figure 4, which have high explanatory power and can be modelled at future climatic and development scenarios: total phosphorus and dissolved nitrogen concentration in river waters, baseflow index and mean annual flow rates of change (compared to natural conditions) and urban and agricultural land use share in each FEC.

For each pressure, a threshold value between good and less than good was defined based on the ecological status reported in the 2nd RBMP. These thresholds are integrated into the ***Scenario Analysis Tool (SAT)*** suggesting what might be the most probable reasons for less than good ecological status (Chapter 7.2).

4. Models for better understanding of pressure-impact relationships

This section highlights the use of models to better understand and represent pressure-impact relationships and stressor interactions for improved system understanding in River Basin Management. From the large variety of MARS case studies, experiments and European data analyses, we learned that there are many ways to quantify the effects of stressors on ecological status. In our case studies, we have used **conceptual models** to generate a holistic overview on a multi-stressor situation based on expert knowledge combined with evidence from existing studies. Further, **statistical data analyses/models** and/or **process-based models** were used in describing the stressor interactions through their impacts on different BQEs or on ecosystem functions.

Models are well suited to estimate interactions between combinations of stressors and their impacts on the abiotic or biotic status and to provide the strength of the relationships in terms of level of significance. In addition, models help to understand the sensitivity of the hydrological and ecological system to (multiple) stressors, global changes and required restoration actions.

Based on the knowledge of the local conditions in their river basins and their technical expertise, River Basin Managers should decide by themselves about the best method using monitoring and modeling, and observing the results. The following pages provide an overview on models available from MARS.

4.1 Conceptual MARS models

The MARS conceptual modelling framework provides a holistic approach for modelling multi-stressors across different scales. Every ***MARS case-study basin*** has populated the MARS conceptual model (Figure 5) to show the basin-specific stressors, indicators of state and indicators of ecosystem services. This approach follows the WFD DPSIR context but also manages to introduce the term stressor (see factbox, Page 4) and the ecosystem service cascade in a joint modelling framework that enables to investigate the impacts of multiple stressors on biotic/abiotic state and on ecosystem services. Furthermore, it provides a tool that facilitates discussing the current state of knowledge with stakeholders in a basin.

Key elements in the MARS conceptual model, describing multi-stress situations are:

- ➔ the relevant basin-specific stressors;
- ➔ appropriate indicators of system status and environmental impact;
- ➔ key ecosystem services to be included in the modelling:
- ➔ conceptual descriptions of the relationships between stressors, states and services;

Examples of these conceptual models are available in the individual basin reports at the ***MARS Freshwater Information System (FIS)***.

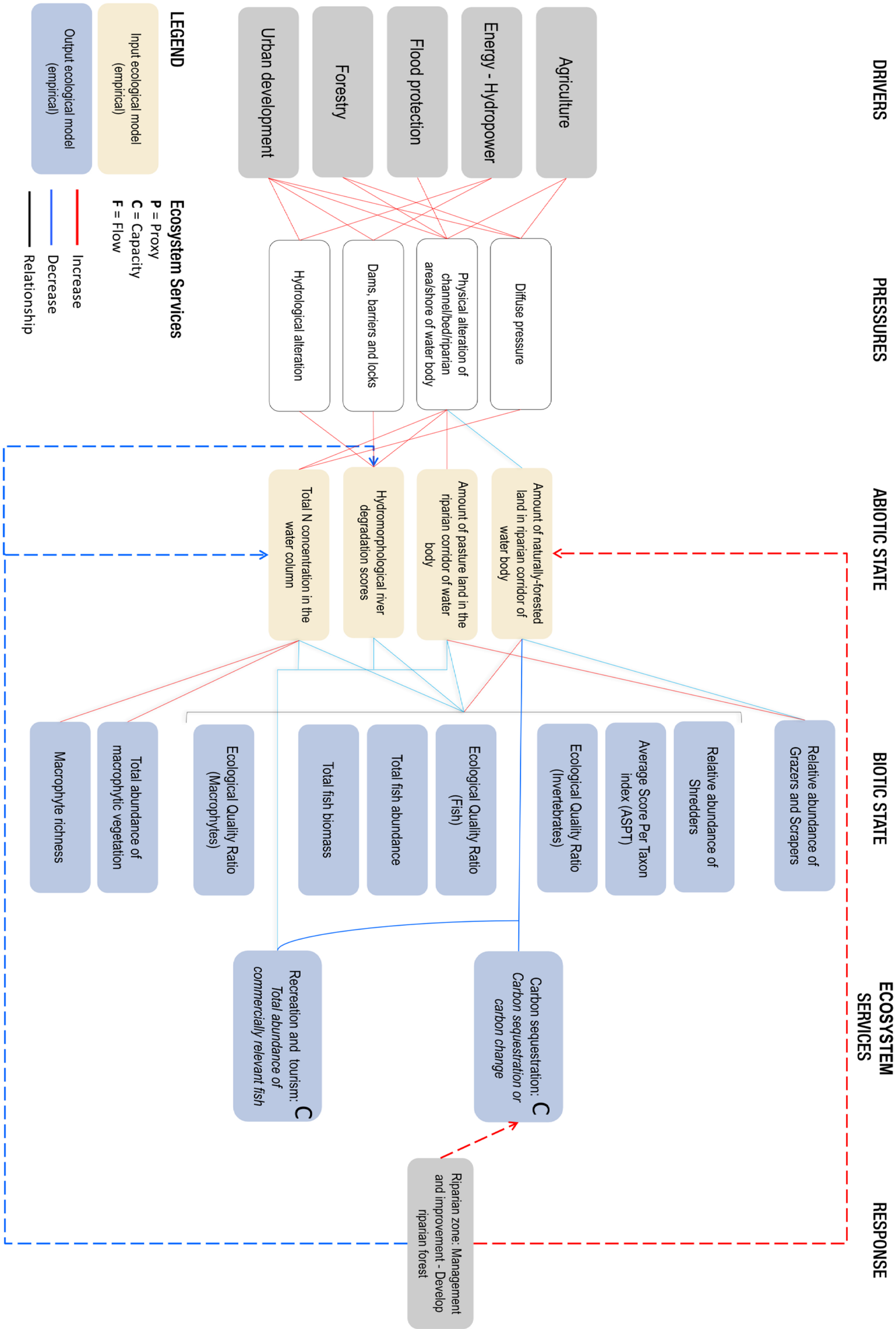


Figure 5: Example of a MARS conceptual DPSIR (Driver-Pressure-State-Impact-Response) model visualising relevant relationships, here within the Ruhr river basin in Germany (the blue and red solid lines indicate relevant relationships between different elements of the conceptual model: red = positive correlation, blue = negative correlation. The dashed arrows indicate on which stressor the response (measure) is assumed to have an effect. The colours of the boxes indicate which elements can be modelled, yellow = input for the empirical models, blue = output of the empirical models) (Gieswein et al., 2017; Birk, 2019).

4.2 Data-driven (empirical) modelling: from stressors to ecological status

In all MARS case studies, **data-driven (empirical) modelling** was used. These models describe statistical relationships between stressors and status indicators, like BQEs in the river basin. Hardly any process-based models are available (see section ***Model Selection Tool*** in Chapter 5.1) to describe the interactions between abiotic status and biotic status. Thus, data-driven modelling is often used and proven valuable for analysing large datasets and translating these into predictions of ecological response to (combined) stressors or to abiotic changes in the system (for examples see Chapters 6.1 and 6.4).

Hence, how to identify and predict multiple stressor and their effects? MARS has developed a cookbook for such analysis and interpretation of results (***Feld et al., 2016***) imposing new challenges to ecosystem management and restoration. Ecosystem managers are required to address and mitigate the impact of multiple stressors, yet the knowledge required to disentangle multiple-stressor effects is still incomplete. Experimental studies have advanced the understanding of single and combined stressor effects, but there is lack of a robust analytical framework, to address the impact of multiple stressors based on monitoring data. Since the year 2000, the monitoring of Europe's waters has resulted in a vast amount of biological and environmental stressors. The MARS cookbook thus accompanied by scripts allowing the user to run a stepwise analysis based on his/her own data in R (R Core Team 2016), an open source language and environment for statistical computing and graphics. Along with the core text, a full R code and examples are provided. The recommended procedure is capable of identifying stressor importance and interaction in respective data sets. It also predicts relationships between stressors and status indicators, to help select measures and obtain good ecological status.

4.3 Process-based modelling: future predictions and increased system understanding

The previous paragraphs should have highlighted that data-driven models can be used to describe current relationships between stressors and ecological status.

- ➔ But what if future predictions in a river basin are needed?
- ➔ What will, for instance, be the effect of climate change, land use changes, and changes in population density in a river basin?
- ➔ How will this overlay the current (multi-) stressor situation?
- ➔ Will these changes imply a need to increase the future program of measures etc.?

The answer is that the effects of future scenarios are often outside the range of validity of data-driven models because datasets do not comprise all possible future situations. This is where process-based modelling can offer a solution. Application of process-based modelling is especially common in hydrology and limnology, where such models, for instance, are used to e.g. determine environmental flow in rivers, as well as nutrient load thresholds ("critical loading") in lakes, current and future nutrient emissions to rivers and lakes, and sensitivity of the system to changes imposed by pressures (stressors) or measures. In addition, process-based modelling is recommended to ***increase system understanding***.

In the MARS case studies, the following process-based models were used:

- **GLM** (General Lake Model)
- **MyLake** for lakes and reservoirs
- **INCA-P** (Integrated Catchments Model - Phosphorus dynamics) estimating phosphorus emissions to rivers
- **SWAT** (Soil and Water Assessment Tool) for rivers
- **MODFLOW and LGSI** (Lowland Groundwater Surface water Interaction) for groundwaters and their interaction with surface waters
- **MONERIS** (Modelling Nutrient Emissions in River Systems) for all water categories

Each model has its own characteristics (e.g. open source availability, domain, space- and time resolution) and its applicability for different water categories (lakes, rivers, etc.) and variables for hydromorphology, physico-chemistry and biology.

MARS developed a ***Model Selection Tool*** to give users an overview on the applicability of these widely used process-based models for River Basin Management, see Chapter 5.

Available data and monitoring networks are often designed to determine changes in status, rather than (long term) effects of measures. Process-based models can be built to link specific (combinations of) stressors or measures to changes in status. These models can be run for various scenarios and can help to predict and improve understanding of system behaviour. We therefore recommend the use of process-based models to support the selection and fine-tuning of appropriate measures and their effects primarily on the abiotic status of a water body. By connecting process-based and data-driven modelling, the best of both worlds can be achieved.

Connecting both types of models allows further quantifying dose-response relationships, their sensitivities and impacts of current and future multi-stressors on BQEs and overall ecological status.

4.4 Bayesian Networks: linking process-based and empirical modelling

In order to connect abiotic and biotic data from data-driven and process-based models, Bayesian modelling was applied and tested in a selection of MARS case studies (see example in Chapter 6.6). Despite several shortcomings, such as the restricted number of cause–effect linkages and the lack of feedback loops, Bayesian modelling (Bayesian Networks) can be an important decision support and communication tool for River Basin Management due to its capacity to combine various inputs (e.g. expert judgment, data analysis, modelling results), its short calculation time, transparency and ease of adjustments (see example in Figure 6). A major advantage is the ability of Bayesian models to provide probabilities for all output variables, thereby quantifying uncertainties.

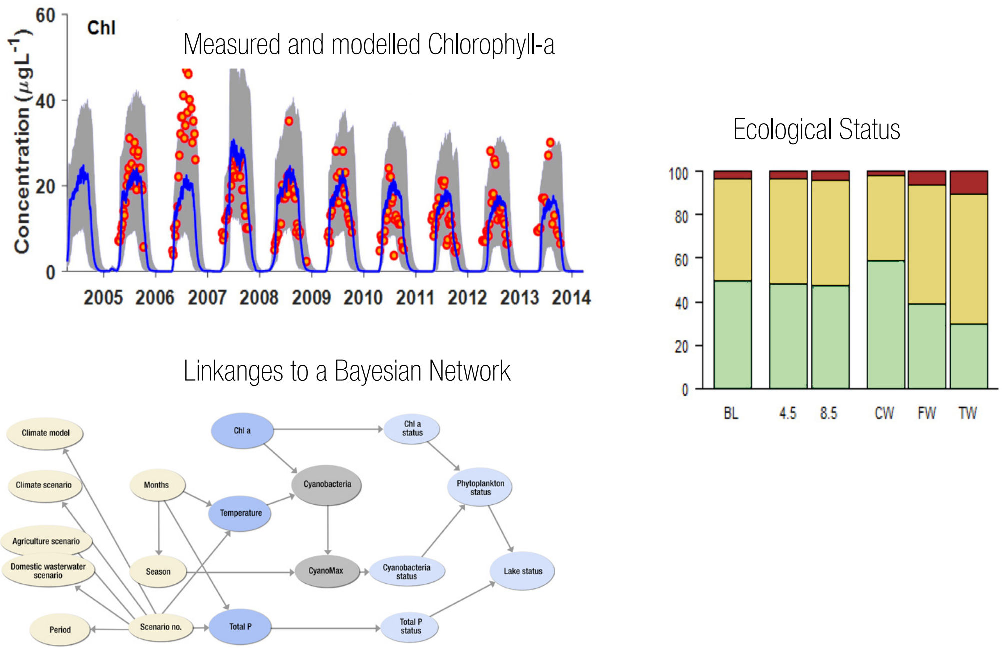


Figure 6: Example of a Bayesian Network chained to a lake model to predict cyanobacteria biomass (Couture et al., 2018; see also Chapter 6.6).

5. MARS tools & results to support multi-stressor analyses

5.1 How to find the most suitable tools: The MARS Model Selection Tool

Process-based models are widely used in water management, for instance to support the interpretation of the monitoring data and predict the possible effects of selected measures. Therefore, MARS developed a Model Selection Tool (Figure 7).

For each model, general characteristics are summarised in a factsheet including contact information and links to websites.

These factsheets are shown when selecting a model. Models can be filtered either through tick boxes or pull-down menus whereby the models meeting the selection criteria are immediately shown. The Model Selection Tool contains 21 models.

Web link
MARS model selection tool

Figure 7: Screenshot of the MARS model selection tool.

5.2 "Heat maps" to analyse and visualise paired stressor-effects

The interplay of multiple stressors, which affect the ecological status, is often difficult to communicate. Tools for the graphical visualisation of multi-stressor effects thus provide valuable aid to increase understanding. Contour plots (aka 'heat maps') allow for visualising the individual effects of two single stressors onto a given response variable. Furthermore, these plots inform whether the stressors are interacting, and where on the stressor gradients these interactions are relevant. Heat maps can, for instance, be used for statistically inferring the magnitude of single or multiple stressor mitigation options to inform water body restoration.

Heat maps are two-dimensional expressions of the effects of stressor 1 and stressor 2 on the response variable (i.e. paired-stressor effects). They are displayed based on the outcomes of statistical (empirical) stressor-response modelling. These models quantify the individual and combined effects of two stressors on the response based on the regression equation. The equations result from multiple regression analysis (e.g. generalized linear modelling) and are based on either time-series data of single water bodies or spatial data of multiple water bodies in a (sub-) catchment.

Figure 8 exemplifies a heat map by showing a stressor-response model of the ecological status using river macrophytes in mid-sized upland streams, including survey data of several water bodies.

How to interpret Figure 8:

- ➔ The two stressors addressed on the x-axis and y-axis are 'nutrient enrichment', given as orthophosphate concentration, and 'morphological degradation', given as percentage of riparian vegetation alteration.
- ➔ The good-moderate status boundary is plotted as a dashed line across the surface spanned by the two stressor gradients.
- ➔ The diagonal orientation of the good-moderate boundary (coloured areas depicting the five status classes) indicates that both stressors have an equal effect on the response variable.

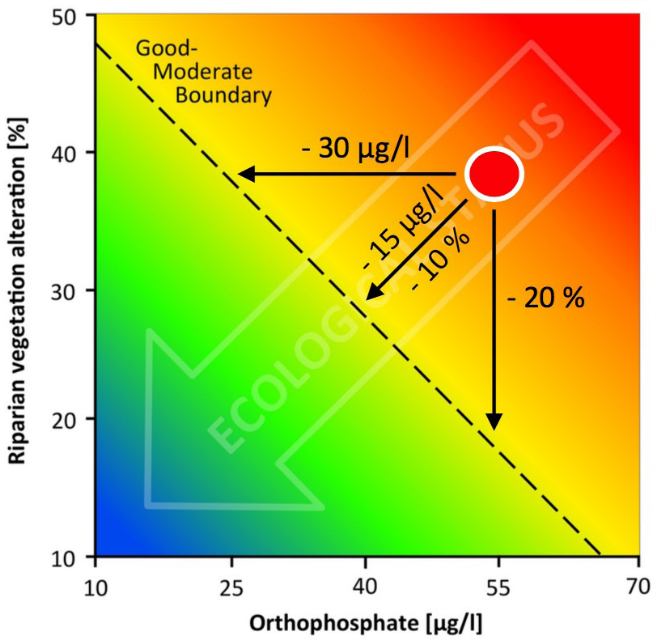


Figure 8: Heat map example/visualisation of paired-stressor effects on the ecological status – case of additive effects.

➔ A vertical orientation would denote an exclusive effect of the nutrient stressor, while a horizontal orientation would denote an exclusive effect of the morphological stressor.

➔ The straight-line shape of the good-moderate boundary indicates that the effect of both stressors is equal across the whole gradient. This characterizes an ***additive*** stressor effect.

➔ The red dot represents a water body in poor status (within particular management context).

To restore this water body to good status, each single stressor can be mitigated individually. In the example of Figure 8, a reduction of 30 µg/l orthophosphate would bring the water body back into good status. Alternatively, a 20 % restoration of riparian vegetation would yield a similar effect. Mitigating both stressors would cost only half the efforts for each single stressor.

Figure 9 is based on an example including the same stressors and responses. However, in this case the good-moderate boundary (incl. the related coloured areas) is convex.

This convexity indicates a *synergistic* interaction effect of both stressors. E.g. at orthophosphate concentrations > 50 µg/l, the ecological status no longer responds to further nutrient enrichment. Here, alterations of the riparian vegetation can have the biggest effect on the status. Accordingly, at levels > 40 % riparian vegetation alteration the ecological status no longer responds to further alteration. Changes in orthophosphate concentration can then have the biggest effect on the status. Compared to the example above (Figure 8), this convex boundary line explains the higher efforts to be made in case of mitigating both stressors together.

Heat maps are useful visualisation tools to help in communicating paired-stressor effects. They graphically distinguish between different interaction types and aid in selecting appropriate mitigation measures and their intensity. ***An important prerequisite for heat maps, however, are sound statistical models with sufficient explanatory power to realistically reproduce the actual conditions. And as heat maps allow for picturing only two stressors and their interactions, their use requires reducing the multi-stressor context to only these two factors.***

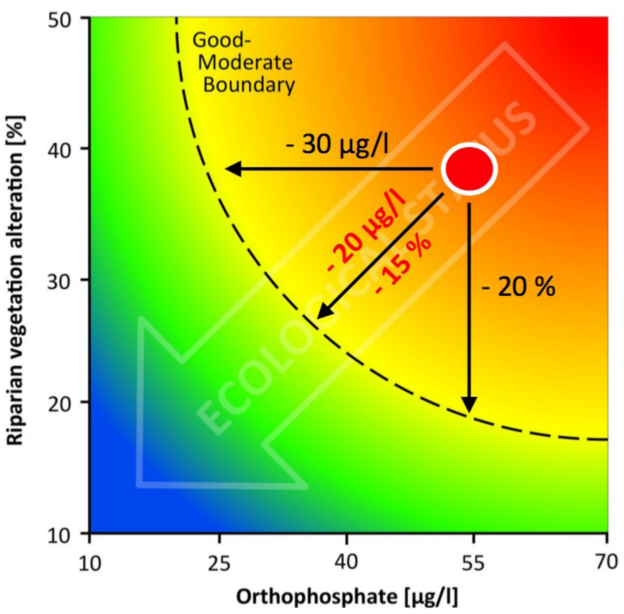


Figure 9: Visualisation of paired-stressor effects on the ecological status – case of synergistic effects.

5.3 The MARS Diagnostic Tool for investigations at the water body scale

5.3.1 Introduction

A water body is the main management unit for WFD implementation in River Basin Management. Biological monitoring and assessment are conducted at the scale of individual water bodies that is, for example, a lake or a stretch of several up to tens of kilometres of a river course. Based on the biological assessment of a water body, measures have to be identified in case a water body fails to meet good ecological status or potential. However, appropriate management or restoration measures to improve ecological status or potential are often not easy to derive from biological assessment. For example, if the biological indicators integrate the impact that multiple stressors impose on a given water body. Then, tracing back from the indicators to individual stressors that putatively have caused the ecological deterioration is often challenging, if not impossible.

To derive appropriate management options, it is necessary to identify two aspects:

1. the stressors operating at a given water body;
2. the strength of their impact on ecological status;

As this knowledge may be difficult to derive from biological assessment systems, alternative tools are required to assist River Basin Managers. MARS has developed such diagnostic tool that in particular aims to help linking water body assessment to the derivation of management options.

As such, the tool is comparable to a doctor, whose first task during the interview with a patient (anamnesis) is to link the symptoms of a patient to the potential causes that might be responsible for the symptoms. Thus, likewise the diagnostic tool might be considered a water body doctor.

5.3.2 Background

The Diagnostic Tool (DAT) links symptoms of water body deterioration with potential causes. The symptoms are represented by the results of the biological assessment, namely by the ecological attributes and indices that are calculated based on the list of organisms found at a water body during the monitoring survey. A symptom may be the number of sensitive insect species found at the river bottom or the amount of algae found in the water column of a lake. The causes are represented by the list of stressors known to affect a water body. Typical causes are pollution by nutrients or organic waste, both of which can dramatically reduce the water quality. Other stressors represent human alterations of the hydrological and morphological conditions of a water body etc.

The link between the symptoms and the causes is implemented by a Bayesian Network. Such a network combines simple knowledge rules, each rule representing a cause-symptom chain.

For example, there may be evidence that whenever large amounts of fine sediments (a cause) enter a river site, the coverage of algae will be reduced (a symptom) at the bottom of the river. This is because fine sediments cover algae and disconnect them from light and nutrients so that they cannot grow. A simple knowledge rule then may be that whenever fine sediments cover more than 50% of the river bottom, there is a low probability that algae have a substantial coverage. Thereby, a knowledge rule does not have to be based on

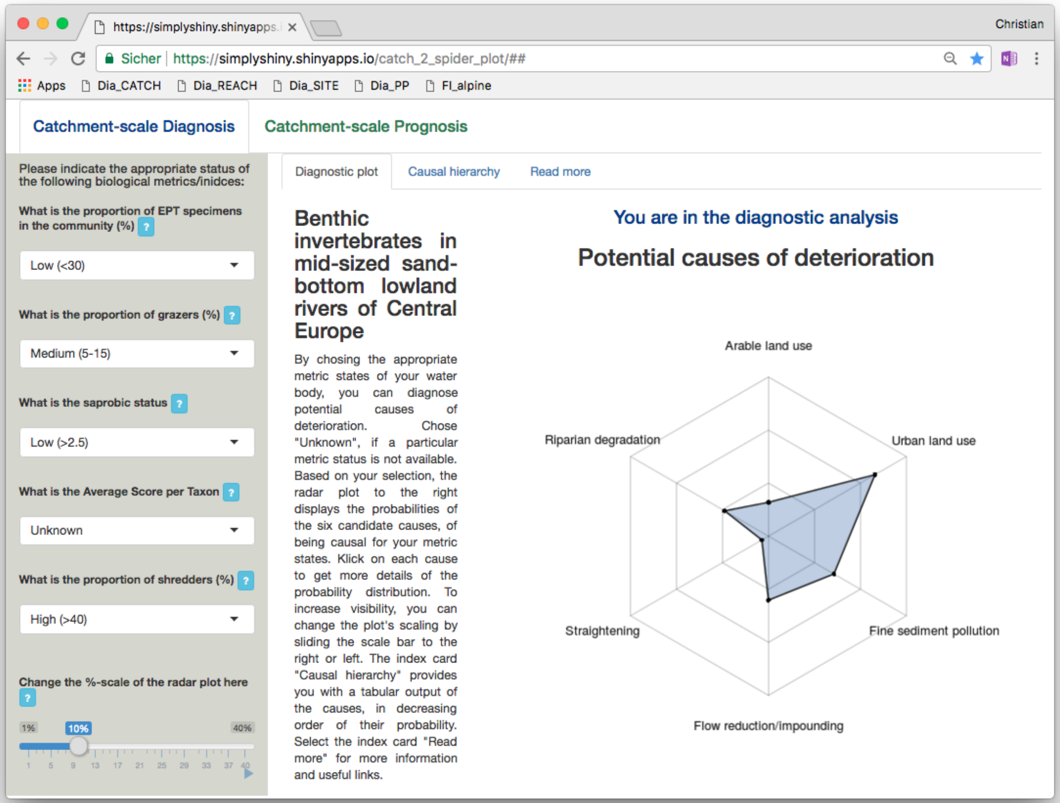


Figure 10: Screenshot of the MARS Diagnostic Tool for benthic invertebrates in mid-sized sandy lowland rivers of Central Europe. The input area (grey bar) is displayed on the left, the output area (radar plot) on the right. The example output shows a strong increase of the probability of urban land use to be causal for the states of metrics.

Web link
[MARS Diagnostic Tool (DAT)]

real data, i.e. it can be based solely on expertise, but can be validated with real data.

Bayesian Belief Networks are the means to combine the knowledge rules. Actually, they calculate the probability of a subject conditional on the states of other subjects. As a result of the DAT, the networks provide the user with probabilities of causes conditional on the states of biological assessment results.

Designing the DAT requires establishing knowledge rules, underpinned by expert knowledge, WFD monitoring data and further scientific evidence, if available. Figure 10 provides an overview on the DAT online tool.

5.3.3 Approach

The diagnostic approach behind the tool is based on the outcome of the biological assessment:

- ➔ The user is required to enter the states of selected diagnostic metrics (e.g. number of sensitive insect species [EPT taxa], proportion of grazers feeding on algae etc.) into the DAT.
- ➔ Based on the metric states indicated by the user, the Bayesian Belief Network behind the online tool calculates the conditional probabilities of each candidate cause included in the network.
- ➔ This probability is compared to the baseline values of each cause, i.e. the probability of a cause without any indication of an effect in a metric.

- The output of the tool is equivalent to the increase in the probability of each cause.
- This increase is displayed as a radar plot, allowing the user to immediately identify the potential causes of deterioration and their order of strength.

Caution! The DAT does not replace the expert! In both the diagnostic and the prognostic direction, it aims to help the expert estimate the probability of selected causes and symptoms. The numbers provided represent increases in the probability, not exact values of the actual states of the causes.

Within MARS, altogether five DAT showcases have been developed:

- CATCHMENT (river basin) -scale causes based on benthic invertebrate symptoms (applicable only for mid-sized sand-bottom rivers in Central Europe, ***web link***);
- REACH-scale causes based on benthic invertebrate symptoms (applicable only for mid-sized sand-bottom rivers in Central Europe, ***web link***);
- SITE-scale causes based on benthic invertebrate symptoms (applicable only for mid-sized sand-bottom rivers in Central Europe, ***web link***);
- Water body-scale versus basin-scale causes of large river phytoplankton symptoms (applicable only in large sand-bottom lowland rivers of Central Europe, ***web link***);
- Water body-scale causes of fish symptoms (only applicable for Alpine rivers, ***web link***);

These showcases of the DAT can be implemented on a wide variety of cases (Figure 11) and are available through the ***Freshwater Information platform***.

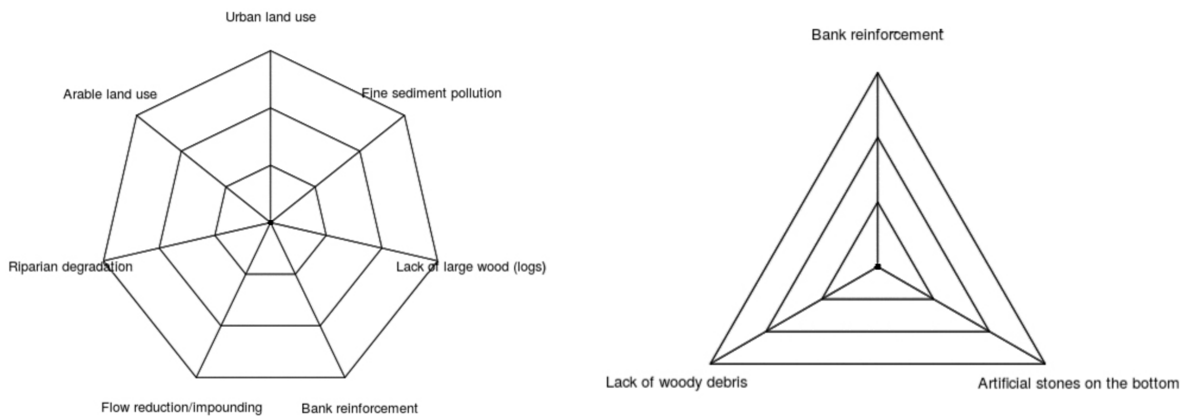


Figure 11: Example output of a Diagnostic Tool with seven (left) and three (right) candidate causes implemented in the underlying Bayesian Network. This flexibility allows the online implementation of a wide variety of cases.

5.3.4 Technical implementation and limitation

It is important to note that the Diagnostic Tools provided by MARS represent showcases, limited to the river types they have been developed for. In general, the diagnostic approach is applicable to any kind of water body (and diagnostic problem), but the underlying cause-symptom (i.e. cause-effect) rules may differ and thus are not universally applicable. Yet, tailoring an existing DAT to one's own demands is possible. Therefore, MARS has compiled an illustrated cookbook available as ***Deliverable 7.1***. The DAT is implemented with ***Shiny***, a freeware graphical user interface that interactively links to the freeware statistical software program ***R***.

Like with medical diagnosis, the DAT thus rather constitutes the starting point of the investigation. The results may suggest asking a specialist or crosschecking highly probable causes with supporting data, to further narrow down the causes and to reduce the uncertainty.

5.4 The MARS Scenario Analysis Tool for investigations at the large scale

5.4.1 Introduction

The MARS scenario analysis tool addresses the type of interactions between multiple stressors and their current and future impact on aquatic ecosystems at the European scale, by also allowing downscaling to Functional Elementary Catchments (FECs, which are sub-catchments, with a mean spatial extent of 62 km²).

The resolution of available data and model results is limited to the FEC level, but at the same time the gradients and number of relevant stressors increase, potentially allowing identification of stressor-response relationships, which are often concealed at smaller scales.

Web link
MARS Scenario Analysis Tool (SAT)

5.4.2 Background

The ***Scenario Analysis Tool (SAT)*** is an online tool allowing visualising and analysing multi-stressor conditions in European rivers. With 6.13 million km², the model extent covers EU-27 countries, EFTA States and hydrological connected areas (e.g. of Ukraine/Danube or Russia/Baltic Sea). The backbone of the SAT is a combination of the models PCR-GlobWB and MONERIS, which are linked with the MARS geodatabase. PCR-GlobWB provides information on daily water balances for near-natural, current and future conditions (i.e. no reservoirs, no water abstraction or addition). These data are used to analyse hydrological alterations (***IHA software package***), and as input data for ***MONERIS***, quantifying nitrogen and phosphorus emissions to surface waters, instream retention and resulting loads and concentrations.

Results of both models, together with an additional extended data collection on various catchment parameters and a complete data set of the ecological status reported by the EU member states feed into the ***MARSgeoDB*** (see Chapter 3.3). The outputs describe linkages between climate, water availability, nutrient fluxes and management options by quantifying and evaluating multi-stressor conditions and the related aquatic responses.

5.4.3 Scope of the SAT

The SAT offers a detailed overview of stressor conditions and potential impact on the ecological status across Europe. The tool also predicts the effect of selected mitigation measures. It operates at the level of 104,300 hydrological sub-catchments, resembling spatial units similar to the 'water bodies' delineated according to the WFD (Figure 12).

The SAT can provide harmonized European-wide assessments, comparing geo-climatic regions under different anthropogenic stress, with an emphasis on aggregation levels larger than 1,000 km² and mean conditions over a ten-year period (due to the underlying data and model features). With this, it targets users working on EU legislation, managers within the international river commissions and scientists interested in multi-stressor conditions in a broad context. However, the SAT cannot replace the basin-specific pressure analysis as prescribed by the WFD.

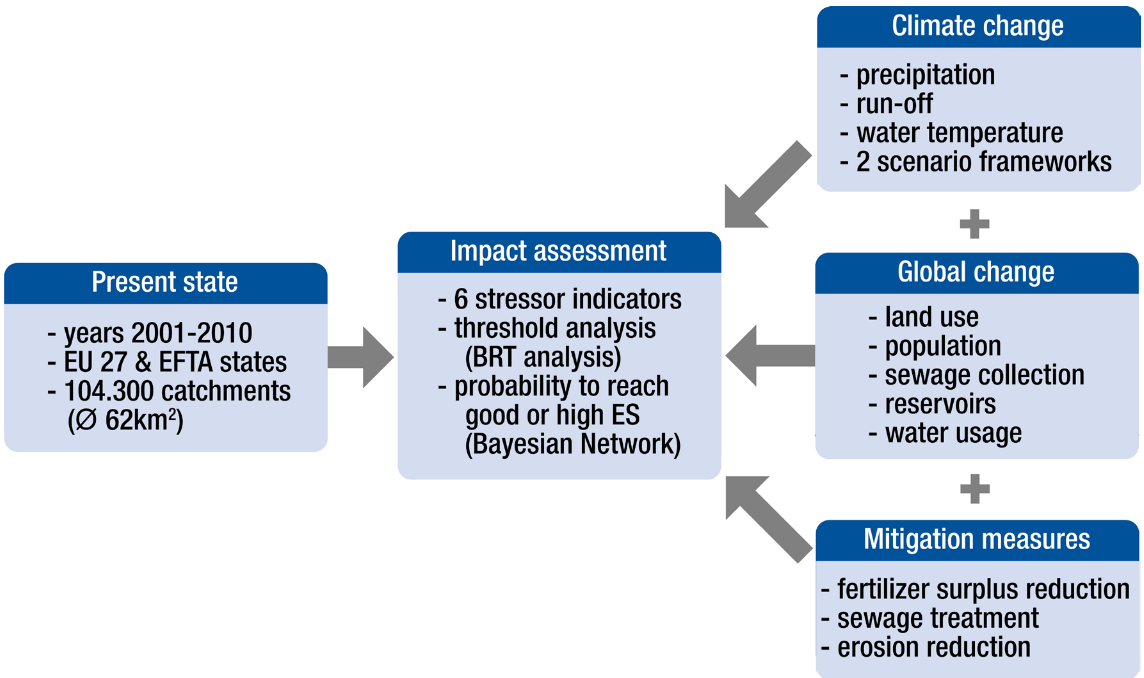


Figure 12: Conceptual model of the data flow in the MARS SAT to assess the impacts of multiple stressors at the European scale. BRT is Broad River Types, see text in 5.4.4, and ES is ecological status.

5.4.4 Approach

- Selected pressures, stressors or state variables were considered as stressor indicators (proxy variables), comprising about 20 candidate parameters.
- Machine-learning techniques and boosted regression tree analysis were applied to identify major stressor indicators and thresholds for significant impacts on the ecological status, derived in a multiple-stressor context.
- A stressor ***is considered active if the threshold is exceeded, and inactive if the value remains below the threshold.***
- As thresholds for active stressors vary considerably between different river types, analysis was conducted for different Broad River Types (BRT) (***Lyche Solheim et al., 2015***, see also ***Surface water bodies: Ecological status or potential, by broad type***).
- The stressor indicators (Table 3) and derived thresholds are used in Bayesian Belief Networks to derive probabilities for a unit to reach a good or high ecological status.
- Changing stressor indicator values modelled for scenario conditions are translated by Bayesian Belief Network changing future probabilities to reach a good or high ecological status.

Table 3: List of finnaly selected stressor indicators for the MARS SAT.

Indicator	Units
Concentration of dissolved inorganic nitrogen (DIN) in main river at outlet of a sub-catchment modlled by MONERIS	mg/l
Concentration of total phosphorus (TP) in main river at outlet of a sub-catchment modelled by MONERIS	mg/l
Area share of agricultural area per sub-catchment derived from land-use maps (CORINE)	%
Area share of urban area per sub-catchment derived from land-use maps (CORINE)	%
Change of mean annual flow (maf) between near natural conditions and current/scenario conditions	%
Change of baseflow index (basef) between near natural conditions and current/scenario conditions. Base flow index is the ratio between 7-day minimum flow divided by mean annual flow. Only positive changes (i.e. increasing baseflow indices) were considered	%

5.4.5 Considered scenarios and management options

The ***SAT*** compares current conditions calculated for the years 2001-2010 to two future scenarios, described as ***MARS scenarios*** shown in Table 4, for the two periods 2026-2035 and 2056-2065. The calculations of the scenarios are split-up into two components: a) exogenous factors (climate, demography, land-use changes) and b) endogenous factors (e.g. mitigation measures, planned and conducted at local or country level). Consequently, changes in the selected six stressor indicators and in the probability of reaching a good or better ecological status are calculated separately for the exogenous factors for both scenarios and periods.

Table 4: Factors and mean changes considered for the scenario modelling to project future conditions of stressors and their impacts on ecological status (years: 2030 and 2060). Mean changes represent pan-European averages, i.e. changes for specific regions can be significantly different from these mean changes.

	Scenario 1: Techno world [1)]	Scenario 2: Consensus world [2)]
Modelling period	2026-2035 (representing 2030) and 2056-2065 (representing 2060)	
Climate/global change scenario	RCP8.5, SSP5	RCP4.5, SSP2
Precipitation change in %	2030: +8 (mean) 2060: +9 (mean)	2030: +9 (mean) 2060: +8 (mean)
Reservoirs	Increase of reservoir area by 0.084 % of land area	
Water abstraction	2030: +2.1 2060: +2.2	2030: +0.7 2060: +2.1
Land-use change in %	Agricultural – 2030: -2, 2060: -3 Urban – 2030: +1, 2060: +2	Agricultural – 2030: -3, 2060: -3 Urban – 2030: +1, 2060: +1
Population change in %	2030: +10 (mean) 2060: +13 (mean)	2030: +6 (mean) 2060: +9 (mean)
Sewage collection	2030: 2010 +10 %-points 2060: 2010 +20 %-points	2030: 2010 +10%-points +10 % of difference to 100% 2060: 2010 +20%-points +20 % of difference to 100%
Sewage treatment	Current run-off concentrations of treatment plants discharges are reduced by 25 %. The domestic water consumption remained unchanged.	

1) In the Techno world economic growth is the main objective and the EU supports innovative technologies and capital increasing solutions. The high energy demand is met by the excessive use of fossil fuels, causing rising CO_2 emissions. Alternative energy sources are also utilized, though without any environmental consideration. The environmental policies stagnate due to the focus on trade and economic growth, thus protecting and improving interventions are mainly initiated by individuals or communes. Locally, provisioning and cultural services are prioritized, while regulating services by nature are neglected. Water management uses technical solutions to minimize risks to human health and capital and to meet current needs, though sustainability is disregarded.

2) The Consensus world connects the objectives for economic growth with a sustainable and effective resource use. Economic and population growth continue like present and energy is saved in order to reduce emissions, using a mix of fossil fuel and renewable sources. The existing awareness and interest in nature conservation is based on strong regulations by the European Union. After 2020, the current guidelines and policies are enhanced in a more integrated way. To meet these regulations, cheap water management strategies with mid- to long-term sustainability are performed. Also, a trend towards green infrastructure is uprising, utilizing the benefits of natural processes and structures.

6. Examples and evidence from MARS studies

6.1 Mapping of multiple stressors: impacts of single and multiple human stressors on riverine fish assemblages

Reference

Schinegger, R., Pucher, M., Aschauer, C., Schmutz, S., (2018). Configuration of multiple human stressors and their impacts on fish assemblages in Alpine river basins of Austria. Science of the Total Environment. 616–617, 17–28.

Introduction

Current knowledge on multiple stressors and related response of fish assemblages is limited in most parts of the world, especially in terms of quantifiable effect of multiple hydromorphological stress – such as morphological alterations, residual flow and connectivity disruption, hydropeaking and impoundments – paired with water quality stress.

Methods

The impacts of single and multiple human stressors on riverine fish assemblages in the Drava and Mura River Basins in Austria were disentangled, based on an extensive dataset. For each water body, five hydromorphological stressors, i.e. 'residual flow', 'morphological alteration', 'connectivity disruption/ barriers', 'impoundment' and 'hydropeaking' were identified according to the Austrian River Basin Management Plan by the Austrian Federal Ministry of Agriculture, Forestry, Environment and Water Management (RBMP database).

Investigated biological response variables were the status for fish assessed with the Fish Index Austria (FIA), as well as the status for all BQEs combined, and the total overall ecological status.

Results

A clear trend of increasing stressor metrics from epirhithral to hyporhithral was observed by the number of stressors. Stressor-response analysis shows divergent results, but a general trend of decreasing ecological integrity with increasing number of stressors was observed.

Conclusions

The knowledge gained in this work provides a basis for advanced investigations in Alpine river basins and beyond, supports WFD implementation and helps prioritizing further actions towards multi-stressor restoration and management.

Further readings on the Drava and Mura basin analyses are also available at the ***MARS Freshwater Information System*** and in a ***Freshwater Blog*** story.

Web link

Reference Schinegger et al.

Key scientific findings

- → Seven stressor categories and up to four stressors at the same site were identified.
- → Of all sites, only 31% were unimpacted.
- → Impacted sites were affected by single stressors (26%) or multiple stressors (30%).
- → Decreasing ecological integrity/status with increasing number of stressors was identified.

MARS example on how to map multi-stressors (Figure 13)

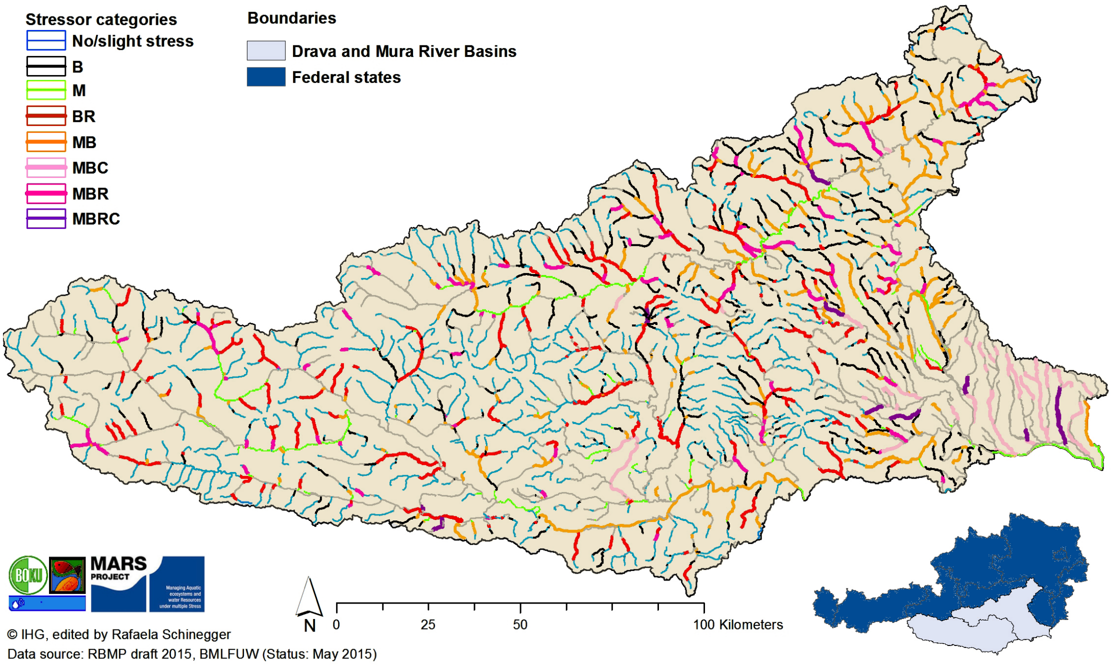


Figure 13: Configuration of stressors in the Austrian Drava/Mura basins (Schinegger et al., 2018). Stressors mapped are: no/slight stressor impact (noS), hydrological stressors expressed as residual flow (R), barriers (B), chemical pollution (C), and morphological alterations (M) and their combinations.

Key findings/support for management

- ➔ How to analyse national River Basin Management Plan data in terms of multiple stressors?
- ➔ How to investigate stressor configuration?
- ➔ How to relate stressor configuration with BQEs?

6.2 Application of conceptual models: evidence on climate change increasing the eutrophication of a Mediterranean large lake

Reference

Bucak, T., Trolle, D., Tavşanoğlu, Ü. N., Çakıroğlu, A. i., Özen, A., Jeppesen, E., Beklioğlu, M. (2018). Modeling the effects of climatic and land use changes on phytoplankton and water quality of the largest Turkish freshwater lake: Lake Beyşehir. Science of the Total Environment 621, 802-816.

Introduction

The key stressors affecting Lake Beyşehir are water abstraction for agricultural irrigation, invasive fish introductions and nutrient loading from agricultural areas. The Mediterranean region in which the Beyşehir basin is located, is projected to be significantly affected by future climate changes, particularly precipitation reductions and temperature increases.

Methods

The MARS team used an ensemble approach by linking catchment model outputs to two different lake models (GLM-AED and PCLake) to simulate the effects of multiple stressors on ecosystem services in Lake Beysehir. The effects of land use on hydrological processes in the catchment were simulated used a Soil and Water Assessment Tool (SWAT), which was calibrated for accuracy using historical datasets. GFDL-ESM2M and IPSL-CMA-LR climate models were used to generate precipitation and temperature scenarios, using the periods 2006-2015 for verification, and 2025-34 and 2055-64 for forecasting.

Results

Although there is variation among the scenarios, climate change is likely to increase water stress and nutrient concentrations in Lake Beyşehir in the future. Hydraulic loading (i.e. the amount of water reaching the lake) decreased in most scenarios, except those with moderate climate change, in which it increased due to higher precipitation. However, despite lowered nutrient loading, in-lake phosphorus concentrations increased for both time periods. Chlorophyll concentrations increased slightly, and cyanobacteria biomass increased significantly in future scenarios.

Conclusions

Most scenarios suggest that water levels will drop in Lake Beyşehir in the future. For the 2060s period, the water level drop is below the minimum management level (possibly even drying out), which is likely to reduce the water available for irrigation, and alter lake ecosystem dynamics. The resulting increases in nutrient concentrations in the lake increase the risk of eutrophication and toxic algal blooms, which is likely to negatively impact drinking water quality, the ecological health and status of the lake, and its recreational value.

Web link

Reference Bucak et al.

Key scientific findings

- ➔ Climate change is likely to increase water stress and nutrient concentrations in Lake Beyşehir in the future.
- ➔ Projected decreases in run-off, reduced precipitation and increased evaporation around 2030 and 2060 suggest that water levels will drop in Lake Beyşehir in the future.

MARS example for the application of conceptual models (linking DPSIR, stressors and ecosystem services, Figure 14)

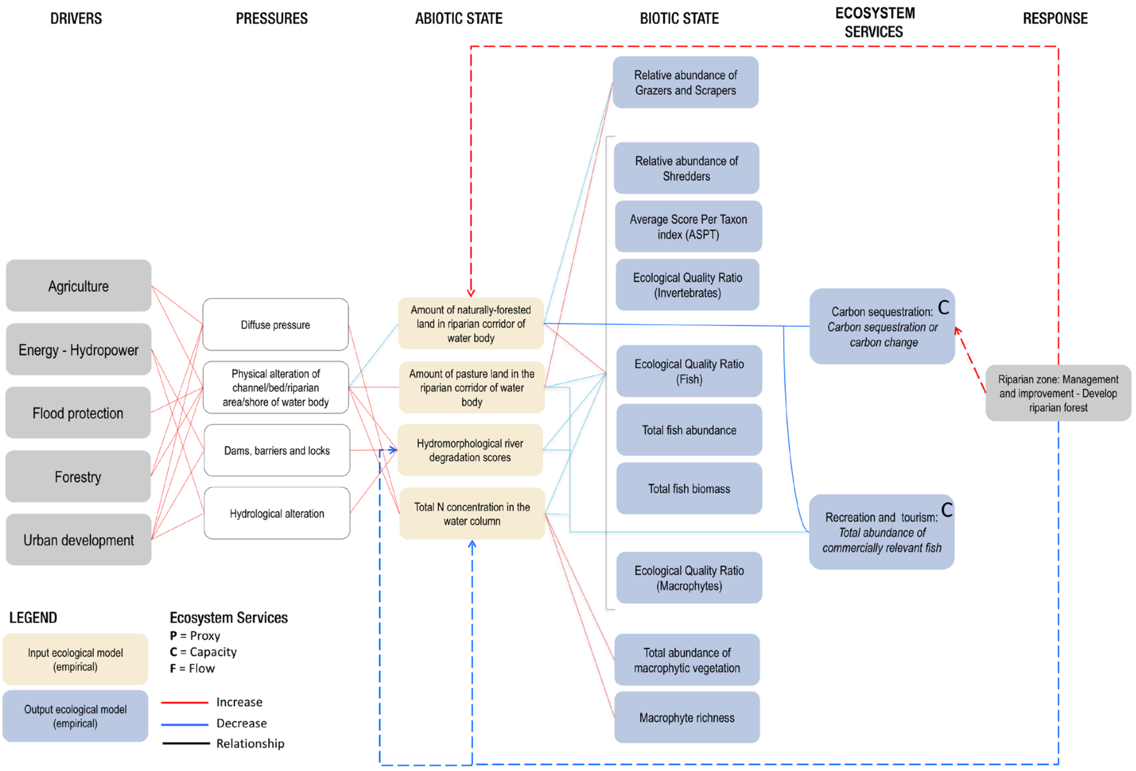


Figure 14: MARS conceptual DPSIR model for the Beyşehir Basin after Bucak et al. (2018).

Further readings on the Beyşehir Basin analyses are also available at the ***MARS Freshwater Information System*** and in a ***Freshwater Blog*** story.

Key findings/support for management

- ➔ Climate modelling studies from other temperate lakes show that substantial reduction in nutrient loads is needed.
- ➔ The promotion of adaptation measures such as drought-resistant crops and the use of efficient irrigation technologies is important in mitigating the effects of future climate change in the basin.
- ➔ Basin management initiatives, which promote reductions in agricultural fertiliser use and abstraction rates, are advised.

6.3 Experimental study: assessing impacts from nutrients and pulsed flow on riverine phytobenthos

Reference

Bondar-Kunze, E., Maier, S., Schönauer, D., Bahl, N., Hein, T., 2016. Antagonistic and synergistic effects on a stream periphyton community under the influence of pulsed flow velocity increase and nutrient enrichment. Science of the Total Environment 573, 594–602.

Introduction

The interaction effects of two strong stressors (higher flow velocity due to daily hydropeaking) and nutrient enrichment can have severe effects for an oligotrophic stream periphyton community. As periphyton has a rapid reproduction rate and very short life cycles, it can therefore be expected to reflect short-term impacts and sudden changes/disturbances in the environment.

Methods

Biomass development, algal group distribution and photosynthesis efficiency during a time period of 33 days was measured in an experimental flume setting in Lunz am See (Austria). The experiment was conducted with two treatments (no hydropeaking and hydropeaking) and three nutrient enrichments (nitrate, phosphate and nitrate + phosphate enrichment) and control (no nutrient addition).

Results

The results showed a significant lower biomass development in the hydropeaking treatment, compared to the no-hydropeaking treatment in a later successional stage. Nutrient subsidy effects were not observed, because the biomass development (chlorophyll-a) of periphyton was highly diminished through the pulsed flow velocity increase. Also a negative synergistic interaction (more negative than predicted additively) was observed.

Conclusions

The study confirmed for periphyton communities that for different algal groups and functional guilds the same multiple stressor combination can be detrimental for one species group (e.g. chlorophyta) while beneficial for another (e.g. diatoms). It is therefore important for multiple stressor studies to consider the successional stage and community composition, when estimating the interaction effects of these stressors.

Weblink:
Reference Bondar-Kunze et al.

Key scientific findings

- ➔ Hydropeaking cancelled out or reduced the impact of nutrient enrichment on phytobenthos biomass (antagonistic effects).
- ➔ For multiple stressor studies the successional stage is important.

MARS example for experimental studies, offering valuable insights for informed management decisions (Figure 15)

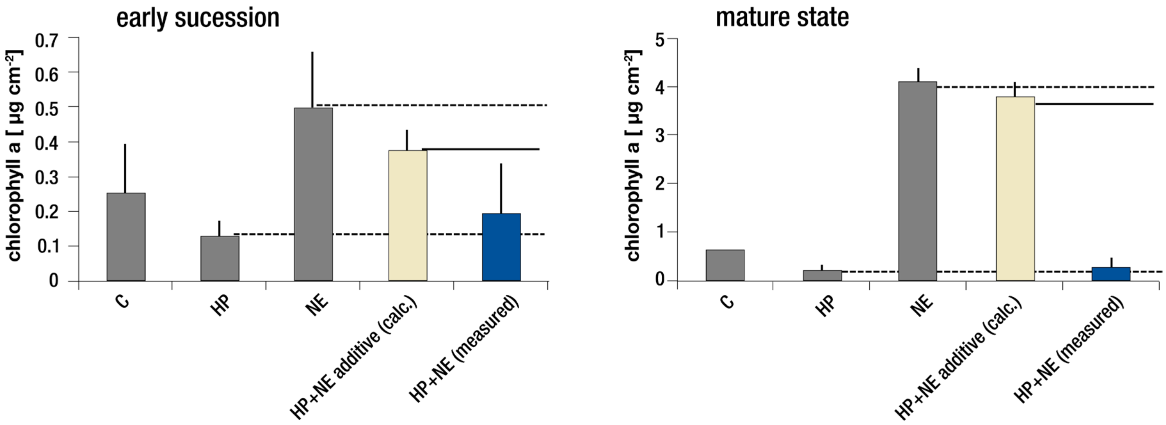


Figure 15: Interaction graphics between hydropeaking treatment (HP) and nutrient enrichment (NE). Chlorophyll-a (mean ± SD), note the different scaling between the 2 days. Grey bars indicate the measured control (C) treatment (no hydropeaking and no nutrient enrichment), hydropeaking treatment (HP) and nutrient enrichment (NE) at day 22 and 33. HP + NE additive (calc.) stands for the estimated response to hydropeaking and nutrients treatment (additive sum of individual effects) and HP + NE measured stands for the actual measured interaction effect for both stressors (blue). The horizontal lines visualise the limit of different interaction terms in relation to the calculated additive effect (less or more negative than additively).

Further readings on the MARS experiments in Lunz/See are also available at the ***facility website*** and in a ***Freshwater Blog*** story.

Key findings/support for management

→ Mitigating the antagonist (flow pulses) first may lead to an unintended increase in effects of the second stressor (nutrient enrichment) on phytobenthos biomass.

6.4 Identification of stressor hierarchies (relative importance of different stressors) in rivers

Reference

Gieswein, A., Hering, D., & Feld, C. K. (2017). Additive effects prevail: The response of biota to multiple stressors in an intensively monitored watershed. Science of the Total Environment 593, 27-35.

Introduction

Freshwater ecosystems are impacted by a range of stressors arising from diverse human-caused land and water uses. Identifying the relative importance of single stressors and understanding how multiple stressors interact and jointly affect biology is crucial for River Basin Management.

Methods

This study addressed multiple human-induced stressors and their effects on the aquatic flora and fauna based on data from standard WFD monitoring schemes. Twelve stressor variables were included covering three different stressor groups: riparian land use, physical habitat quality and nutrient enrichment. Twenty-one biological metrics calculated from taxa lists of three organism groups (fish, benthic invertebrates and aquatic macrophytes) were analysed. Stressor and response variables were subjected to Boosted Regression Tree analysis to identify stressor hierarchy and stressor interactions and subsequently to linear regression modelling to quantify the stressors standardized effect size.

Results

Riverine habitat degradation was the dominant stressor group for the river fauna, notably the bed physical habitat structure. The explained variation in benthic invertebrate metrics was higher than it was in fish and macrophyte metrics. General integrative (aggregate) metrics such as % Ephemeroptera, Plecoptera and Trichoptera (EPT) taxa performed better than ecological traits (e.g. % feeding types).

Conclusions

Additive stressor effects dominated, while significant and meaningful stressor interactions were generally rare and weak.

Web link

Reference Gieswein et al.

Key scientific findings

- ➔ Quantified stressor effects and interactions can help River Basin Managers to derive suitable management actions.
- ➔ Biological and abiotic data resulting from monitoring schemes provide a solid basis to disentangle multiple-stressor effects.
- ➔ Stressor interactions were rare and weak, thus implying independently acting stressors.
- ➔ Physical modifications of the habitat and the riparian areas were much more important than the nutrient enrichment.

MARS example for the identification of stressor hierarchies (Figure 16)

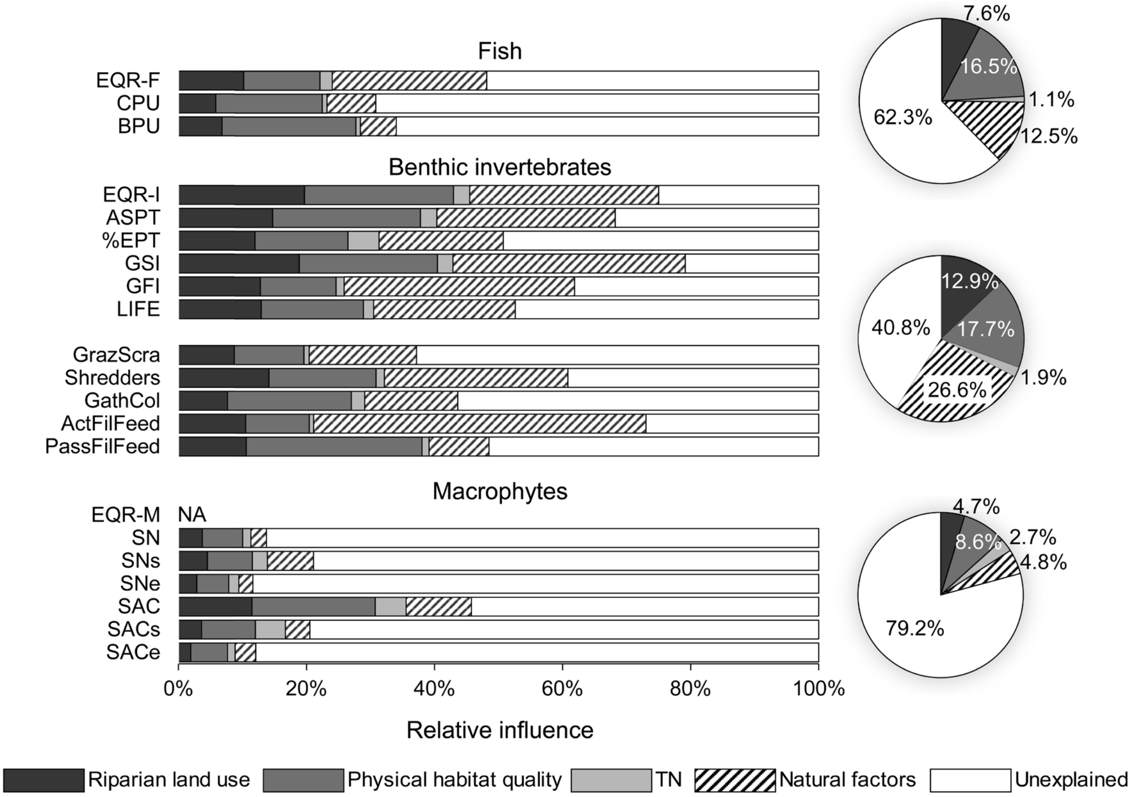


Figure 16: Relative influence of natural and anthropogenic predictor groups on the metrics of the three investigated organism groups. Pie charts show mean relative importance of natural variables and stressor groups summarized for all metrics of each organism group.

Further reading on the Ruhr Basin analyses is also available at MARS ***Freshwater Information System***.

Key findings/support for management

- ➔ Which analytical techniques to be used for the identification of stressor hierarchy?
- ➔ Which surrogate parameters can be used complementary to RBMP data (e.g. riparian landuse)?
- ➔ In this case: Prioritise restoration of the habitats and riparian areas first.

6.5 Ranking the benefits of restoration measures in estuaries for fish

Reference

Teichert, N., Borja, A., Chust, G., Uriarte, A., & Lepage, M. (2016). Restoring fish ecological quality in estuaries: implication of interactive and cumulative effects among anthropogenic stressors. Science of the Total Environment 542, 383–393.

Introduction

Estuaries are subjected to multiple anthropogenic stressors, which have additive, antagonistic or synergistic effects. Current practice includes the use of large databases of biological monitoring surveys to help environmental managers prioritizing restoration measures.

Methods

This study investigated the impact of nine stressor categories on ecological status for fish based on data derived from 90 estuaries of North East Atlantic countries. A random forest model was used to: 1) detect dominant stressors and their potential non-linear effects; 2) evaluate improvement of ecological status expected from reducing the stressors and 3) investigate interactions among the stressors

Results

Results show that largest restoration benefits were expected when mitigating water pollution and oxygen depletion. Non-additive effects represented half of pairwise interactions among stressors, and antagonisms were the most common. Dredged sediments, flow changes and oxygen depletion were predominantly implicated in non-additive interactions, whereas the remaining stressors often showed additive impacts.

Conclusion

The prevalence of interactive stressors reflects a complex scenario for estuaries management; hence, a step-by-step restoration scheme is proposed focusing on the mitigation of stressors providing the maximum of restoration benefits under a multi-stress context.

Web link

Reference Teichert et al.

Key scientific findings

- ➔ Mitigation of water pollution and oxygen depletion yields the largest improvement of ecological status.
- ➔ Non-additive effects represented half of pairwise interactions among stressors.
- ➔ Antagonistic interactions of multi-stressors on fish are widespread in estuaries.

MARS example for ranking the benefits of restoration measures (Figure 17)

Simulations of mitigation			Individual and combined effect		
Stressor A		**Stressor B**	**A**	**B**	**AB**
Water pollution	x	Oxygen depletion	+	+	A
Water pollution	x	Flow changes	+	ns	AD
Water pollution	x	Intertidal area loss	+	ns	AD
Water pollution	x	Dredged sediments	+	+	A
Water pollution	x	Coast urbanisation	+	+	AD
Water pollution	x	Port developement	+	+	AD
Water pollution			+		
Water pollution	x	Fisheries	+	ns	A
Oxygen depletion	x	Intertidal area loss	+	ns	AD
Oxygen depletion	x	Dredged sediments	+	+	A
Oxygen depletion	x	Flow changes	+	ns	S
Oxygen depletion	x	Coast urbanisation	+	+	AD
Oxygen depletion	x	Port developement	+	+	A
Oxygen depletion			+		
Oxygen depletion	x	Fisheries	+	ns	A
Dredged sediments	x	Intertidal area loss	+	ns	A
Dredged sediments	x	Coast urbanisation	+	+	A
Coast urbanisation	x	Intertidal area loss	+	ns	AD
Intertidal area loss	x	Flow changes	ns	ns	S
Dredged sediments	x	Flow changes	+	ns	AD
Dredged sediments	x	Port developement	+	+	AD
Port developement	x	Intertidal area loss	+	ns	A
Dredged sediments			+		
Coast urbanisation	x	Port developement	+	+	AD
Intertidal area loss			ns		
Dredged sediments	x	Fisheries	+	ns	A
Coast urbanisation	x	Flow changes	+	ns	A
Intertidal area loss	x	Fisheries	ns	ns	AD
Coast urbanisation			+		
Coast urbanisation	x	Fisheries	+	ns	AD
Port developement	x	Flow changes	+	ns	A
Flow changes			ns		
Flow changes	x	Fisheries	ns	ns	AD
Port developement			+		
Port developement	x	Fisheries	ns	ns	AD
Fisheries			ns		

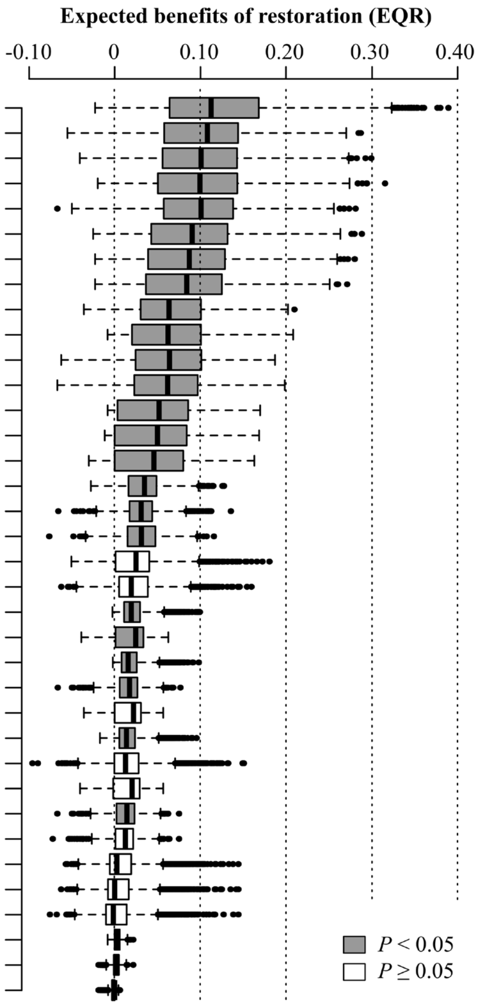


Figure 17: Restoration benefits predicted for individual and combined actions of stressor restoration, as evaluated by the improvement of fish ecological status (Teichert et al., 2016). Individual effect of restoration is presented for each stressor category ('+' positive benefit, 'ns' non-significant benefit). Type of combined effect among stressors is specified for pairwise combinations ('AD' additive effect, 'A' antagonistic interaction, 'S' synergistic interaction). EQR is Ecological Quality Ratio.

Key findings/support for management

- ➔ For antagonistic effects, a step-by-step restoration scheme focusing on the mitigation of stressors providing the maximum of restoration benefits is proposed.
- ➔ Management plans should consider type and strength of interactions to select the most effective combination of mitigation measures and avoid potential disappointments. Combined mitigation of synergistic stressors will provide largest restoration benefits.
- ➔ The largest restoration benefits were expected for mitigating water pollution, oxygen depletion and flow changes.

6.6 Linking process-based and empirical models: predicting impacts of land use and climate change on ecological status of phytoplankton in lakes

Reference

Couture, R. M., Moe, S. J., Lin, Y., Kaste, Ø., Haande, S., & Lyche Solheim, A. (2018). Simulating water quality and ecological status of Lake Vansjø, Norway, under land-use and climate change by linking process-oriented models with a Bayesian network. Science of the Total Environment 621, 713–724.

Introduction

Excess nutrient inputs and climate change are two of multiple stressors affecting many lakes worldwide. Lake Vansjø in southern Norway is one such eutrophic lake impacted by blooms of toxic blue-green algae (cyanobacteria), and classified as moderate ecological status under the EU Water Framework Directive. Future climate change may exacerbate the situation.

Methods

A set of chained models (global climate model, hydrological model, catchment phosphorus (P) model, lake-model, Bayesian Belief Network) was used to assess the impact of combined stressors from land use and climate change on the possible future ecological status of phytoplankton in an eutrophied lowland lake, given a set of climate- and MARS scenarios.

Results

The model simulations indicate that climate change alone will increase precipitation and runoff, and give higher P fluxes to the lake, but cause little increase in phytoplankton biomass or changes in ecological status. For the scenarios of future management and land-use, however, the model results indicate that both the phytoplankton biomass and the lake ecological status can be positively or negatively affected. For all scenarios, cyanobacteria contribute to worsening the status assessed by phytoplankton, compared to using chlorophyll-a alone.

Conclusions

Chaining climate-, hydrologic-, catchment- and lake models is a useful approach to simulate the outcome of climate and land-use changes. The results also show the value of predicting a biological indicator of lake ecological status, in this case cyanobacteria abundance, with a BN model.

Web link

Reference Couture et al.

Key scientific findings

- ➔ A Bayesian Network chained to a lake model allows predicting cyanobacteria biomass (Figure 18).
- ➔ The choice of both, climate model and climate scenario influence the phosphorus loads to the lake.
- ➔ Land use and different management options to reduce the phosphorus loads to the lake (Figure 19: CW, FW, TW) are more important than climate change (Figure 19: BL, 4.5, 8.5) on the probability of achieving good ecological status for phytoplankton.
- ➔ Modelling highlights the need for more data on legacy phosphorus in the catchment soils and also considering the impacts of browning.

MARS example for linking process-based and empirical models (Figure 18 and Figure 19)

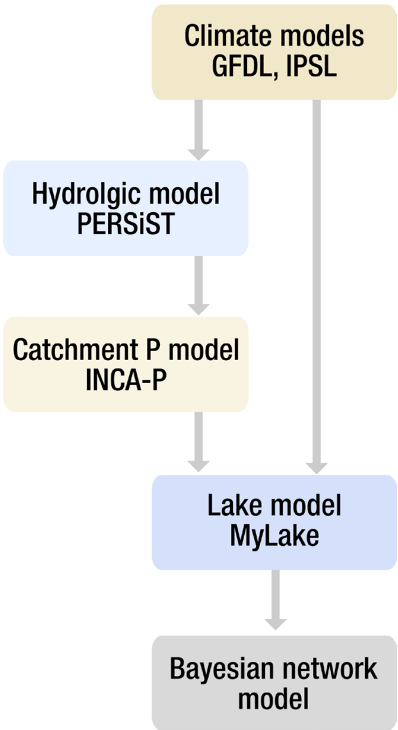


Figure 18: Model chain for predictions of ecological status of phytoplankton in lake Vansjø (from Couture et al., 2018).

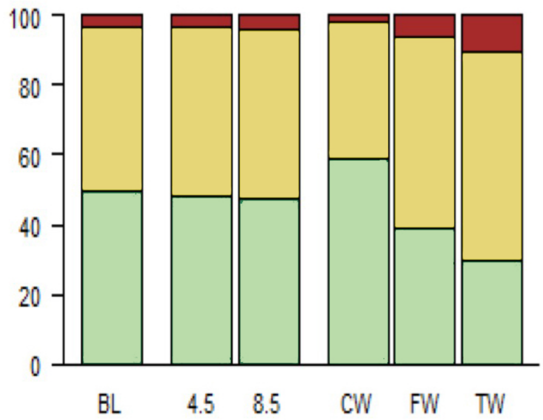


Figure 19: Probability of good or better (green), moderate (yellow) and poor or bad (red) ecological status of phytoplankton in an eutrophied lake Vansjø under different climate change scenarios (BL: baseline, 4.5 and 8.5: climate), and land-use scenarios (CW: Consensus world, W: Fragmented world, TW: Techno-world) (from Couture et al., 2018).

Further readings on Lake Vansjø are also available at the MARS ***Freshwater Information System*** and in a ***Freshwater Blog*** story.

Key findings/support for management

- ➔ Chaining process-based climate-, hydrologic-, catchment- and lake-models with a Bayesian network model using empirical biological data is a useful approach to simulate the outcome of climate and land-use changes on the ecological status.
- ➔ Land-use scenarios largely determine the probability to achieve good ecological status.
- ➔ Nutrient legacies at the river basin and lake scales, and novel stressors of increasing importance (browning) should be considered in further predictions of ecological status of lake phytoplankton.

6.7 Recovery of cultural ecosystem services in restored estuaries

Reference

Pouso, S., M. C. Uyarra, Á. Borja, 2018. The recovery of estuarine quality and the perceived increase of cultural ecosystem services by beach users: A case study from northern Spain. Journal of Environmental Management, 212: 450-461.

Introduction

Little is known about how improvements in bathing waters influences the provision of cultural ecosystem services and human well-being. This study investigated the recovery of cultural ecosystem services (i.e. beach use, bathing waters, recreational fishing) in a historically degraded estuary (Nerbioi, in Northern Spain), which in past 20 years has been restored with a recovery of the ecological status.

Methods

Environmental data and a questionnaire to beach users were used to: 1) assess the evolution of bathing waters status through environmental data; 2) analyse if beach users' perceptions and behaviour has changed over time in accordance with environmental changes registered in the beaches; and 3) inverstigate if there is a correspondence between beach users' perceptions and environmental recovery.

Results

Most respondents perceived an improvement in bathing water quality and linked it to the estuarine sanitation. Nearby beaches are important recreational areas, mainly for local visitors, and water quality improvement was found to be a critical factor for deciding to visit these beaches. Furthermore, most visitors answered that they would not return if water conditions deteriorate. Significant differences existed between beaches, with the most inner beach presenting worse environmental conditions than the other two beaches, matching users' perceptions.

Conclusions

The findings highlight that water sanitation actions are important for the recovery of degraded coastal environments and for the maintenance of ecosystem services. Also, that multidisciplinary research is necessary to better comprehend the links between environmental recovery and the provision of ecosystem services.

Web link
Reference
Pouso et al.

Key scientific findings

➔ Restoration of a long-term degraded system increases ecosystem services.

➔ Long-experience beach users better perceived the recovery of ecosystem services after restoration.

➔ Time- and space-gradients of recovery are perceived by beach users.

➔ The use level of recreational ecosystem services is mediated by the quality of the system.

MARS example for the recovery of cultural ecosystems (Figure 20)

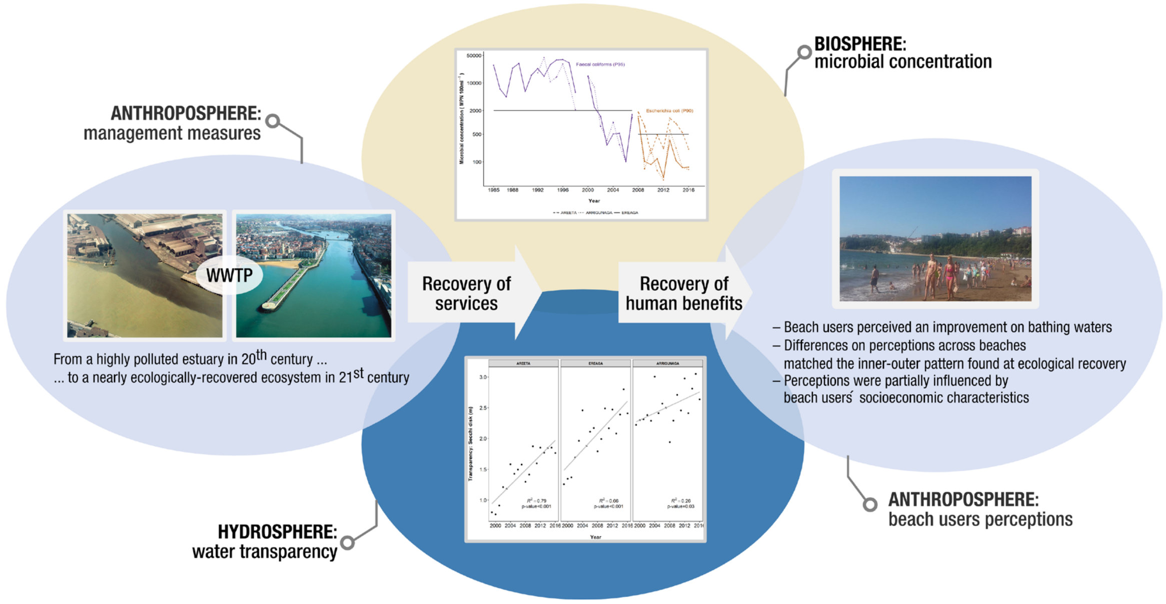


Figure 20: Restoring degraded estuaries results in a recovery of biophysical and ecological elements, which finally increase the delivery of cultural ecosystem services, which is perceived by citizens, changing their perceptions and behaviours accordingly.

Key findings/support for management

- ➔ Policymakers and managers should consider ecological restoration as means to improve ecosystem services provision, especially cultural (i.e. recreational) ones.
- ➔ Raising awareness campaigns on the recovery of ecosystem services will be valued by citizens using them.

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