PROJECT FINAL REPORT

Grant Agreement number: *603378*
Project acronym: *MARS*
Project title:
Managing Aquatic ecosystems and water Resources under multiple Stress
Funding Scheme:
ENV.2013.6.2-1 (Water resources management under complex, multi-stressor conditions)

Period covered: *from 1 February 2014 to 31 January 2018*

Name of the scientific representative of the project's co-ordinator, Title and Organisation:
Prof. Dr. Daniel Hering
Tel: *+49 201 183-3084*
Fax: *+49 201 183-2179*
E-mail: *daniel.hering@uni-due.de*
Project website address: *www.mars-project.eu*

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

Final Report

Edited by

Sebastian Birk & Daniel Hering

Contributors:

Daniel Hering, Sebastian Birk, Erik Jeppesen, Angel Borja, Stefan Schmutz, Vít Kodeš, Steve Ormerod, Jenica Hanganu, Marijn Kuijper, Tom Buijse, Tiina Nõges, Markus Venohr, Ana Cristina Cardoso, Christine Argillier, Meryem Beklioğlu, Laurence Carvalho, Anne Lyche Solheim, Yiannis Panagopoulos, Marko Järvinen, Lidija Globevnik, Teresa Ferreira, Helena Alves, Helena Mühlmann, Jo-Ann Pitt, Edith Hödl, Corina Boscornea

and collaborators

April 2018

Table of contents

1 Executive summary

Water resources globally are affected by a complex mixture of stressors resulting from a range of drivers, including urban and agricultural land use, hydropower generation and climate change. Understanding how stressors interfere and impact upon ecological status and ecosystem services is essential for developing effective River Basin Management Plans and shaping future environmental policy. The EU-funded project MARS (Managing Aquatic ecosystems and water Resources under multiple Stress) addressed the nature of these problems for Europe's water resources and the need to find solutions at a range of spatial scales.

MARS was operating at three scales: At the water body scale, the mechanistic understanding of stressor interactions and their impact upon water resources, ecological status and ecosystem services were examined through multi-factorial experiments and the analysis of long time-series. At the river basin scale, modelling and empirical approaches was adopted to characterise relationships between multiple stressors and ecological responses, functions, services and water resources. The effects of future land use and mitigation scenarios in 16 European river basins have been assessed. At the European scale, large-scale spatial analysis were carried out to identify the relationships amongst stress intensity, ecological status and service provision, with a special focus on large transboundary rivers, lakes and fish. The project offered support to managers and policy makers in the practical implementation of the Water Framework Directive (WFD), of related legislation and of the Blueprint to Safeguard Europe's Water Resources by advising the 3rd River Basin Management Planning cycle, the revision of the WFD and by developing new tools for diagnosing and predicting multiple stressors.

The final report at hand overviews the project's objectives and provides a concise summary of the main scientific results obtained in MARS. It furthermore outlines the potential impact and the main dissemination activities. Given that the project has published about 230 scientific publications, the results presented in this report are necessarily selective and aim at a comprehensive overview of the MARS outcome illustrated by a few examples, which are described in more detail.

2 Summary description of project context and objectives

Europe's water resources and aquatic ecosystems are impacted by multiple stressors, which affect ecological and chemical status, water quantity and ecosystem functions and services. The relevance of multiple stressors differs regionally: in Alpine and upland northern regions hydropower plants have fundamentally changed river and lake hydrology, morphology, sediment transport and connectivity; in lowland areas of Northern and Central Europe intensive agriculture and flood protection are important drivers of degradation, while Mediterranean catchments are impaired by riparian degradation and water scarcity. In addition, climate change increases the risk of floods, erosion and pollution in wet regions and of droughts in water scarce regions.

According to Europe's first River Basin Management Plans (RBMPs), 56 % of European rivers, 44 % of lakes, 25 % of groundwater bodies and 70 % of transitional waters failed to achieve the good status targets of the Water Framework Directive (WFD) (EEA, 2012). There are, however, strong regional differences: in some Eastern European countries such as Estonia or Slovakia more than two thirds of river water bodies are in high or good status, while in Central European countries such as Belgium, the Netherlands and Germany more than 80% failed to achieve the WFD quality targets. The reasons are manifold. The EEA (2012) report lists the most important pressures impacting individual water categories: only 19 % of water bodies were not significantly impacted, while two pressures prevail: diffuse pollution (rivers: 45 %, lakes: >30 %) and hydromorphological degradation (rivers: >40 %, lakes: >30 %). Viewed in more detail, both diffuse pollution and hydromorphological degradation are composed of several individual components with complex interactions. Diffuse pollution mainly refers to increased nutrient loads and associated eutrophication effects, often in conjunction with fine sediment and pesticides. Hydromorphological degradation is an even more vague term, including hydrological stress from low flows and water abstraction, flash floods, and morphological stress from barriers, straightening, bank fixation, removal of riparian vegetation and subsequent increase of water temperatures (ETC-ICM, 2012).

From this evidence, it is apparent that the causes of degradation of Europe's waters are manifold and complex. While single stressors such as strong organic pollution or acidification are declining, Europe's water bodies and water resources are now affected by a complex mixture of stressors resulting from urban and agricultural land use, water power generation and climate change. Although the Programmes of Measures (PoMs) included in the RBMPs should reduce stressors and improve water body status, their potential to address increasingly complex, multiple stress situations is limited by current knowledge. In the first RBMPs, there was a strong focus on measures targeting single pressures such as point-source pollution or river continuity (Kail & Wolter, 2011). Under conditions of multiple stress, however, restoration actions may also initiate complex cause-effect chains of recovery, which are poorly understood (Feld et al., 2011).

Overall, the first RBMPs had several problems:

- Programmes of Measures are often decoupled from ecological assessment.
- Although the majority of European water bodies are affected by more than one stressor, little is known about their combined effects.
- For multiple-stress situations, simple dose-response relationships between stress intensity and biological effects based on empirical data are not sufficient for developing appropriate management measures. There is a need for improved process understanding of how multiple stressors affect degradation and restoration.
- Besides the existing tools to *assess* water body status, tools are needed to prioritise measures and to *predict* ecological status following restoration.
- The implementation of measures requires convincing arguments beyond the concept of ecological status, whose value is difficult for the public and policy makers to understand. Supplementary indicators targeting ecosystem functions, ecosystem services and human benefits are required.

Yet, there is no summarising evaluation of the second RBMPs available, but the above-mentioned problems are obstacles for the successful implementation of the WFD. The review of the WFD in 2019 offers a unique opportunity to advance the conceptual basis underlying the WFD. Major challenges for water resource management have emerged since the ratification of the WFD in 2000: New stressor combinations, including climate change, new pollutants, emerging pathogens and exploitation of the sub-surface for alternative forms of energy; more intense land use due to increased food prices and demand for biofuel; and increasingly diverging targets for food production, energy generation, water resource protection and biodiversity protection.

The WFD is the core of Europe's water policy, but there are several other relevant directives with manifold (and sometimes contrasting) approaches and targets. These include the Urban Waste Water Treatment Directive (91/271/EEC), the Nitrates Directive (91/676/EEC), the Marine Strategy Framework Directive (2008/56/EC), the Habitats Directive (92/43/EEC), the Flood Risk Management Directive (2007/60/EC), the Strategy on Water Scarcity and Drought and the White Paper on Adaptation to Climate Change. The implementation of these policies to protect Europe's water resources strongly interacts with other policy domains, such as the Renewable Energy Directive (2009/28/EC) and in particular with the Common Agricultural Policy. The Fitness Check of EU Freshwater Policy outlined the strength of the current legislative framework, but also exposes conflicts with other EU policies and the weaknesses in its implementation. Problems identified include the incorporation of water quantity issues into RBMPs, including the definition of ecological flows, land use impacts in particular from agriculture, translation of the ecosystem services concept into practice, and insufficient dissemination and sharing of data. Implicit in all these issues is the need to address multiple stressors.

The Blueprint to Safeguard Europe's Water Resources described 39 actions to strengthen the implementation of Europe's water policies. Key among them are land use and ecological status, chemical status and pollution of EU waters, water efficiency, vulnerability of EU waters, the need for cross-cutting problem solving and global aspects. Overall, the Blueprint provided a realistic assessment of achievements and problems of European water management and embeds Europe's water policy into a wider political context. As with the Fitness Check, it identifies complex stressors resulting from intense land-use and over-abstraction as key problems, and outlines solutions possible through other policy fields such as the Common Agricultural Policy. According to the Blueprint, the Common Implementation Strategy (CIS) of the WFD ensures its prominent role for European water policies.

To address the new challenges in implementing the Blueprint and the WFD, new, modernised and often simplified tools (e.g. indicators, scenarios, models) are required. Key needs are i) to accommodate regionally contrasting stressor combinations; ii) address the spatial scales over which stressors operate and management is undertaken; iii) diagnose impacts of multiple stressors on water body status, water resources and ecosystem services; and iv) provide advice on the most appropriate mitigation measures given the timescales for achieving the environmental objectives. These need to be implemented within the four main activities, on which European water management is based:

River Basin Management Planning: The over-arching framework for risk assessment, status assessment, economic assessment and stakeholder engagement in water resource management is provided by River Basin Management Plans under the WFD. It incorporates risk assessment and characterisation, monitoring of robust indicators for status assessment and stakeholder engagement with the economic assessment of management options. Integrated water resource management is often best exemplified at a local water body scale, where competing demands of different users and stakeholders can be communicated and managed effectively. However, conflicts can still exist between users and services across a catchment; therefore, management of floods, environmental flows and of restoration is often best coordinated at the river basin scale. Despite the obvious strengths of the RBMP concept, and though most RBMPs fulfil the requirements of the WFD from a formal point of view, in reality many plans are vague in defining measures. Multiple-stressors make it particularly difficult to diagnose causes of deterioration and decide upon the best management options. For example, climate change was not considered in the first RBMPs at all, and many water bodies were not assessed fully or require further investigation to identify how causes of degradation interact.

Status assessment: The WFD has been very successful in indicator development for status assessment of surface waters (e.g. Hering et al., 2013) and to a lesser extent of groundwaters. Research has predominantly examined the effects of individual stressors on various static biological indicators (Birk et al., 2012). WFD status assessments integrate these indicators through the one-out-all-out principle lacking a holistic vision of what individual indicators represent and how they could potentially be used for more integrated assessments of ecosystem health, functioning and resilience in response to multiple stressor interactions (Hering et al., 2010). Additionally, robust indicators of freshwater and coastal ecosystem processes and related services are lacking, as is the establishment of effective indicators for groundwater. At the same time, the development of new indicator types for monitoring stressors, status and ecosystem health is an active area of innovation, including biomarkers of stress, genetic methods (high throughput bar-coding and gene expression in relation to stressors), ecosystem metabolism and remote sensing tools. Review and testing of these new approaches is needed to determine whether they could substitute or complement the classical indicator types. To be widely applicable, they need to be reviewed and tested in the context of ecological status and ecosystem services.

Risk assessment: Recent approaches are well established for single toxic chemicals (Crane et al., 2006), drought and flood management (Prudhomme et al., 2003), and for predicting the spread of invasive species in relation to climate change (Leung et al., 2002). Risk assessment tools have also been developed for application in RBMPs, to assess risks of failure to achieve good status (Duethmann et al., 2009), to decide on mitigation strategies, and evaluate risks faced by water service providers or potential harm from water management actions (e.g. dam building or river restoration). Compared to the wide variety of existing indicators for status assessment, the capabilities to predict ecosystem responses to stress, to restoration or more generally to alternative management measures is underdeveloped. In particular, greater knowledge is needed on exposures to multiple stressors, stressor interactions (synergistic, additive or antagonistic effects), and the sensitivity to stress combinations. Such interactions have only been described in detail for few stressor combinations, e.g. the impact of climate warming and eutrophication in shallow lakes on selected organism groups (Jeppesen et al., 2007). Mechanistic understanding of the effects of multiple stressors on ecosystem functioning and services was rudimentary and obstacle for more integrated risk assessment and for effective mitigation and restoration.

Valuation of ecosystem services: There is an implicit need to include ecosystem services into River Basin Management Planning, particularly in the economic analysis of water use and in the design of the Programmes of Measures. Ecosystem services provided by surface water bodies (rivers, lakes and estuaries) and to a lesser degree by groundwater bodies include provisioning services (e.g. water supply, food from fish farms, energy from hydroelectric power generation), regulating services (e.g. flood and drought regulation, climate regulation through carbon sequestration, water purification), supporting services (e.g. biodiversity, dispersal of matter, organisms and energy, nutrient cycling) and cultural services (e.g. recreation such as angling and water sports, tourism, and inspiration for arts and religion). The development of indicators specifically targeting ecosystem services could greatly benefit from the experience of using WFD indicators for ecological status (e.g. Carvalho et al., 2013), resulting in a more coherent, integrated and applicable suite of indicators in advance of the WFD review in 2019.

While these four activities are implicitly connected, their linkages have rarely been put into practise.

Against this background, MARS supported water managers and policy makers at the water body, river basin and European scales in the practical and modernised implementation of the WFD, taking account of related legislation, by:

- Conducting new research and syntheses of existing knowledge concerning the effects and management of multiple stressors on surface water and groundwater bodies;
- Advising the 3rd RBMP cycle and the revision of the WFD on integrating new indicator types to diagnose and predict changes in ecological status, ecosystem services and water quantity;
- Developing and improving integrated tools to support decision making in Programmes of Measures to mitigate the effects of multiple stressors on water resources. These management tools are based on an enhanced process understanding and on quantified links between the status of water systems and ecosystem services, thus contributing to the toolbox proposed in the 'Blueprint to Safeguard Europe's Water Resources'.

Our specific objectives at the three different scales were:

- At the water body scale, to enhance the mechanistic understanding of how stressors interact and impact upon water resources, status and ecosystem services, and identify threshold responses to optimise stress reductions. We address stressor combinations and response variables characteristic for major European regions. A focus is on the effect of extreme climate events such as heavy rainfall, heatwaves as well as water scarcity and the effects of environmental flows.
- At the river basin scale, to characterise relationships between multiple stressors and ecological responses, functions, services and water resources, and assess the effects of future land use and mitigation scenarios. Work in 16 river basins in Europe, chosen to represent a wide range of multiple stress conditions, focuses on water scarcity and flow alterations (Southern Europe); hydrology, morphology and nutrient alterations (Central Europe); and hydrology and temperature alterations (Northern Europe).
- At the European scale, to identify the relationships among stress intensity, status and service provision, with a special focus on large transboundary rivers, lakes and fish as sentinels of multiple stressor impacts on biodiversity and direct providers of ecosystem services.

Finally, we aimed at combining the newly generated information at the different scales with existing knowledge in the form of information systems, diagnostic and predictive tools and guidances, applicable at the three spatial scales.

3 Description of the main S&T results/foregrounds

This chapter provides a concise summary of the main scientific results obtained in the project. Its structure follows the project's design into tasks and workpackages. Most of the contents has been taken from the three periodic reports delivered over the course of the project. Given that MARS has published about 230 scientific publications, the results presented below are necessarily selective and aim at a comprehensive overview of the MARS outcome illustrated by a few examples, which are described in more detail. The results of Workpackage 8, which dealt with dissemination, are describe in Chapter 4.

3.1 Multiple stressor framework (Workpackage 2)

The multiple stressor framework defined the concepts, knowledge base and methodologies for the entire project. It reviewed the dose-response relationships between multiple stressors, ecosystem status and ecosystem services from the literature and on-going projects. It specified the project's overall concepts and methodologies for assessment and valuation of ecosystem services and for benchmark and diagnostic indicators. Finally, it was responsible for the overall data flow within the project and the scenario selection to be used in the project.

Review of multistressor-impact relationships

We reviewed 219 papers and built an inventory of 532 items of ecological evidence on multiple stressor impacts in rivers, lakes, transitional and coastal waters, as well as groundwaters. Our review revealed that, despite the existence of a huge conceptual knowledge base in aquatic ecology, few studies actually provide quantitative evidence on multi-stress effects. Nutrient stress was involved in 71 % to 98 % of multi-stress situations in the three types of surface water environments, and in 42 % of those in groundwaters (Figure 3.1). However, their impact manifested differently along the groundwater–river–lake–transitional–coastal continuum, mainly determined by the different hydromorphological features of these ecosystems. The reviewed papers addressed two-stressor combinations most frequently (42 %), corresponding with the actual status-quo of pressures acting on European surface waters as reported by the Member States in the WISE WFD Database. Across all biological groups analysed, higher explanatory power of the stress-effect models was discernible for lakes under multi-stressor compared to single stressor conditions, while these relationships were lower for coastal and transitional waters. Across all aquatic environments, the explanatory power of stress-effect models for fish increased when multi-stressor conditions were taken into account in the analysis, qualifying this organism group as a useful indicator of multi-stress effects. In contrast, the explanatory power of models using benthic flora decreased under conditions of multiple stress (Nõges et al., 2016).

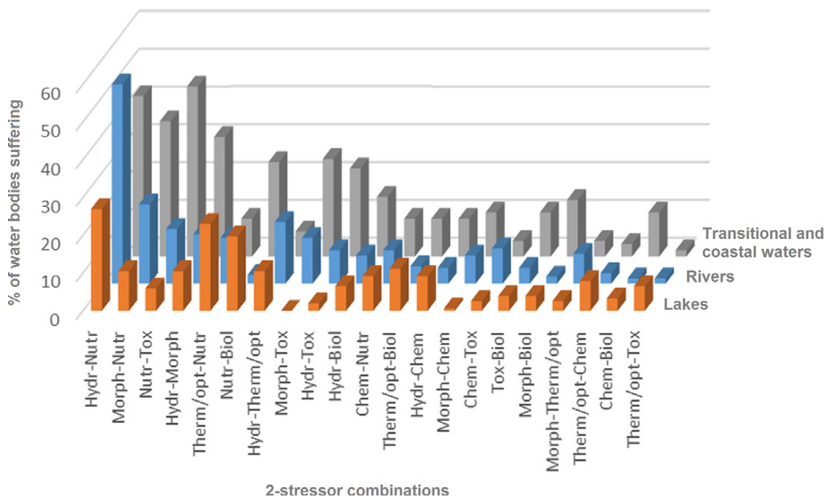


Figure 3.1: Frequency of two-stressor combinations occurring at different water categories as reported by the scientific literature.

Methodology for ecosystem service assessment and valuation

We developed a methodological framework for the biophysical assessment and the economic valuation of water ecosystem services at the water body, the catchment and the European scale. It suits the intent of understanding how changes in pressures may affect the delivery and the value of these services. To this end, we integrated the existing knowledge from literature review and on-going research activities with experience and needs of the partners of the MARS project. We prepared a guideline document that (i) discusses the concepts of ecosystem services and their integrated assessment and valuation, (ii) presents the results of the consultation of the project partners, and (iii) exposes in a concise and practical way the approach and methodologies proposed (including biophysical and economic methods) to assess and value water ecosystem services. The methodological framework links the assessment and valuation of water ecosystem services to the ecosystem status and to the analysis of impacts of pressures at different spatial scales (water body, catchment and European scale). The final report provides guideline methodology for the assessment of ecosystem services in the MARS project, but it is also relevant for the scientific debate in the field of water ecosystem services.

Identification of benchmark indicators

To allow for a streamlined analysis of multi-stressor effects across the different spatial scales and environmental conditions targeted in MARS, we selected 'benchmark indicators'. These indicators mainly address ecological status and ecosystem services. Based on questionnaires circulated to the MARS partners we concluded on a list of 15 indicators that meet pre-defined selection criteria and were considered meaningful and practicable by the responders. Most of the indicators represented 'classical' state indicators applied in WFD-related water management, some of which also cover abiotic state variables acting as direct pressures impacting on the biological state (e.g. total phosphorus concentration). In addition, two impact indicators were selected (toxic/nuisance phytoplankton, commercially-relevant fish).

The benchmark indicators mainly comprised simple metrics and indices of abiotic and biotic ecosystem properties, covering physico-chemical, hydrological and riparian features of the water body and selected attributes of its biological community. The proposed indicators are known to respond to anthropogenic pressure. They are applicable in various geographical contexts and to different water categories and types of water bodies. They generally do not require acquisition of specific data but refer to data already available. Most the benchmark indicators represented conventional (and approved) measures of single ecosystem properties. The selection of benchmark indicators was meant to support the research for novel indicators by covering a broad range of relevant ecosystem properties, allowing for the linkage of abiotic and biotic indicators, or indicators of different trophic levels; or relating state and impact indicators.

Data management/data flow

The metadata delivery supervised in the data management task resulted in the online release of the 19 MARS datasets, so that all MARS catchment data are now visible in the Freshwater Metadatabase and are openly available to other interested scientists for future re-use of data. Based on the willingness of data compilers these information were published in ten articles of the Freshwater Metadata Journal. The publication efforts contribute to the sustainable availability of MARS dataset characteristics. Data management also entailed the linkages of MARS products with the Freshwater Information Platform (www.freshwaterplatform.eu) – a sustainable dissemination outlet for freshwater related research – to guarantee a high degree of visibility of these tools. This relates to the MARS Freshwater Information System, MARS Diagnostic Tool and MARS Scenario Analysis Tool.

Definition of future scenarios

Various future climatic and socio-economic scenarios have been chosen within MARS to define three storylines describing the future of Europe. Each storyline framed the conditions leading to certain combinations of drivers and pressures for Europe. Based on the latest versions of the Shared Socioeconomic Pathways and the Representative Concentration Pathways, the combinations SSP5 and RCP8.5, SSP3 and RCP8.5 and SSP2 and RCP4.5 were selected as starting points through a participatory process. With this base and the objectives of MARS in mind, three storylines were defined to be used throughout MARS (Figure 3.2): *Techno World*, *Consensus World* and *Fragmented World*. The three defined storylines differ mainly in four main aspects; main drivers in the economy, economic growth, policies regarding the environment, and public concern about the environment and protection of ecosystem services.

Figure 3.2: Features of the three storylines developed in MARS.

The aim was to assess the possibility of extracting suitable quantitative values for the parameters and variables required as input data for the models. The required data included principally climate and socio-economic data for each MARS scenario. The focus was put on defining data for the European scale models, which in many cases coincide with those necessary at the river basin scale. Data were extracted from the repositories of the projects/modelling tools *ISI-MIP*, *SCENES*, *BASE* and *CLIMSAVE*, including comparison and approximation to allow for implementing the data into the MARS scenarios. The result was a suite of quantitative values for diverse parameters and variables on grid or vector format, which range from daily to yearly time steps and

5 by 5 arc minute to 0.5° by 0.5° spatial resolution, that are readily available for the MARS modelling partners. Given that different climate models provide climate data with severe differences for the scenarios, we selected the datasets created by two climate models to be used as input data for the MARS models. The selection was done based on the median accumulated precipitation generated by the climate models. Those climate models giving the least extreme values were chosen to be used for the European and catchment modelling.

Deliverables

The main results of WP2 are documented in the following deliverables:

- D2.1-1 *Four manuscripts on the multiple stressor framework:* Review of multiple stressors and their effects on European surface waters
- D2.1-2 *Four manuscripts on the multiple stressor framework:* Cook-book for ecosystem service assessment and valuation in European water resource management
- D2.1-3 *Four manuscripts on the multiple stressor framework:* Framework to select indicators of multistressor effects for European river basin management
- D2.1-4 *Four manuscripts on the multiple stressor framework:* Report on the MARS scenarios of future changes in drivers and pressures with respect to Europe's water resources

3.2 Multiple stressors at the water body scale (Workpackage 3)

The water body scale, we performed manipulative multifactorial experiments addressing various climate-related extremes in multiple-stressor contexts, combined with time-series analyses from rivers and lakes in Europe, including data from lake sediment records. There were three mesocosm experiments focussing on shallow and deep lakes (Figure 3.3), and four coordinated flume experiments in northern, Central European and Mediterranean rivers (Figure 3.5).

Lake experiments: Extreme rainfall

The UK experiment on temperature, rainfall and eutrophication started in July 2014 and ran for one year. In 32 mesocosms situated in north-west England, we investigated the response of various parameters on warming (ambient and +4°C), nutrient addition (no addition and high nitrate and phosphate addition) and simulated extreme rainfall events (every three months) – eight different treatments with four replicates each. The experiment was finished in July 2015.

Phytoplankton and cyanobacteria biovolume both increased with warming and increased with nutrient addition, as expected. However, the combination of the two stressors revealed an antagonistic (negative) interaction. Extreme rainfall events resulted in plankton losses, however only short-lived, suggesting that one-off events like our twelve-weekly 'flooding' are unlikely to reduce algal blooms in highly productive systems. Toxin analysis revealed increased microcystin concentrations with warming as well as nutrient addition.

The stress response in fish was measured via determination of cortisol levels during extreme rainfall events. Cortisol levels increased during the simulated rainfall events in some of the treatments already experiencing high pH and algal abundance, exacerbated the impact of an additional stressor upon the fish.

Samples from the experiment were also used to further improve a spectroscopic model for measuring dissolved organic matter (DOM). This model previously underestimated DOM derived from algae. New extinction coefficients were introduced to the model to allow the contribution of algae-derived DOM to dissolved organic carbon in surface water sample to be estimated.

Figure 3.3: The MARS lake mesocosm facilities in UK [left], Denmark [middle] and Germany [right].

Lake experiments: Extreme heatwaves

The Danish experiment on the effect of an extreme one-month heatwave in mesocosms adapted for eleven years to contrasting nutrient and temperature conditions started in June 2014 and ran to the end of December 2014. In 24 mesocosms, we investigated the response of various parameters to an extreme heatwave (+5°C) on top of an already enhanced temperature representing the IPCC A2 scenario and A2+50%, run at low and high nutrient inputs (flow-through system with two-month retention time, four replicates of each treatment).

Analysing changes in phytoplankton assemblages and zooplankton biovolumes revealed that during heat waves the total phytoplankton biovolume significantly increased with temperature, especially in the A2+50% scenario under low nutrient conditions. Nutrients had a strongly significant effect on cyanobacteria in all periods. During the heat wave, the interaction effect of nutrients and the A2+50% scenario had a positive effect on the cyanobacteria biovolume. Chlorophyta biovolumes significantly increased in low nutrient treatments during and after the heat wave periods, while it decreased in high nutrient treatments, especially when coupled with A2+50%.

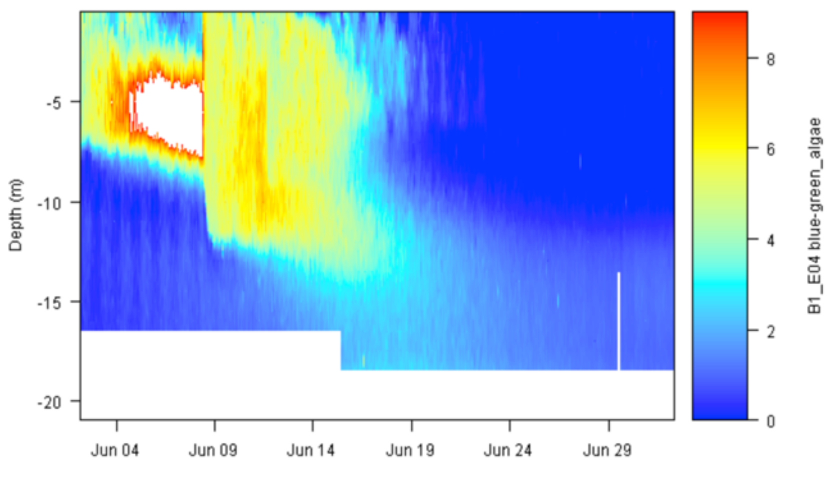
Analysing the microbial loop (bacteria, heterotrophic flagellates, ciliates) revealed that changes in water temperature within a few days induced a strong effect on the microbial loop functioning, demonstrating a quick response of microbial communities to the changes in environment, due to their short generation times. Warming and nutrients showed synergistic effects. All microbial assemblages responded positively to the heating, the abundances of bacteria, heterotrophic nanoflagellates and ciliates increased in quite a similar way, the increase being largest in the enriched mesocosms. The results indicate that warming and nutrients in combination can set off complex interactions in the microbial loop functioning.

In addition, we have measured the greenhouse gas exchange between water and air before, during and after the heatwave (June, July and August, respectively). The heat wave significantly increased the emission of greenhouse gases. However, besides the direct response of metabolic processes to the increasing temperature, biotic interactions were also important controllers of greenhouse gas emissions. Hence, a decline in primary producers (abundance of submerged macrophytes cover or phytoplankton) led to an increase in emissions. Mesocosms with high nutrient status were lower emitters of CO_2 and CH_4, while N_2O emissions did not differ significantly between low and high nutrient mesocosms.

Furthermore, growth of periphyton on artificial substrate was studied, showing that increased nutrient and temperature levels resulted in increased total biovolume, higher percentage of cyanobacteria and low percentage of diatoms, potentially also changing species composition.

Lake experiments: Nutrients, DOM loading and extreme mixing

The mesocosm experiment in north-eastern Germany was run from June to September 2015. The aim was to assess the ecological impacts of nutrient enrichment and loading with humic substances (DOM), as well as extreme mixing simulating the effect of increased frequency of major wind events. The assessment of impacts of these multiple stressors focused on responses of cyanobacteria and other phytoplankton to multiple stressors but included an array of additional variables. The experiment was conducted in 21 large enclosures situated in a deep stratified clear-water lake, Lake Stechlin, in north-eastern Germany (http://www.lake-lab.de). The enclosures are 9 m in diameter and extend from the water surface into the lake sediment at ca. 20 m depth.



Browning had a huge effect on phytoplankton, rapidly reducing both its total biomass and the relative proportion of cyanobacteria (Figure 3.4). These effects were most probably due to light limitation and strong absorption of blue light by the humic substances. The chlorophytes decreased in the brown compared to the clear control mesocosms, whereas the proportion of cryptophytes increased, possibly because of their mixotrophic life-style. These changes in the phytoplankton community suggest that the humic substances caused a shift from an autotrophic to a more heterotrophic food web.

Figure 3.4: Cyanobacteria biomass estimated from fluorescence measurements in the mesocosm with medium addition of humic substances. This mesocosm received no extra nutrients.

Nutrient effects were less clear, probably because of top-down control by dense zooplankton populations developing in the absence of fish predation. However, nutrients were also lost to the periphyton growing on the walls of the mesocosms, although these were partly removed weekly throughout the whole experiment. It is also conceivable that phytoplankton cells stored nutrients internally.

Mixing of the water column below the thermocline (deep mixing) appeared to have slightly increased phytoplankton biomass in the nutrient-enriched enclosures without humic substances. However, opposite responses were found in the enclosures with medium and high levels of humic substances. This pattern may be caused by upwelling of dissolved nutrients in the clear enclosures and strong light limitation in the humic enclosures.

A message to water managers would be that the on-going browning of lakes all over Northern Europe may not increase cyanobacterial blooms. More frequent strong wind events causing deep mixing of the water column might have clear negative effects by increasing phytoplankton biomass in clear, stratified eutrophic lakes, whereas in humic lakes the response could well be opposite.

River experiments: Extreme flows in Nordic rivers

The flumes were located at Sagelva (63.135° N, 9.853° E), a stream near Trondheim, Norway. We constructed four metal flumes, each 4 m long and 32 cm wide, that were equipped with water delivery containers with large diameter taps allowing for separate manipulation of water flow in each flume. The multi-stressor experiments were run in August/September 2015, studying the combined effects of flow and nutrient enrichment.

Figure 3.5: The MARS flume channel facilities in Norway [left], Austria [middle] and Denmark [right].

As single stressors, nutrient addition and an increased flow velocity from 1.3 to 2.8 cm s^{-1} lead to an increase in the biomass of benthic algae, likely reflecting an improved transfer of nutrients into algal patches. However, the combined effect of flow and nutrient addition was smaller than the sum of both individual effects, likely because an increased biomass also was more susceptible to scouring, i.e. antagonistic interactions were observed between nutrients and flow for total chlorophyll a, diatoms and cyanobacteria.

We found substantial differences in macroinvertebrate and benthic algal taxon identity and abundance between the nearby stream, from which the flumes were supplied with water, and the flumes. Since biodiversity is assumed to stabilize ecological functioning in response to disturbances and variation, we suggest that care should be taken in applying results from small scale experiments to stream ecosystems.

River experiments: Peak flows in Alpine rivers

The experiments focussed on the effects of hydropeaking, in combination with thermopeaking, nutrient increase and alterations of channel morphology.

Algae: The effect of hydropeaking and nutrient enrichment on periphytic algae development showed that a significantly lower periphytic biomass development (expressed as chlorophyll a) in a later successional stage (Day 33) in the hydropeaking treatment compared with the no-hydropeaking treatment. Nutrient subsidy effects were not observed, because the biomass development was highly diminished through the pulsed flow velocity increase. Also, a negative synergistic interaction was observed. Our study confirmed that for different algal groups and functional guilds the same multiple stressor combination can be detrimental to one species group while beneficial for another. The interactions of hydropeaking and nutrient enrichment discriminate against large-celled taxa (e.g. filamentous green algae) and provide colonization space for smaller, tightly adhering taxa (e.g. diatoms) that are more resistant to velocity shear.

Macroinvertebrates: Drift experiments indicate significant differences between macroinvertebrate drifting behaviour in response to hydropeaking, thermopeaking, season and time of day. Drifting behaviour was highest where only hydropeaking was simulated and was lower under combined hydropeaking-thermopeaking (warm and cold) conditions, indicating antagonistic effects. Drifting behaviour was highest at night, as well as in June, and significantly higher than the drifting behaviour of macroinvertebrates in the control experiments under constant flow conditions. Other experimental results suggest that increased upramping rates (speed of water level increase) can lead to increased macroinvertebrate drift. However, these effects were only measurable in periods when drift was generally high (June and night). Responses to hydropeaking were also generally taxa-specific. Taxa likely to drift tended to be swimming taxa and surface dwelling taxa with small body sizes as well as cased caddisflies.

Fish: We conducted experiments on larval and juvenile graylings (*Thymallus thymallus*), simulating a single hydropeaking event and a control scenario without hydrological alteration. Our results showed a significant difference of drift-rates between the two scenarios resulting in higher drift-rates during phases of increasing discharge. Furthermore, we could confirm previous results showing a negative correlation between drift-rates and fish age and upramping rate, respectively. Video capturing during experimental executions enabled observations of individual fish behaviour.

The next set of experiments dealt with the influence of lateral gravel bar slope and the time of the day on drift and stranding of young graylings and brown trout (*Salmo trutta*) caused by hydropeaking. Results for the grayling showed that neither time of day nor lateral gravel bank slope had a significant influence on drift rates during a single peak event. Stranding rates increased significantly during night-time events with a slight decrease of stranding for peaking events on a steeper slope. Compared to that, results for experiments with brown trout showed that bank slope had a significant impact on the stranding risk. Drift rates were not influenced by the lateral slope, whereas drift during the night-time experiments was slightly increased compared with the day-time experiments.

River experiments: Water scarcity in Mediterranean rivers

Macroinvertebrates: The study focused on the response of macroinvertebrates by drift to single and combined effects of water scarcity and dissolved oxygen (DO) depletion over two seasons. Results showed that both stressors individually and their interaction had a significant effect on macroinvertebrate drift rate, for both seasons. Single stressors effects showed that macroinvertebrate drift ratio significantly decreased with flow velocity reduction and increased with the highest DO depletion, in both winter and spring experiments. Despite single stressors opposing effects in drift ratio, combined stressors interaction (vL x dM and vL x dH) induced a positive synergistic drift effect for both seasons, but the drift ratio was different between the levels of DO depletion only in winter. Water scarcity seems to exacerbate the oxygen depletion conditions, resulting in greater drifting of invertebrates. We suggest that the potential effects of oxygen depletion should be evaluated when addressing the impacts of water scarcity on river ecosystems, since flow reductions will contribute to a higher oxygen deficit, particularly in Mediterranean rivers.

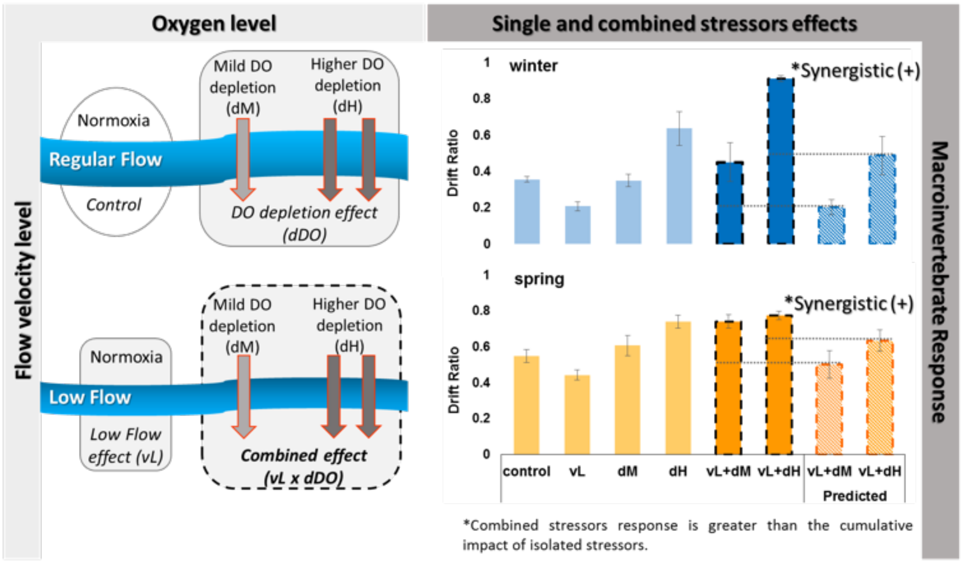


Figure 3.6: Combined effects of water scarcity and oxygen depletion on macroinvertebrate drift ratio.

Fish: The goal of this study was to assess the responses of potamodromous fish facing combinations of (1) a primary stressor (two levels of connectivity reduction due to water scarcity), and (2) a secondary stressor (three levels of oxygen depletion due to increased organic load of anthropogenic origin). Both stressors and their interaction had a significant effect on fish behaviour expressed as upstream, downstream and total number of movements. At the unconnected level, the primary stressor (lack of connectivity) overrode the effect of the secondary stressor (oxygen depletion), but when connectivity existed oxygen depletion caused a reduction of fish movements with decreasing oxygen concentrations. The interaction of combined stressors induced a negative synergistic classification. This multifactorial study contributed to improved prediction of fish responses upon actual or projected pressure scenarios.

River experiments: Low flow in Nordic rivers

Two years of channel experiments were performed in Danish streams, conducted in twelve large outdoor flumes with a sequence of riffle and run habitats. We investigated the effect of three stressors and their combinations (low flow, fine sedimentation and nutrient enrichment) on the ecosystem structure, represented by three stream compartments: Benthic algae, benthic macroinvertebrates and hyphomycetes / benthic fungi.

Concerning the benthic algae, we found strong responses of the benthic algae trait composition to the stressors, which was mainly due to effects of low flow and fine sedimentation. Here, motile species reacted positively to the treatments, whereas all other traits did not react or revealed a negative response. Within the same study, we showed that the algal biovolume strongly reacted to low flow and to fine sedimentation. Concerning benthic macroinvertebrates and fungi, we found clear responses of the macroinvertebrate community to the multiple stressors; here, low flow and fine sedimentation were the most pervasive stressors.

In addition to ecosystem structure, we investigated the reaction of important stream ecosystem functions to multiple stress: Benthic primary production and benthic organic matter degradation. The data on benthic net-primary production shows an increase with nutrient enrichment during low flow and low values with fine sedimentation. Therefore, fine sedimentation affects this in addition to benthic algae trait composition. We found that the degradation of organic matter (beech leaves) also followed clear stress-dependent patterns with fine sedimentation strongly reducing it.

Times series analyses

The analysis of 35+ years data collected from rivers across Wales showed that there is clear chemical recovery from acidification stress, chemical recovery has been matched by the partial recovery of some acid-sensitive invertebrate taxa; but whole community recovery is still only partial or incomplete. A key implication is that recovery from this large-scale stressor is not a straightforward reversal of acidification effects. Further analysis including climate data showed how ecological attributes such as abundance and trait character affect responses to climatic fluctuation, although such effects appear to weaken during more intense periods of climatic change or fluctuation. Understanding aggregate water-body responses to multiple stressors therefore requires cognizance of such biological factors.

A study of a 20 years' data series from two inter-connected Anatolian lakes – Lakes Mogan and Eymir, earlier subjected to sewage input followed by a restoration– was conducted. The results highlight that the recovery of lakes after a nutrient loading reduction and biomanipulation may be complicated by hydrological conditions. Furthermore, the on-going global climate change is predicted to lead to even more frequent and intensive droughts that may complicate the recovery efforts. Hence, it is concluded that hydrological process should be considered when introducing management measures in freshwater ecosystems.

Sediment cores, covering the last 50-100 years, were taken from littoral and pelagic locations of three large shallow lakes: Lakes Beyşehir, Marmara and Uluabat located in the semi-dry warm to hot Mediterranean climate zone in Turkey. The geochemical and physical proxies indicated longer-term (decadal) pronounced water level changes; however, short-term (1–10 years) water level changes were almost not discernible in the cores. During low water level periods, both lakes became more turbid, probably owing to wind-induced sediment resuspension, especially during low water level periods due to the wide open large surface area of the lakes as well as eutrophication.

A two-decade (1989–2008) time series of lake phyto- and zooplankton, water characteristics and climate in 17 Danish lakes was analysed to elucidate the long-term changes and the effects of lake restoration efforts and climate warming. The analyses of pair-wise correlations across time series revealed a strong synchrony in climatic variables, with a significant increase in air temperature and a weaker synchrony for the physico-chemical variables. Synchrony in lake chemistry and the taxonomic richness of the plankton groups and phytoplankton biomass was apparent, most pronounced for the lakes with a significant and strong negative trend in their TP concentrations. Phytoplankton biomass decreased and plankton richness increased in these lakes.

In Lake Võrtsjärv, a large and shallow eutrophic lake in Estonia, we analysed > 30 year data on biota, fish catches, hydrochemistry, hydrology, and meteorology. The study showed that fish impacts down the food chain were often non-stationary depending on the abundance of fish size groups and catch intensities (Figure 3.7). Adding here the numerous positive and negative feedbacks existing between ecosystem components, creates a seemingly stochastic pattern easily masking the important players in the game. New insights into the potential role of cyanobacteria in the grazing food chain and into fish and fisheries impact on lower trophic levels gained in this study will hopefully ease the future application of an ecosystem model for more in-depth investigation of the cascading effects in this lake.

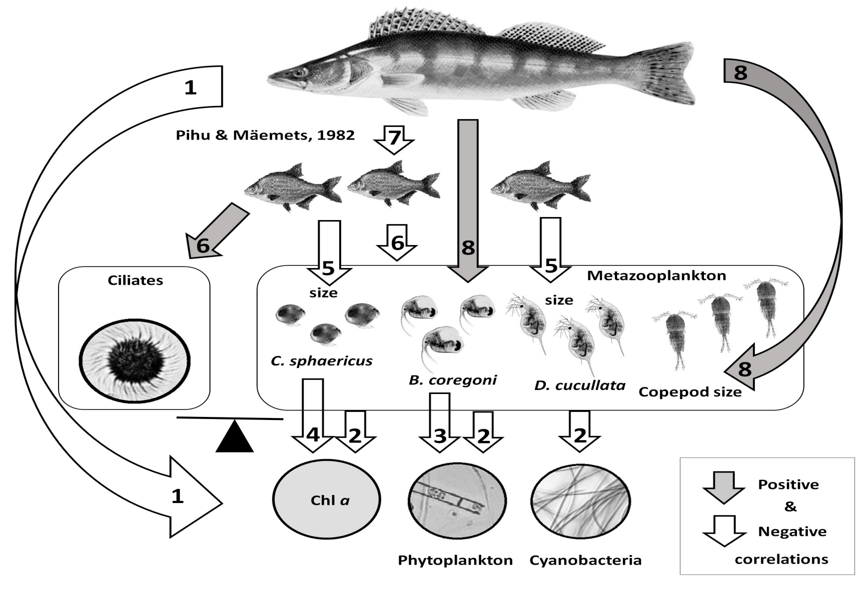


Figure 3.7: Evidence for top-down cascading effects in the food-web of Lake Võrtsjärv. Negative relationship was found between phytoplankton and pikeperch biomasses (1). Chlorophyll a and biomasses of phytoplankton and cyanobacteria were negatively correlated with zooplankton biomass (2). Among zooplankton species the biomasses of *Bosmina coregoni* (3) and *Chydorus sphaericus* (4) were negatively correlated with phytoplankton biomass/chlorophyll a concentration. The individual weight of metazooplankton and cladocerans, most clearly that of *Daphnia cucullata* and *Ch. sphaericus*, were all negatively correlated with small fish (ruffe + bleak + roach + smelt) biomass (5). At high biomasses (WPUE) of small fish, ciliate domination over metazooplankton increased (6).

For the same lake, we quantified the importance of limnological variables in the decadal rise of cyanobacteria biomass in large and shallow hemi-boreal Lake Võrtsjärv by using of a more than 50 years monitoring database comprising 28 limnological variables. The model revealed that the combined rise of lake water temperature and pH coupled with the still high availability of phosphorus in the water column enabled a steady growth of cyanobacteria biomass during the last decades. At a global scale, the continuation of warming trends and eutrophication could lead to more frequent harmful cyanobacteria blooms in shallow eutrophic lakes. The results suggest that the decadal rise of blue-green algae in shallow lakes lies in the interaction between cultural eutrophication and global warming, which bring in-lake physical and chemical conditions closer to cyanobacteria optima.

Finally, we reviewed different organic matter (OM) metrics used in the EU lake surveillance monitoring programmes and assessed their suitability to provide sufficient data about the brownification and enrichment with oxygen consuming substances in European lakes. The different national OM metrics used avoid getting a broad picture of lake OM concentration changes in Europe over the last decades. The possibilities to convert different OM parameters to each other are limited because empirical relationships between them are region-specific. OM sensors for continuous measurements and remote sensing surveys could improve the effectiveness of lake OM monitoring, especially its temporal and spatial representativeness. We strongly recommend to also include methods into lake monitoring programmes (e.g. absorbance or fluorescence spectroscopy), allowing to characterize the composition of OM as it influences strongly the biogeochemical role of OM in lakes.

Deliverables

The main results of WP3 are documented in the following deliverables:

- 3.1-1 *Two manuscripts on time series analysis and temperature effects:* Manuscript on time series analysis in the north temperate region
- 3.1-2 *Two manuscripts on time series analysis and temperature effects:* Manuscript on temperature effects on shallow lakes based on existing experimental data
- 3.2-1 *Manuscripts on experimental results:* Heat-wave effects on shallow lakes experiments
- 3.2-2 *Manuscripts on experimental results:* The effect of extreme mixing and pulsed DOM loading in a deep stratified lake
- 3.2-3 *Manuscripts on experimental results:* The effect of extreme rainfall in the UK lake experiment
- 3.2-4 *Manuscripts on experimental results:* Interactive effects of climate, water quality and land use on river structure, function and ecosystem services
- 3.2-5 *Manuscripts on experimental results:* Impacts on river biota caused by extreme flows caused by hydropeaking effect in combination with eutrophication in Nordic rivers
- 3.2-6 *Manuscripts on experimental results:* How extreme flows caused by hydropeaking and climate change affect river biota in combination with altered morphology and temperature in Alpine rivers
- 3.2-7 *Manuscripts on experimental results:* How low flows affect river biota in combination with fine sediment dynamics and nutrients in Nordic rivers
- 3.2-8 *Manuscripts on experimental results:* How low flows affect river biota in combination with organic load and varied temperature in Nordic and Mediterranean rivers

3.3 Multiple stressors at the catchment scale (Workpackage 4)

This workpackage developed predictive linkages between indicators of environmental quality and ecosystem services, and different types of pressures for 16 river basins from all over Europe across a broad geographical gradient, featuring very different conditions of climate and land use drivers. Using such predictive linkages resulting both from empirical and process-based modelling, and following a common approach for climatic scenario changes, we have studied the future trends of ecological status and services in these basins. The basin-specific Programmes of Measures (POM) implemented for the Water Framework Directive were analysed to provide recommendations on their effectiveness based on the analytical results obtained in our studies. The 16 case-studies analysed comprised catchments of eleven rivers and large rivers, three lakes, one estuary and one delta, encompassing a wide variety of basin conditions and data specificities.

For all case-studies empirical data was available, both natural environmental data as well as abiotic and abiotic data, most of it directly related to WFD indicators, e.g. chlorophyll a, cyanobacteria biomass, or Ecological Quality Ratios for biological quality elements. In all cases several years of datasets were available, and in some cases data was collected for decades. In most cases simulated data using process-based models was also used, either to fill in gaps on series, dates or sites, or to obtain variables quantifying the hydrological alteration. In most MARS basins process-based models were already implemented or tested, and were used by us to establish the final data sets.

Multi-stressor interactions

Although significant stressors were easily found to determine biological responses, we obtained 59 multiple stressor models using linear modelling, and the majority of them were additive, i.e. no significant interaction among stressors were detected. There was a general difficulty to identify significant pair-wise multi-stressor interactions with only 37 % of the linear models showing significant non-additive effects. A predominant number of non-additive models included antagonistic effects. No common significant multi-stressor interactions for the same metric were identified between case-studies. The interaction signal (type, direction) varied across basins and for the same biological indicator, revealing the indicator-specific and case-specific nature of the multi-stressor interactions. Considering the variability of stressor length and strength across case-studies and basins, there is the need for each water manager to address his/her basin as a unique case, identifying the multi-stressor combinations that are unique to each case, and taking into consideration the within-basin influence of natural gradients.

Future scenarios

In all basins the future trends of status indicators and ecosystem services were simulated under the three MARS storylines (compare WP2), which are based on two *Shared Socio-economic Pathways* with two *Representative Concentration Pathways* referenced to the years 2030 and 2060. Three storylines were tailored to each basin characteristics and pressures, to the features of the process-based models therein, and to the POM that should/could be implemented in the next decades.

On general terms, future impacts seem to be highly case-specific, and considering the variation on the indicators used, trends are difficult to generalize. We compared the evolution of two benchmark indicators (i.e. chlorophyll a and Ecological Quality Ratio) until 2060. For all scenarios, models predict an increase in chlorophyll a, with the best scenario being *Consensus World* where a few storylines point to a decrease (Figure 3.8). The current efforts to control eutrophication will, at best, maintain the present levels of eutrophic indicators, and there will be a need for much more effort and time to obtain significant mitigation results under a climate change context. In spite of all the efforts for improvement, the current ecological status will be maintained in the next decades. This is consistently the case for the various biological elements including fish, invertebrates or macrophytes, with a variability associated with the climate projections, the basin specificities and the chosen storylines.

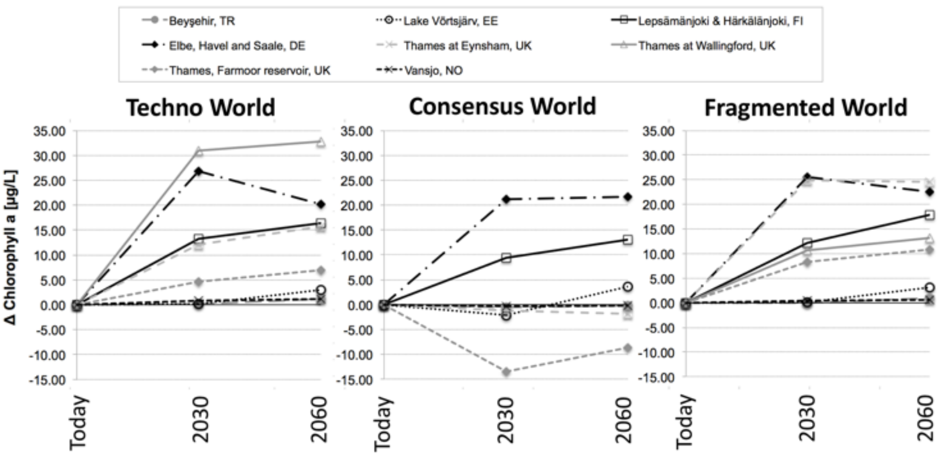


Figure 3.8: Relative change in Chlorophyll-a concentrations for the future scenarios across eight case-studies.

The overall results of studies already published within the MARS project present a pessimistic consistency. In many basins the deterioration of quality will continue in the future: Chlorophyll a increases in Finnish rivers, in the Elbe and in Thames basin, and chemical deterioration in the latter; cyanobacterial blooms increase in the lakes Vansjø, Võrtsjärv and Beyşehir, with dry-out of the latter; nutrient concentration increase in the Odense and the Wye catchment; biotic quality decreases in the Pinios basin, or the ecological status remains the same in the Sorraia basin; pathogen peaks maintained in the Thames. In fact, only in the Otra catchment an improvement of water quality is predicted, eventually enabling salmon populations to thrive; but still it will fail to achieve the WFD good status. Pro-active scenarios are generally able to maintain the present ecological conditions and status at most.

Management of multiple stressors

Effectively managing the multiple stressor effects is a difficult task, as each stressor itself changes its effect along other stressor gradients or even along environmental gradients. It is thus impossible to apply static measures with similar effectiveness throughout the stressor gradient. First, water managers need to understand the relevant array of significant stressors and their gradient length, and if there are significant interactions between them. Appropriate datasets provided, chaining the climate, hydrologic, catchment and lake models seems to be the best approach to simulate the outcome of climate and land-use changes (and related POM). In fact, catchment approaches to multiple stressors should be based on effective science through monitoring, organized investigation, predictive modelling and constant evaluations of management actions.

When stressors act at very high levels, mitigation responses cannot be obtained when only a certain percentage of reduction is imposed (e.g. nutrients: Thames, Elbe). Thus, management alternatives may not result in relevant improvements. Climate change effects are generally interfering via flow and runoff changes or biological growth, either positively in some cases and scenarios (e.g. Odense, Pinios) or negatively in others (e.g. Beyşehir). If a stressor overrides the others (e.g. nutrients: Thames, Elbe), and management is not able to solve the problem (nutrient control), only other (‘collateral’) mitigation options are existing (light control, flushing; Bowes et al., 2016). However, reducing nutrients may be necessary to maintain at least the present quality, in view of the increasing trends related to climate change (Bussi et al., 2016). The benefits of better management and land use practices seem to be counteracted by future warming under most scenarios (e.g. cyanobacterial blooms; Moe et al., 2016). However, this is not necessarily the case in Northern European countries, in which precipitation and flow will increase in the next decades. The efficacy from phosphorus load decrease and improved fertilization techniques may decrease the values in stressed biological indicators such as in Vansjø catchment (Couture et al., 2018).

In the absence of reference values to help water managers set the appropriate targets, one possibility is to define these targets (e.g. for nutrients) using controlled experimentation as in mesocosms (see chapter above) and go back to see how much and what type of management is needed to attain that threshold. Also, most of the PoMs relate to small-scale interventions or interventions limited to the river corridor, while there is a need to include a wider perspective of land and water management, which is more difficult to implement (e.g. landscape greening, use of non-conventional water, design of forest patches, alternative types of crops or improved crop species etc.). However, such a concept has rarely been addressed or demonstrated, although evidence from riparian woods show that landscape management at the catchment scale is needed to improve the ecological status (Feld et al., 2018).

There are trade-offs for land uses and water management, so decisions that relate to socio-economic aspects have to be made. For example, efficient irrigation, reduced water abstraction and lower fertilizer application entail a higher water yield and less nutrient loads in water scarce environments (Bucak et al., 2018). However, the concomitant expansion of the area of agriculture, profiting from collateral economic benefits, will increase nutrient leaching despite reduced runoff. This trend is observed in all Mediterranean areas at the moment, due to water use efficiency measures such as precision irrigation and improved genetic crop material. Ultimately, these trade-offs have to be considered in order to obtain proper ecological improvement, e.g. addressing 'externalised' aspects such as the energy costs of water use efficiency measures.

Linkages to ground water and riparian zone

Our studies also showed the dependencies between water and land compartments that need further attention to characterize stressor causes and indicator effects. This is, for instance, the case between ground waters and surface waters, and between the riparian and the aquatic zone (Kaandorp et al., 2018; Feld et al., 2018). We demonstrated that such interfaces interfere with the ecological status of surface waters. For example, a stressor located somewhere in a ground water–surface water connected catchment may have an impact on the surface water downstream, even without any direct surface connection. Long ground water residence times create a time lag in the contribution of historic pollution input, which causes pollution even after management actions in a catchment (Figure 3.9). But more important, such interfaces differ for each basin, and therefore water management has to recognize and adapt to such conditions and differences. Elements of disturbance in the ecological status assessment include such interfaces, but also the influence of biological interactions, such as food chains. MARS, for instance, has demonstrated that the fish community structure also affects the biological elements on a case-by-case situation (Nõges et al., 2018).

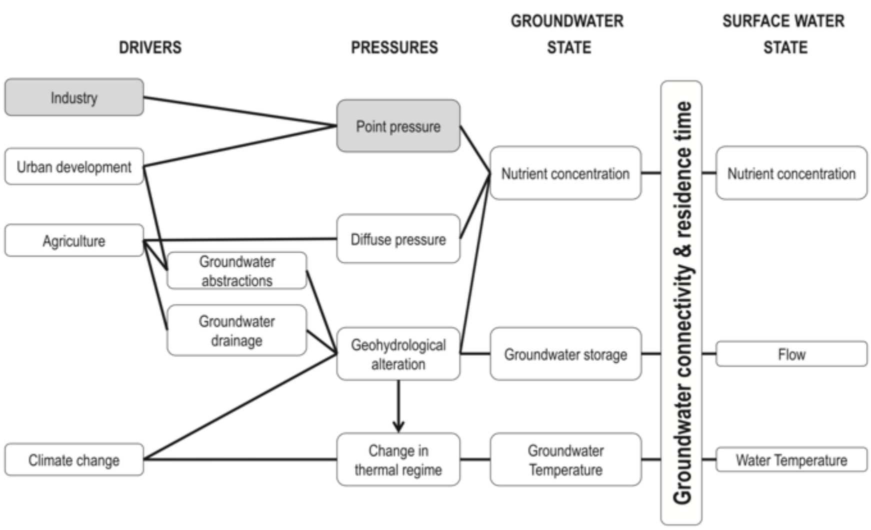


Figure 3.9: The Groundwater Driver-Pressure-State conceptual model shows how drivers are connected through groundwater with surface waters where they function as a pressure and affect abiotic state.

Concluding remarks

Among the lessons learned, there is one of humbleness. In many situations, we do not find predictable relationships between stressor causes and biological effects, even when theoretical support enables the implementation of sophisticated models or when the subject seems already well established. One such case is the relationship between waterborne pathogens and its sources, notably livestock – an important issue for river management and for public health. Usually pathogen concentrations are evaluated using proxies such as faecal indicator organisms, and a series of studies with the INCA-pathogen model have successfully simulated the routing of sources and sinks of coliforms across riverscapes (Rankinen et al, 2016; Whitehead et al., 2016). However, Read et al. (2017), using new molecular approaches to target pathogens, demonstrated that, whilst faecal and sewage indicators showed that contamination via these routes is occurring in the river Thames, it is not associated with high loads of pathogen species. This finding requires careful consideration when devising land use and water treatment policies and its alternative future pathways.

Furthermore, there is frequently an environmental background influence, which interferes/masks the stressors and makes each case study unique, and with its own scales of time and space variability. This background can either be geoclimatic (gradients in rainfall, temperature, geology and altitude), or hierarchical (size of catchment, slope, distance to source, altitude). Several studies showed biotic alterations associated with human-induced disturbances that have a strong regional pattern in terms of the degree of impact imposed on streams (Branco et al., 2013). Part of the MARS studies addressed such background gradients by embedding them (e.g. fish zones of Austria, soil types in Finland), others accepted its interference on models (Bussi et al., 2018) and more rarely, such co-variation was taken into account within the models (Gieswein et al., 2017; Segurado et al., 2018). Multiple stressor combinations varied deeply along longitudinal river gradients and among different ecoregions (Schinegger et al., 2012), causing difficulties in disentangling their effects on biotic components from natural causes due to the co-variability of environmental conditions (Alahuhta & Aroviita, 2016). Moreover, very often the effect of single stressors may depend on the environmental and biotic settings where they were acting.

The individual studies conducted at the catchment scale resulted in a total of 52 Web-of-Science indexed journal papers acknowledging the MARS project. A Virtual Special Issue from the journal *Science of Total Environment*, entitled 'Understanding and Managing European River Basins', gathers 26 articles from the MARS project and 16 articles from the GLOBAQUA project, which are dedicated to aspects of river basin management of stressors and multiple stressors.

Deliverables

The main results of WP4 are documented in the following deliverables:

- 4.1-1 *Case study synthesis:* Report on case studies from Southern river basins
- 4.1-2 *Case study synthesis:* Report on case studies from Central river basins
- 4.1-3 *Case study synthesis:* Report on case studies from Northern river basins
- 4.2-1 *Manuscripts on stressor effects at the river basin level:* Riparian-to-catchment management options for stressor reduction and service enhancement
- 4.2-2 *Manuscripts on stressor effects at the river basin level:* Stressor propagation through surface-groundwater linkages and management consequences
- 4.2-3 *Manuscripts on stressor effects at the river basin level:* Stressor propagation through inland-transitional linkages and management consequences
- 4.2-4 *Manuscripts on stressor effects at the river basin level:* Fisheries as a source and target of multiple stressors
- 4.2-5 *Manuscripts on stressor effects at the river basin level:* Multiple-stressor risks for pathogens and toxicity
- 4.3-1 *Manuscripts on river basin management:* Management of complex multi-stressor hierarchies in time and space
- 4.3-2 *Manuscripts on river basin management:* Emergent lessons from diagnosis, detection and management of multiple stressors using static, functional and dynamic indicators

3.4 Multiple stressors at the European scale (Workpackage 5)

This workpackage quantified interactions among stressors and their combined effect on indicators across large regions and for Europe as a whole, based on existing European databases and modelling tools. Multiple explanatory variables (including point, diffuse, and hydromorphological pressures) and response variables (including ecological status and ecosystem services) were assembled and integrated at appropriate geospatial resolutions, and then investigated in cause-effect analyses. Special emphasis was placed on multi-stressor effects in large rivers and lakes, and on the fish fauna in different water categories across pan-European scales.

MARS geo-database

We compiled a European geo-database based on EU-wide reporting activities (EEA databases, WISE SoE) and results from modelling activities at European scale (MONERIS, LISFLOOD). These data were integrated using spatial analysis tools and ECRINS GIS reference layers. The database includes vector features and raster features, comprising the Functional Elementary Catchment (FEC) layer with lakes; the broad hydroregions; hinterlands of lakes and estuaries; WISE SoE quality and quantity stations shifted to ECRINS river segments; a layer of dams; climate data (precipitation and temperature) for the period 2001–2010, resampled to 1 km grid cell; river broad type; lake broad type and FEC broad type. All pressure indicators selected for the subsequent multi-pressure – state analyses as well as new climatology data were determined for the FECs. For identifying proxies of morphological alterations, four buffer models were established and applied to fish (EFI+ and intercalibration) stations, WISE SoE stations and rivers in general. The MARS geo-database is further described in Globevnik et al. (2017).

Analysis of pan-European stressor-response relationship

We quantified multiple human pressures and their relationship with the ecological status for all European rivers (Grizzetti et al., 2017). A set of twelve indicators was used that could inform on the quantitative presence of these pressures and could be computed consistently across Europe, using already established models or available spatial data. The indicators of pressures proposed in this study for pollution were nitrogen and phosphorus concentration in surface waters (based on the GREEN model) and load from urban runoff (Heaney model). As indicators of hydrological alterations, we considered the total water demand (based on the LISFLOOD model) and two indicators of flow regime alteration (computed as the number of days in which the actual stream flow is below the 10th and 25th natural flow percentile, normalised by the corresponding natural duration, using the LISFLOOD model). A series of indicators of hydromorphological pressures were considered to reflect the conditions of floodplains, including the share of the floodplain occupied by agricultural land, by artificial areas and by natural areas (riparian functional areas), and the density of infrastructures (roads and railways) in the floodplain. Finally, the fraction of the drained catchment occupied by urban areas and by agricultural land were considered as two additional integrated indicators of pressures on rivers related to the land use in the catchment.

We developed a proxy indicator of the ecological status of rivers that could be representative at the scale of catchments, the same spatial unit at which pressure indicators were aggregated. For each catchment, we considered the ecological status assigned to all centroids of water bodies falling in that catchment. We analysed the relationship between multiple pressures, including pollution, hydrological and hydromorphological alterations, and the river ecological status, using statistical methods (regression trees, logistic regression and random forest). We found that better ecological status is associated with the presence of natural areas in floodplains, while urbanisation and nutrient pollution are important predictors of ecological degradation. Figure 3.10 shows the estimated probability of European rivers to be in good ecological status given the combined effects of multiple pressures.

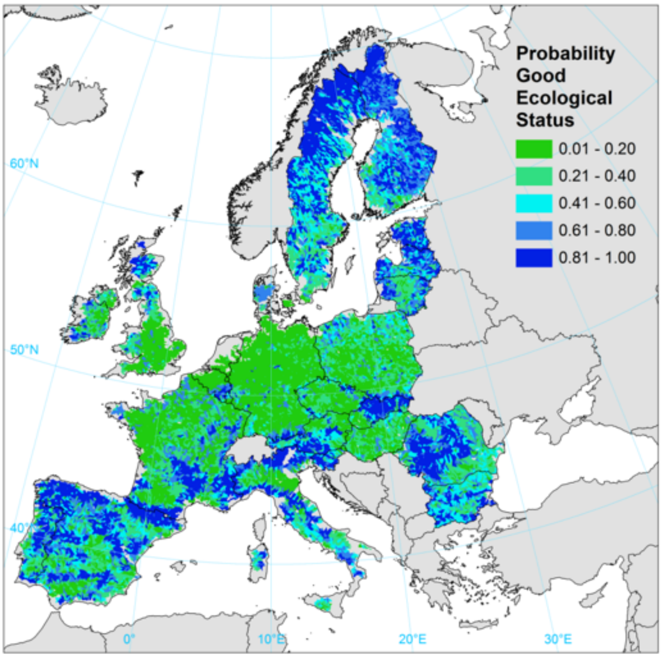


Figure 3.10: Probability of good ecological status of rivers under multiple pressures. Values are estimated by the random forest method applied to all catchments with complete data on pressures.

Analysis of river type-specific stressor-response relationship

To address type-specific stressor-response patterns, an alternative analysis was stratified by broad river types and regions representing distinct natural and geographic entities. We used empirical and distribution-free methods and worked with empirical data collated in the MARS geo-database. A set of 20 broad European river types was used that were characterised by altitude, size and geology (ETC-ICM, 2015). Nutrient pressure data, nitrogen balance and degree of phosphorus saturation were calculated with the MONERIS model. We used the *Copernicus* land cover / land use data in buffer zones around WISE SoE stations as a proxy for hydromorphological alterations. Indicators of hydrological alterations were the average base flow characteristics, floods, duration of high flow pulses and duration of low flows. These indicators were derived from time series on daily run-off (period 2001 – 2010) for natural and altered conditions modelled with the global water balance model PCR-GLOBWB. Physico-chemical data reported by countries for WISE SoE stations were also used as pressures on river biota.

The importance of pressures for supporting good ecological state varied a lot among river types and regions in Europe. At large rivers, for instance, chemical stressors, percentage of broad-leaved forest and share of agricultural land in floodplain were the most important pressures. At lowland, medium to large rivers, high flow hydrological characteristics were also very important. Share of coniferous forest in floodplain was an important pressure in mid-altitude rivers, whereas base flow and oxygen demanding substances (BOD) were important for highland rivers. Nutrient pollution and decrease of riparian vegetation correlated to moderate and worse ecological status mainly in the Mediterranean and Atlantic regions. In the Central and Baltic region, the most important cause for deteriorated ecological status was the combination of nutrient pollution and hydrological alterations. In the Eastern Continental region all three types of pressures, namely, hydrological, morphological and chemical were equally important.

We produced European multi-pressure maps. For each river type, we identified threshold values of the four most important pressures. For each FEC we tested real values of important pressures against their threshold and counted the number of pressures that may, individually or in combination, cause deterioration of ecological status. For 5 % of all FECs at least three pressures did not satisfy threshold conditions. Most of these FECs were located in the Central-Baltic and Atlantic region (1,743 FECs, or 2 % of all FECs included in the analyses) and the Baltic-Continental broad sub-hydroregion (1,247 FECs or 1.4 % of all FECs included in the analyses).

Analysis of stressors affecting groundwater status

Groundwaters are impacted by various stressors leading to either depletion of groundwater quantity or/and quality, including groundwater dependent ecosystems. We analysed groundwater status and stressors (pressures) relevant for groundwater using available data at European scale reported by European countries (WISE-WFD and WISE-SoE datasets managed by the EEA). In particular, a definition of spatial extent of ground waters in poor status, acting single stressors (pollution, abstraction, saltwater intrusion) and stressor combinations including an identification of prevailing pollutants causing failure of good groundwater status. The aim of the statistical analysis was to use simple statistical models to investigate the large-scale pressures on the chemical status and quantitative status of groundwater reported by EU Member States. In particular, our objective was to see if it is possible to use these models to investigate and understand any interactions between different pressures on groundwater status.

The analysis of stressors and status showed that the prevailing stressor causing failure of good groundwater status is pollution, followed by groundwater abstraction. Pollution in combination with groundwater abstraction appears to be most common stressor combination in Europe. Salt water intrusion is almost always associated with groundwater abstraction or/and pollution, but it does not take place in all coastal areas. The most common type of groundwater pollutants are agrochemicals (nutrients and pesticides) affecting whole Europe and especially agricultural areas. We demonstrated how 'data-led' methods, such as stepwise regression, can be used to suggest and estimate models of groundwater status (Figure 3.11). However, we note that they should be used with caution as such approaches can include spurious relationships which result from not accounting for multiple hypothesis tests. Only limited interactions have been investigated to date, however, there is some evidence for a synergistic interaction between arable farming and winter precipitation (when the regression does not include country as a random effect) on the chemical status of groundwater. There is, however, less confidence in the results of models of groundwater quantitative status which appears, as may be expected, to be largely driven by weather variables.

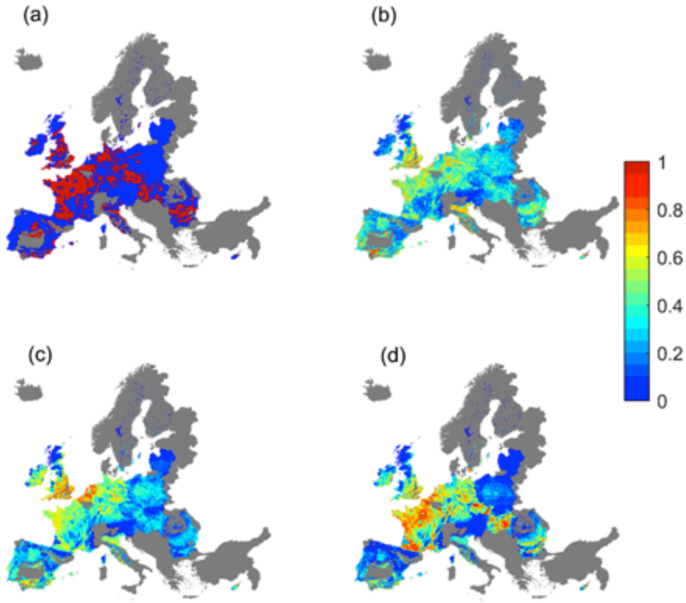


Figure 3.11: (a) Recorded groundwater chemical status (blue good, red poor); modelled status (b) based on agricultural area, population and precipitation; (c) based on agricultural area, population and precipitation with countries as a fixed effect; and, (d) based on stepwise regression of all variables.

Relation of low flows and ecological flows (E-flows) to ecological status

We conducted a European scale analysis of hydrologic data at the resolution of the Functional Elementary Catchment (FEC). Simulated daily time-series of river flows from the PCR-GLOBWB model were used based on a hypothetic near-natural scenario where water abstractions from water bodies do not exist and an anthropogenic scenario with water abstractions occurring. Many hydrologic indicators expressing the characteristics of the rivers' hydrologic regime were calculated for all FECs with the *Indicators of Hydrologic Alteration* methodology and software package, and the deviations of the indicators' values between the two scenarios were used as proxy metrics of hydrologic alteration or hydrologic stress of rivers. Regressions between indicators with the rather limited dataset of EQR values of two BQEs (macroinvertebrates and phytobenthos) showed insignificant or very weak relationships when processed with the entire dataset for Europe or separately for each of the 20 Broad River Types. However, by conducting two examples at smaller scales (catchment or region) with better ecological response datasets, clearer relationships were found.

Spatial assessment of services delivered by European aquatic ecosystems

We assessed the ecosystem services (i.e. the contribution of nature to human well-being) provided by European rivers, lakes, and coastal waters. We mapped them at the European scale and we analysed whether enhanced ecosystem conditions and biodiversity support higher benefits for people. We quantified the main ecosystem services provided by aquatic ecosystems at the European scale, including: fish provisioning, water provisioning, water purification, erosion prevention, flood protection, coastal protection, and recreation. These services are provided by aquatic ecosystems, such as lakes, rivers, groundwater and coastal waters. We showed European maps of ecosystem service capacity, flow (actual use), sustainability or efficiency and, when possible, benefit.

Our results indicate that the ecosystem services are mostly positively correlated with the ecological status of European water bodies, except for water provisioning, which strongly depends on the climatic and hydrographic characteristics of river basins. We also highlight how provisioning services can act as pressures on the aquatic ecosystems. Based on the relationship between ecosystem status and delivery of services, we explored qualitatively the expected changes of ecosystem services under scenarios of increase in different pressures.

We performed an economic valuation of the ecosystem services provided by European lakes, considering the current conditions and scenarios of improvement of the ecological status. Using a benefit transfer approach, we estimated that the average economic value of ecosystem services delivered by a European lake is 2.92 million EUR per year. We also demonstrated that the ecological status of lake has an impact on valuation. The expected benefit from restoring all European lakes into at least a moderate ecological status was estimated to be 5.9 billion EUR per year, which corresponds to 11.7 EUR per person and per year.

Multiple stressors in large rivers

The analysis of stressor conditions in large rivers highlighted the need to consider the long history of human-induced stressors on the biological communities of these ecosystems. Timelines on how pressures evolved in large rivers have shown a dramatic increase during the second half of the 20th century. However, typical faunal elements have been already lost at the beginning of the 20th century due to early channelization and morphological degradation. The effects on the typical faunal elements of large rivers, such as the Plecoptera species, proceeded across major parts of Europe afterwards. Hence, the taxonomical reference of the biological communities in large rivers, especially for macroinvertebrates that have not been economically relevant, is largely unknown. A collection of current and historical occurrence records of selected Plecoptera species showed the loss of distribution areas across Europe, and in turn highlighted river systems where those potamotypic species still occur indicating the integrity of the geo-morphological processes of these river that are necessary to identify reference conditions. These findings also showed that bio-assessment of large rivers needs to consider taxonomical characteristics, as functional traits are not able to indicate the loss of potamotypic species.

Multiple stressors in lakes

We assessed the impacts of multiple stressors on lake ecosystems at the European scale. The ecological responses of two main biological quality elements were examined, namely phytoplankton and macrophytes, to a range of stressor combinations in large populations of lakes. Moreover, the impacts of future multiple stressor scenarios – future climate and nutrient concentrations – have been assessed for a phytoplankton community index. Total P was the stressor that correlated best with ecological status of phytoplankton, while Secchi depth better explained the ecological status of macrophytes. Climatic variables such as air temperature and precipitation, in contrast, had apparently no effect on the ecological status. This result does not contradict that climate change may cause additional stress for lake ecosystems. Instead, the space-for-time approach (using geographic variation in climate as a substitute for temporal variation) in these analyses may not be the most appropriate for detecting real effects of climate change. For the individual phytoplankton indicators (cyanobacteria and PTI), interactions between effects of nutrients and climatic stressors (temperature and/or precipitations) were found for some of the lakes or lake types. Increased temperature and precipitation will result in higher PTI scores, indicating impaired ecological status. In the short term (2030), however, climate-induced changes in PTI will probably not be sufficient to change the ecological status class of lakes (e.g., from Good to Moderate) (Figure 3.12).

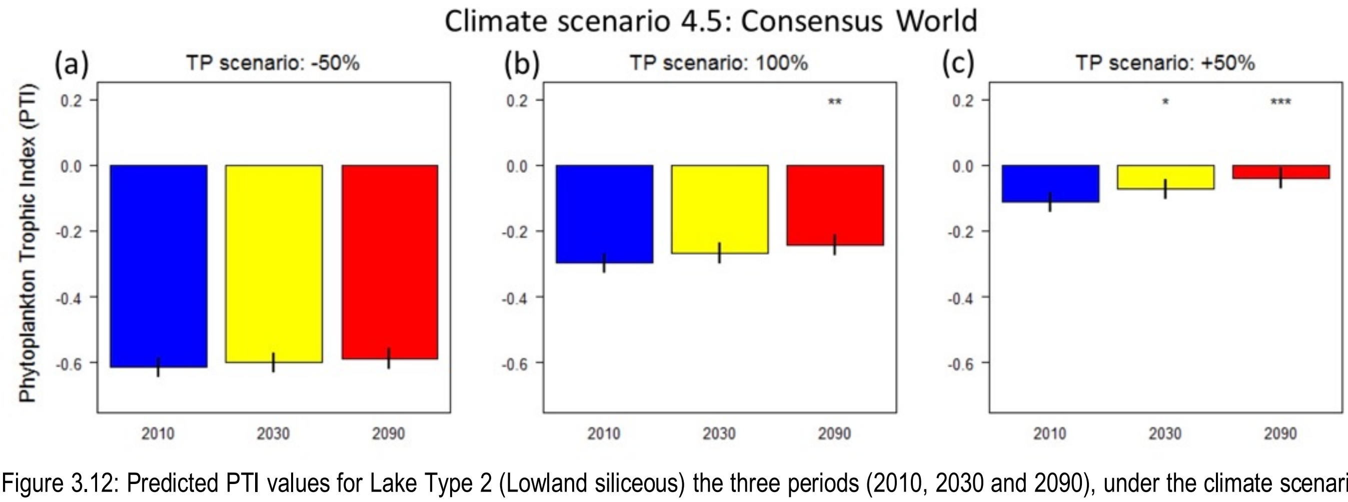


Figure 3.12: Predicted PTI values for Lake Type 2 (Lowland siliceous) the three periods (2010, 2030 and 2090), under the climate scenario Consensus World. The three panels represent different scenarios of Total P concentrations: current TP (100%) [b]; Low TP (-50%) [a]; and High TP (+50%) [c].

The analysis of Mediterranean (i.e. Turkish) lakes suggests that warming together with expected changes in land use in this region may result in higher salinization and eutrophication with more frequent cyanobacteria blooms and loss of biodiversity. Consequently, under such conditions, the ecosystem services potential (e.g. drinking and irrigation water, biodiversity etc.) are likely to be deteriorated if not lost completely. To counteract, stricter control of nutrients emissions and human use of water is urgently needed.

Multiple stress effects on European fish assemblages

Studying the impact of species loss following different scenarios, we demonstrated that in rivers and estuaries rare fish species support singular ecological functions not shared by dominant species. Our results suggest also that functional diversity of fish assemblages in rivers can be more affected by environmental disturbances than in lakes and estuaries. Using functional redundancy and taxonomic vulnerability, we proposed a composite index of functional vulnerability. Considering investigated freshwater types and countries altogether, non-native species represented 26 % of the species pool, with an equal number of translocated and exotic species. The latter were mainly originating from America. Their relative occurrences and abundances were on average low in rivers when compared to lakes, and non-native species were functionally distinct from native faunas. The relationship between non-native species and native species with fishing interest was contrasted. Lakes, especially those located in France, seemed to be the most ‘sensitive systems’. Indeed, for several French lakes the proportions of native species with fishing interest and the proportion of non-native species were perfectly negatively correlated.

Deliverables

The main results of WP5 are documented in the following deliverables:

- D5.1-1 *Reports on stressor classification and effects at the European scale:* EU-wide multi-stressors classification and large scale causal analysis
- D5.1-2 *Reports on stressor classification and effects at the European scale:* Relation of low flows, E-flows, and Ecological Status
- D5.1-3 *Reports on stressor classification and effects at the European scale:* Impact of multi-stressors on Ecosystem Services and their monetary value
- D5.1-4 *Reports on stressor classification and effects at the European scale:* Effects of multiple stressors on ecosystem structure and services of phytoplankton and macrophytes in European lakes
- D5.1-5 *Report on stressor classification and effects at the European scale:* New functional diversity indices allowing assessing vulnerability in abiotic multi-stressor context

3.5 Synthesis: stressors, scenarios and water management (Workpackage 6)

This work systematically collated the results obtained at the water body, river basin and European scale and compared responses to multiple stressors across scales and water categories. We adopted a meta-analysis approach to examine the relationships obtained in the previous workpackages. The synthesis resulted in models for assessing multiple stressor mitigation options, allowing, amongst others, to delineate levels of stressor mitigation for European running waters affected by multi-stressors. To guide appropriate management actions, we identified the consistent stressor-interaction effects found in the MARS project.

Diagnosing the cause of river deterioration using stressor-specific metrics

Aim of this study was to analyse a large set of bioassessment metrics to identify and quantify stressor-specific metric responses reacting to one group of stressors but not to another. We hypothesised that stressor-specific responses occur when the individual stressors show independent ‘modes of action’ (i.e. the specific stress-induced changes of environmental factors that modify the ecological niches of the species constituting the biological community). The data used comprised three aquatic organism groups (macrophytes, benthic invertebrates, fish) covering three broad river types in Western and Central Germany. The stressor groups under investigation were physico-chemical, hydromorphological and hydrological stress. We performed linear variation partitioning to reduce the large set of metrics to a set of candidates for further non-linear analyses using a combination of boosted regression tree modelling and variation partitioning.

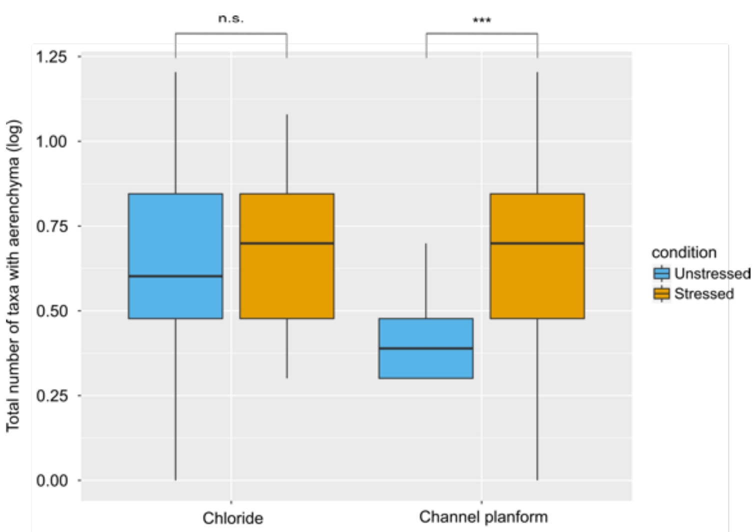


Figure 3.13: Value ranges of the metric ‘Total number of macrophyte taxa with aerenchyma’ across sampling sites in stressed and unstressed conditions for the stressors ‘chloride concentration’ and ‘channel planform’.

The linear analyses revealed 16 candidate metrics that met our criteria, most of them for the medium to large lowland rivers. Macrophyte- and fish-based metrics were most relevant. In a geographically and methodologically more precise data subset, invertebrate metrics revealed more promising models than in the full dataset. Subsequent non-linear modelling resulted in two truly stressor-specific metrics, both based on invertebrate data: The Index of Biocoenotic Region (specifically indicating hydromorphological stress) and the Share of alien species (specifically indicating physico-chemical stress). We concluded that the biological community responds to stressors in rather an integrative than a specific way, but stressor-specific metrics can be identified (Figure 3.13). Future research on diagnostic metrics should focus on quantifying those stressor parameters that represent individual 'modes of action'.

Models for assessing multiple stressor mitigation options

Currently, practical management of water bodies focusses on the control of single stressors which are assumed to be dominant. Work by the MARS project and others using ecosystem scale and experimental observations has demonstrated that the relationships between primary stressors and ecological response indicators can be confounded through interactions with secondary pressures, giving rise to a potentially novel approach in the management of water bodies to achieve ecological recovery: the multi-stressor-response approach.

Theoretical and experimental studies have confirmed that stressor interactions do occur, for example between nutrient and climate change stressors, resulting in novel ecological responses. In addition, the MARS project has developed a common statistical approach for the determination of multiple stressor interactions on ecological response indicators using field data (see sub-chapter above). However, the data produced from such analyses carries little practical benefit to water managers. This issue was addressed by using the MARS common analytical approach to produce quantifiable terms associated with the common risk assessment concept. We utilized data from three demonstration studies (Loch Leven catchment, UK; Pinions catchment, Greece; Lepsämänjoki catchment, Finland) to develop this concept into a practical decision support tool with which future management scenarios can be tested.

Statistical models were developed to predict ecological response variables as a function of two main stressor effects and their interactions, within the framework of linear mixed effects models. From the best fitted models, risks of the response variable exceeding the site-specific thresholds values were evaluated across both stressor gradients and visualised as a 'heat map'. Climate change scenarios were constructed based on published literature and stressor scenario plots were produced showing the effects on ecological indicators relative to critical thresholds of predicted changes in climate change stressor indicators.

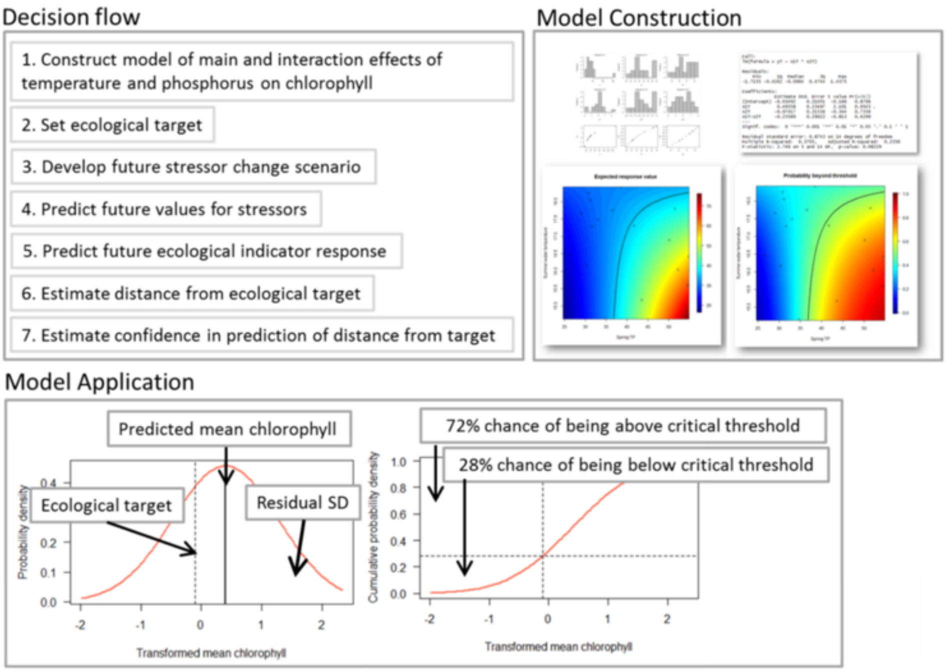


Figure 3.14: General analytical framework for approach and description of assessment of risk factors including expected responses in relation to critical threshold (or 'severity') and the probability that the critical threshold will be exceeded for a given stressor combination (or 'likelihood').

Multiple stressor models were produced for all three demonstration studies indicating the effects of multiple stressors. In all cases nutrient stressors were identified as the primary stressor with climate change related stressors acting as weaker secondary stressors. The effects of the secondary stressors varied along the primary stressor range in most cases, although a significant interaction was only returned for the Lepsämänjoki catchment, Finland. It appeared as though the secondary climate stressor became more dominant at higher nutrient concentrations in Lepsämänjoki catchment but at low nutrient concentrations in Loch Leven. The general implications of the results are discussed and should be assessed further using this common analytical procedure for other sites.

Ultimately, we have developed a novel approach with which to construct multiple stressor maps to explore interactions across stressors gradients (Figure 3.14). The approach has been designed to allow comparable analysis of any field data type (e.g. experimental, spatial, temporal, spatiotemporal) from any ecosystem type or scale. This approach has been demonstrated using three demonstration sites but offers potential for a global analysis.

Delineating levels of stressor mitigation for European running waters affected by multi-stressors

The statistical approach outlined above was applied to a wider range of 'demonstration studies' to support more general mitigation scenarios and to provide data with which to synthesise responses and mitigation effects across ecosystem types and scales. We applied this new risk-based approach to 13 MARS case studies modelled by paired-stressor-response GLMs. In order to quantify the 'severity' of stressors on ecological indicators we requested case studies' analysts provided us with critical values of the ecological indicators (Good-Moderate boundaries according to the WFD). Risks of the response variable exceeding the study specific thresholds values were evaluated across both stressor gradients and visualised as a heat map (Figure 3.15). Exceedance probabilities were calculated from the model for a range of stressor combinations. Then we quantified the distance from target, or effort required of mitigation, that managers should apply under single- and dual-stressor mitigation options to achieve two different management targets. These were defined as follows: (i) 'Relaxed management target', i.e. least 50 % of monitoring sites/water bodies should achieve good ecological status with a probability of failing the good status target below 50 % and (ii) 'Stringent management target', i.e. least 80 % of monitoring sites/water bodies achieve good ecological status with a probability of failing the good status target below 20 %.

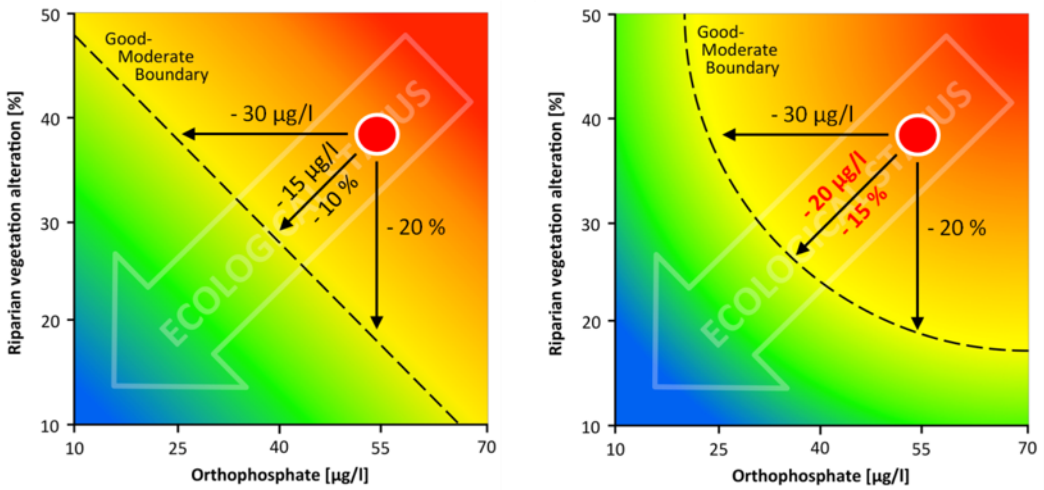


Figure 3.15: Conceptual diagram indicating the practical application of the model outputs for models which contain significant effects of two stressors with (right plot) and without (left plot) significant interaction terms.

We found that under conditions of multiple stress 'heat maps' can be used as a visual diagnostic tool for detecting types of interactions between paired stressors (e.g. additive or non-additive) as well as the strength of the interaction effect. For example, the absence of a significant interaction would result in a more or less 'linear' response contour plot indicating the dominant or additive character of the stressors. When a significant interaction is present the heat maps would generate more complex response plots depending on the type of the interaction effect (e.g. synergistic vs. antagonistic). Additional information can be briefly assessed such as a rough estimation of the share of sites (or measurements) that fall below or above the critical threshold.

It was shown that for several cases high mitigation levels are necessary to achieve even the first management target that refers to a more realisable goal (only half of sites/data measurements in each case study meet the WFD good ecological status). Particularly it was shown that single-stressor mitigation requires management of the stressor to unrealistic levels (e.g. reduce nitrate concentration in rivers to almost zero) in order to achieve the desired targets.

In contrast, dual-stressor mitigation allows mitigation of stressors at more realistic levels. Especially for nutrients, which was the dominant stressor in all the case studies. The results showed that the required mitigation of nutrients, in order to achieve even the relaxed management target, can be as high as 75 or 94 % resulting in concentrations of nitrate at 0.7 or 0.2 mg/L, respectively. Practically these results imply that managers will have to tackle other stressors as well, such as hydromorphological alteration, in order to meet the management targets.

Synthesis

We applied the analytical risk approach described above in 156 case-studies covering various stressor combinations acting on different biological response variables (Figures 3.16 and 3.17). In particular, paired-stressor effects were analysed including nutrient stress co-acting with other stressors (e.g. hydropeaking, flow alteration, temperature increase). We identified remarkable differences in the effects between lakes and rivers (Figure 3.18). While for lakes the effects of nutrient stress were dominating across biological response groups, rivers showed a more heterogeneous picture. Nutrient effects dominated the response variables covering river autotrophs (phytoplankton and benthic fauna). In contrast, this biological group reacted exclusively to hydropeaking stress. River heterotrophs (benthic invertebrates, fish) were most responsive to morphological stress (e.g. channelization, riparian vegetation alteration), but ambiguous in their response to flow alteration and temperature increase.

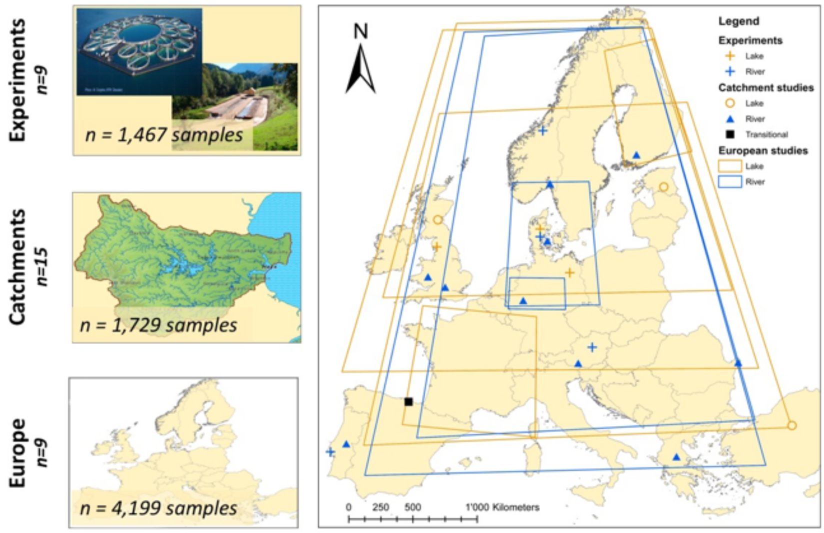


Figure 3.16: Number and location of the 156 case-studies analysed to synthesize the multi-stressor evidence gained across the three spatial scales.

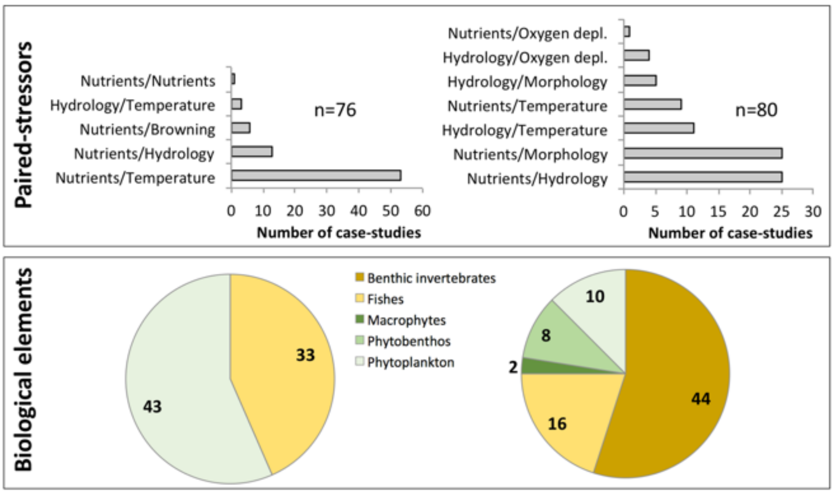


Figure 3.17: Summary of case studies contributing to the synthesis analysis indicating the stressor combinations studied and the biological responses, broken down by lakes [left] and rivers [right].

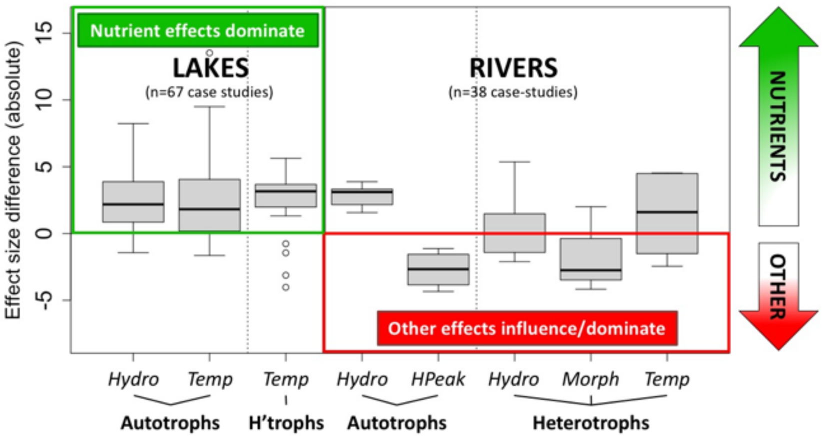


Figure 3.18: Paired-stressor effects (Nutrients and other stressors) on biological response groups at lakes and rivers (N=105 paired-stressor–impact relationships).

Consistent stressor-interaction effects found in the MARS project

Out of the 156 single results of the paired-stressor combinations analysed within studies of MARS, about two-thirds were additive (i.e. had no significant interactions), while one-third showed significant interactions. For most studies, the response variables applied are not directly comparable to the intercalibrated WFD metrics for different biological quality elements (BQEs). However, a few pair-wise stressor combinations were found to have consistent stressor-interaction effects on BQE metrics relevant for managers in certain types of lakes and rivers (Table 3.1). Explanations describing likely mechanisms, as well as implications for mitigation measures are given for each of the consistent pair-wise stressor interaction results below, including quantified interaction effects and references to the studies and datasets.

Table 3.1: Consistent interactions of stressor pairs and related effects on different BQEs and 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	Phytoplankton 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	Channelization	Benthic invertebrates and Fish	Rivers	Rivers	Antagonistic, but small interaction effect

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 in nutrient-limited lakes and rivers due to accelerated primary production of opportunistic phytoplankton species. The ambition level of nutrient reduction measures should be enhanced to achieve and maintain good ecological status for phytoplankton. The interaction effect varies from 25 % (Danish mesocosms) to 100 % (Finnish rivers) and is supported by other MARS studies of impacts on phytoplankton taxonomic composition, using large-scale spatial datasets, 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 in eutrophic (nutrient-saturated) very shallow, unstratified lakes due to self-shading and/or high turbidity from resuspension of sediments, causing lower net primary production (higher respiration than primary production). The interaction is antagonistic as such lakes are over-saturated with nutrients. The ambition level for nutrient reduction measures should therefore be enhanced to achieve and maintain good ecological status for phytoplankton, as nutrient reduction measures will decrease the self-shading and thus reduce the antagonistic interactions. This interaction effect was found in three different single studies in MARS, all showing an interaction effect of > 60 %: UK mesocosm experiment, Võrtsjärv case study in Estonia, European large-scale dataset focusing on eutrophic lakes.

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 ambition level of nutrient reduction measures can be decreased, as the risk of cyanobacterial blooms are less in humic lakes, but potential risk for blooms of other harmful algae (e.g. *Gonyostomum semen*) should also be taken into account. This interaction effect ranges from 4 % to 42 % based on three different spatial scales: MARS experiment in large, deep mesocosms in lake Stechlin in Germany, the Vansjø case study in Norway (using extended timeseries) and a large-scale spatial dataset from 500 Northern lakes.

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

Nutrient enrichment combined with high flow 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. The ambition level for nutrient reduction measures should be increased and/or combined with measures to reduce high flow episodes. This interaction effect ranges from 14 % to 69 % found in three MARS studies: The Vansjø case study in Norway (Couture et al., 2018), the Thames case study in the UK and in a large scale European dataset. 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. Differences between the net effects of 'dilution' versus 'nutrient inflow' depends on specific lake morphometry, catchment land use etc.

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

Nutrient enrichment combined with regular 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. The ambition level for nutrient-reduction measures can be decreased if nothing is done to reduce the hydropeaking, however, taking into account potentially negative impacts of the nutrients on downstream water bodies. If hydropeaking is reduced, the other effects become more important, meaning that also nutrient reduction measures will be needed. This interaction effect ranges from 18 % to 62 % and is based on two different MARS studies: two MARS river flume experiments in Norway (Bækkelie et al., 2017) and Austria (Bondar-Kunze et al., 2016).

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

Nutrient enrichment combined with channelization 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 ambition level for nutrient reduction measures 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 % to 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., 2018).

Deliverables

The main results of WP6 are documented in the following deliverables:

- D6.1-1 *Synthesis of stressor interactions and indicators:* Stressor interactions and most sensitive indicators of impact at the species, ecosystem and landscape scale that are relevant to sustaining ecosystem services and human benefits
- D6.1-2 *Synthesis of stressor interactions and indicators:* Manuscript on evaluation of methods for diagnosing cause of deteriorations in ecological status
- D6.1-3 *Synthesis of stressor interactions and indicators:* Recommendations for more integrated river basin management and gaps in tools
- D6.2 Synthesis report describing potential risks to status and services in relation to future scenarios of land-use change in combination with extreme climate events and possible mitigation options

3.6 Multiple stressor tools (Workpackage 7)

The project results were integrated into practical, easy-to-use tools to support water resources management. The tools aim to contribute to designing cost-effective POM, thus contributing to the tool-box called for by the 'Blueprint to Safeguard Europe's Water Resources'. Design and performance of the tools are described in the following.

Web-based information system

The web-based MARS Freshwater Information System (FIS) is providing access to information and practical tools generated in MARS (Figure 3.19). The FIS contains informative factsheets for DPSIR, stressors, ecosystem services and MARS case studies on the impact of multiple stressors for ecological status as well as a model selection tool for river basin management. The design and functionality has been discussed internally with MARS partners and with end-users during two workshops. The FIS has been integrated in the Freshwater Information Platform, which brings together the results of many projects dealing with freshwater ecosystems in one a single platform.

The FIS provides an information library containing factsheets for various drivers and pressures including their impact and mitigation options; factsheets for ecosystem services and storylines for future scenarios; factsheets for individual stressors and multiple stressor combinations; selected case-studies on the impact of multiple stressors in river basins under present conditions and contrasting future scenarios; a model selection tool for river basin management; guidelines supporting 3rd cycle of river basin management planning.

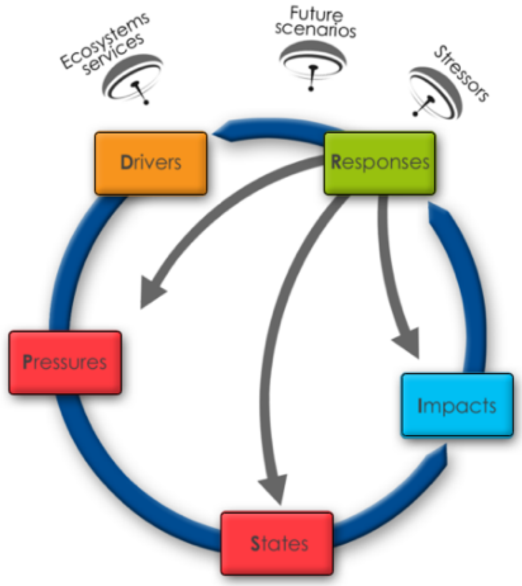


Figure 3.19: The information library is structured according to the DPSIR, ecosystem services, future scenarios and stressors.

Diagnostic tool for water bodies

While the assessment of the ecological status of surface water bodies has become quite straightforward nowadays, almost two decades after the WFD has been launched, the inference of appropriate management options from the assessment is still challenging. The ecological status assessment of a given water body integrates the impact of single or multiple stressors impacting the water body. The challenge is to identify the most-impacting stressor(s) and to distinguish them from the minor ones. Such stressor hierarchies are required to infer the appropriate hierarchy of management options to address the relevant stressors. The MARS Diagnostic Tool can assist water managers to identify appropriate options to address the impact of multiple stressors on surface water bodies. The results comprise:

- A conceptual model to visualise the published evidence of the impacts of combined stressors on river organisms. Such a structured evaluation can help identify potential interactions of stressors, which then require consideration in water body management.
- An approach to diagnose the causes of deterioration of lowland rivers based on the effects on selected diagnostic metrics for benthic invertebrates. The approach uses a Bayesian (Belief) Network (BN) to statistically infer the probabilities to be causal for the detected effects at the water body.
- An interactive online diagnostic tool that builds upon the BN. The tool provides a graphical interface that allows the user to easily enter evidence (i.e. the states of selected effect variables). The results are graphically displayed and accompanied by helpful background information and web links to relevant sources of information.

Combining abiotic and biotic models for river basin management planning

Bayesian Belief Networks: Many restoration or mitigation measures have been carried out or are planned to improve the ecological status of water bodies. For this, models are useful to forecast the effects of the measures planned. Bayesian (Belief) Networks (BN) models that couple abiotic conditions to biotic responses are increasingly applied for this purpose. BNs have a number of advantages, such as explicit incorporation of uncertainty in the outcome, the ability to handle incomplete datasets, expert opinions and model simulations, and a relatively simple graphical representation of complex ecosystems interactions. Accordingly, there is an increasing interest in the construction and application of BNs in water management. In the framework of this task, predictive BN models have been developed for five case studies catchments across Europe to explore the effects of future scenarios on biological responses and ecological status of water bodies. The case studies cover:

- Three regions of Europe (North, Central, South), with case studies from Finland (Lepsämänjoki), Denmark (Odense), The Netherlands (Regge and Dinkel), Portugal (Sorraia; Figure 3.20) and Norway (Vansjø);
- Two water categories: rivers and lakes;
- Three story lines: Techno, Fragmented and Consensus world that have been used in MARS;
- Various stressor types: Total P, Total N, hydrology, hydromorphological alterations, temperature etc.
- Biological indicators: chlorophyll a in rivers and lakes, cyanobacteria in lakes, macrophytes, macroinvertebrates, fish and total ecological status of the water body.

For all case studies, the BN method enabled the prediction of biological responses under the different future storylines, and therefore gave better informed assessments of ecological status compared to the process-based catchment models. The application of BNs for prognostic and diagnostic application, the advantages and disadvantages of using BNs and the need for validation are discussed.

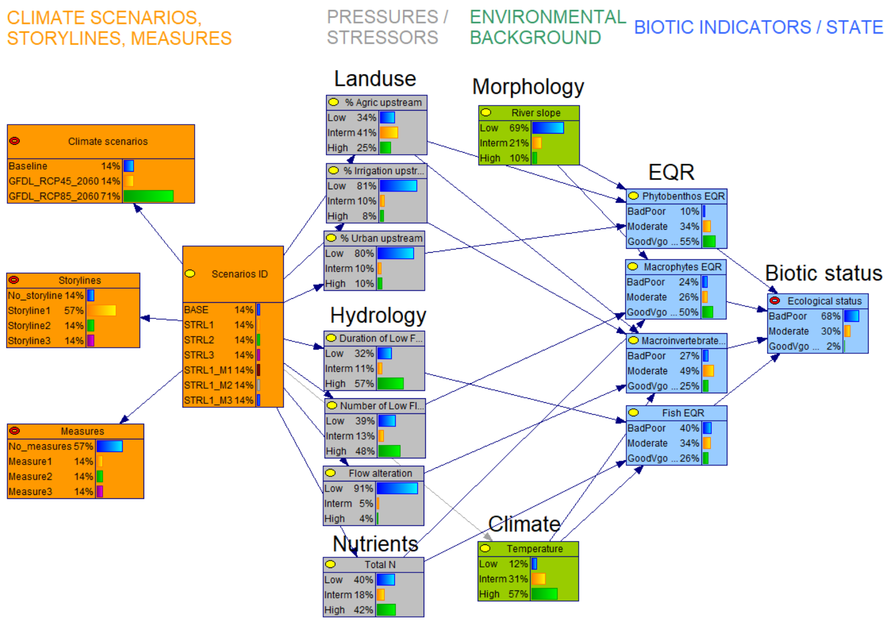


Figure 3.20: Bayesian Belief Network model developed for the Sorraia Basin (Portugal).

Model Selection Tool: Models are widely used in water management. Quite often models are chosen, which people are familiar with or have heart of. There was, however, no simple tool presenting an overview of the applicability of widely used models for river basin management. Therefore, MARS developed the Model Selection Tool. At present, the tool comprises 21 models. For each model general characteristics (e.g. open source, domain, space and time resolution), applicability for the various water categories (lakes, rivers etc.), hydromorphology, physico-chemistry and biology are given, all of which is summarised in a factsheet including contact information and links to websites. Models can be filtered either through tick-boxes or pull-down menus whereby the selection of relevant models is immediately shown to the right.

Scenario analysis tool at the European scale

The MARS Scenario Analysis Tool (SAT) addresses the type of interactions between selected main stressors and their current and future impact on aquatic ecosystems at the European scale (Figure 3.21). The resolution of model results is limited to the FEC level (Functional Elementary Catchments, with a mean spatial resolution of 58 km²), but the European wide application opens long gradients and increases the number of relevant stressors, thus potentially allowing to identify stressor-response relationships which are often concealed at smaller scales.

The backbone of the SAT is a combination of the models PCR-GlobWB and MONERIS, and is linked with the MARS geo-database. PCR-GlobWB provides information on daily water balances for near-natural (i.e. no reservoirs, no water abstraction or addition) current and future conditions. These data are used to analyse hydrological alterations and as input data for MONERIS, which in turn quantifies nitrogen and phosphorus emissions to surface waters, in-stream 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 MARS geo-database. The outputs link climate, water availability, nutrient fluxes and management options by quantifying and evaluating multi-stressor conditions and the aquatic response.

Machine learning approaches have been used to identify major stressor indicators with the strongest power to explain the ecological state reported for the 2nd WFD monitoring and assessment cycle. Six dominant stressor indicators were identified and thresholds, i.e. tipping points describing the impact of a stressor indicator on the reported ecological state, were derived using regression tree analysis. 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, the analysis was conducted for different broad river types. The stressor indicators and derived thresholds are used in Bayesian Belief Networks to derive probabilities for a FEC to reach at least good ecological status. This allowed estimating probabilities to reach a good ecological status not only in regions outside the EU, considered in this modelling task, but also under future conditions.

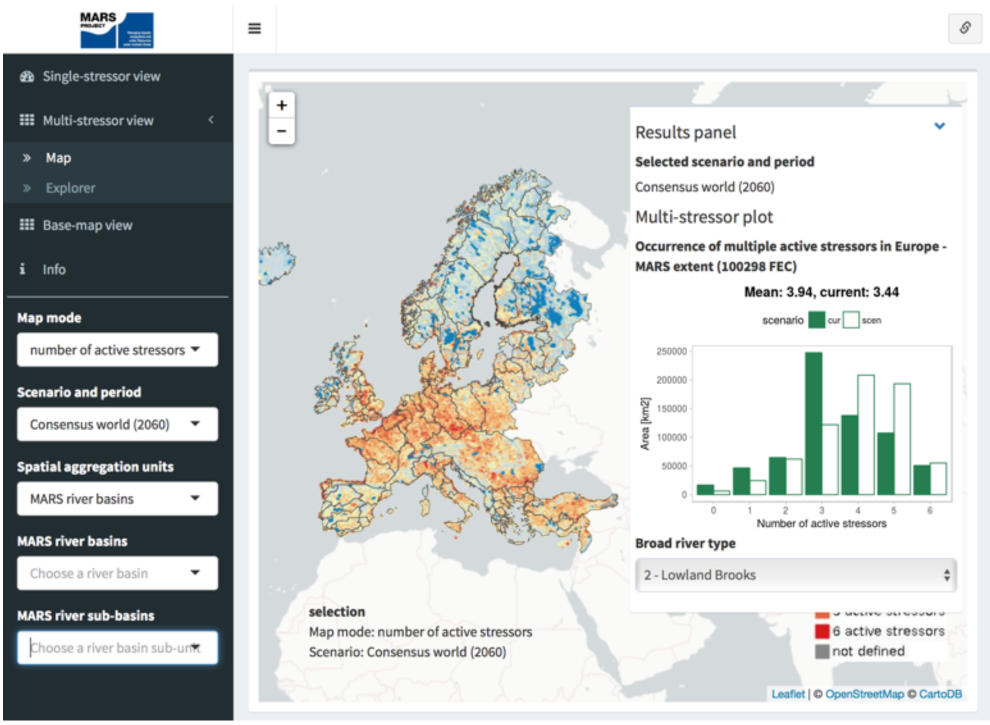


Figure 3.21: Graphical user interface of the MARS Scenario Analysis Tool. The map depicts the number of stressors active in the different FECs covering Europe. The results panel [right] shows the distribution of multiple stressors at lowland brooks across Europe for the current situation (green) and the future Consensus world scenario in the year 2060 (white).

Deliverables

The main results of WP7 are documented in the following deliverables:

- D7.1 MARS suite of tools I
- D7.2 MARS suite of tools II

4 Potential impact and main dissemination activities and exploitation of results

4.1 Potential impact

MARS has addressed the FP7 call ENV.2013.6.2-1, which has mainly been issued to support the implementation of EU water policies, in particular the Blueprint to Safeguard Europe's Water Resources, and to better link the WFD to other relevant legislation. While the WFD is the core of Europe's water policies, further legislative building blocks include the Floods Directive, the Marine Strategy Framework Directive, the Habitats Directive, the Biodiversity Strategy to 2020, the Strategy on Water Scarcity and Drought and the White Paper on Adaptation to Climate Change. Legislation targeting other policy sectors also strongly impact water resources management (e.g. the Renewable Energy Directive and the Common Agricultural Policy). The Blueprint to Safeguard Europe's Water Resources attempts to better integrate this multitude of directives and identifies key challenges for the implementation of European water policies.

While several calls in FP6 and FP7 and resulting projects have addressed research questions associated with the implementation of the individual, above mentioned directives, the call 'water resources management under complex, multi-stressor conditions' had a broader, more integrative, perspective. Though focussing on the next steps of WFD implementation, it dealt to a large degree with the linkages of the WFD with other policies, in particular those related to water quantity and socio-economy (ecosystem services) as well as emerging issues (e.g. climate change and land use change). MARS was therefore of an integrative nature and mirrored the Blueprint, which is the most integrative political instrument within the European water policy.

In summary, MARS has addressed the call's objectives by:

- developing an indicator database and derive dose-response relationships between multiple stressors and indicators, derived from experiments, modelling and data analyses;
- linking the status of surface and groundwater bodies to ecosystem services through a variety of experimental and modelling activities;
- diagnosing the effects of multiple stressors on status and services in a wide range of river basins by linking 'abiotic' and 'biotic' models in 16 catchments and by upscaling the results;
- analysing and predicting the effects of management measures and land use changes on water body status and ecosystem services, by applying scenarios to catchments and large-scale data;
- developing and disseminating tools for River Basin Management (information system, diagnostic tool, scenario analysis tool, River Basin Management guidance);
- developing recommendations for the future of European water management, in particular the review of the WFD.

Specifically, MARS has addressed these elements by activities listed in Table 4.1 and their associated impacts. Structure and contents of Table 4.1 stem from the MARS proposal and have just marginally been updated; all MARS impacts predicted in the proposal phase have actually been achieved and can now be expected to unfold their impacts on European water management as specified in the table.

Table 4.1: Summary of the project's results to address the elements of the call text.

Elements of the call text	MARS key activities	Key deliverables
Underpin decision making, risk assessment and management of water systems under complex multiple stress conditions (combination of organic and inorganic pollution, flow and morphology alteration, surface and groundwater abstraction, land use change, climate variability and change, invasive species, pathogens, etc.).	Coverage of a broad range of commonly occurring stress combinations in WPs 3-5 to enhance mechanistic understanding of multiple stressor impacts. Transfer process understanding of multiple stressors and their impacts into practical tools at different scales, also including optimal combinations of management measures for different combinations of multiple stressors (WP7).	D6.1, D7.1, D7.2, D8.2, D8.3
Clear user perspective	Development of tools for water managers at three spatial scales (WP7); including river basin authorities and national WFD authorities as applied partners in the MARS consortium; close dialogue with local river basin managers responsible for WFD implementation in each of 16 case studies (WP4), organising workshops to specify product needs and development with these applied partners and other external end users at the River Basin and European scales (WP8). Attending CIS workshops to present results and provide inputs to new CIS guidance documents (WP8).	D4.1, D4.2, D7.1, D7.2, D8.1, D8.2, D8.3
Enhance our understanding of stressors interactions, species interactions, species-stressor-relationships and impacts on the ecological functioning, stability and resilience of the aquatic ecosystems	Experiments, time series analyses (WP3), coupled models (WP4), large-scale data analysis (WP5) and synthesis (WP6) on interactions of common stressor combinations and their effects on a wide range of biotic metrics, functions and ecosystem services.	D3.1, D3.2, D4.1, D5.1, D6.1
Innovative methodologies	Innovative conceptual model, broad range of new methodologies to develop and test indicators (including genetic indicators, high frequency automated sampling, environmental flow markers, ecosystem metabolism; WP 3-5), new approaches to link biotic and abiotic models (WP4).	D3.2, D4.2, D5.1, D7.2
Develop holistic approaches and tools to diagnose changes in the ecological, quantitative and chemical status of water bodies (…) and in water availability, in relation to multiple stress conditions, identify the relevant stressors which are responsible for their deterioration	Conceptual link of DPSIR, risk assessment and ecosystem services. Benchmark indicators covering ecological, chemical and quantitative status, trends and services were developed in WPs 2, 6 and 7 and tested in WPs 3-5. Large scale scenario analyses of exposure to stressors, impacts on water status using the benchmark indicators and on the related services (WP5, WP7).	D2.1, D6.2, D7.2
Forecast and predict the ecosystem responses and ecological recovery as a consequence of alternative management measures on different spatial scales	Scenario development targeting land use, restoration / mitigation (including the actions defined in the first cycle of RBMPs) and climate; scenario application at the scales of river basins (WP4) and Europe (WP5). Development of predictive tools at river basin and European scales (WP7).	D2.1, D4.1, D4.3, D7.2

Table 4.1: Summary of the project's results to address the elements of the call text.

Elements of the call text	MARS key activities	Key deliverables
Development of integrated impact assessment tools, coupling biophysical with socio-economic assessment of impacts (provision of ecosystem services) to improve water resource protection and management, including water related extreme event prevention and management, at EU and river basin levels	Benchmark indicators developed in WP2, which include indicators on status (qualitative, quantitative), function and services. Application of scenarios on the future of Europe's water resources testing impacts of extreme events on these assessment tools and which management measures would be best to counteract and mitigate impacts of such events.	D2.1, D6.2, D7.1, D7.2
Expected impact: Improved water status and availability of clean water	Europe-wide overview of water resources, water quality and ecological quality as affected by multiple stress. Tools and guidance on the implementation of management measures to achieve good water status and clean water to be available for the third cycle of RBMPs. These will contribute to improve water quality and quantity.	D5.1, D7.2
Expected impact: Better implementation of water policy	New concepts to link underlying approaches of different policies (WP2), advise WFD (and daughter Groundwater Directive) revision. Advice to set priorities in the implementation of water related legislation through large-scale overview of water quality and stress (WP5).	D2.1, D5.1, D8.3
Expected impact: Optimal decision making in water resources management under complex multiple stress conditions	New indicators at the water body and river basin scales, for the first time integrating the effects of different stressors (WP6). Tools to support the selection of appropriate models under multiple stress conditions (WP7). Guidance papers for WFD review (WP8).	D6.2, D7.2, D8.2
Expected impact: With the aim of achieving sustainable resource use and flood risk reduction	Integration of ecosystem services and water quantity with WFD goals at all spatial scales (WP2, WPs 3-5) to provide greater transparency on the human benefits of the WFD. Modelling effects of various flood risk reduction measures (e.g. restoration of riparian zones) (WPs 4, 5, 7)	D2.1, D4.2, D6.2
Expected impact: Development of more cost-effective Programmes of Measures (POMs) to improve the ecological status of surface water bodies from the local to the river basin scale also in the context of ecosystem goods and services – in line with the EU Water Framework Directive	Guidance on how stress combinations affect water resources and ecological quality; Europe-wide overview of stress and response, enabling water managers to set more targeted priorities. Implementation will be supported by tools developed for all scales in WP7.	D5.1, D6.2, D7.1, D7.2
Expected impact: Improve the groundwater body status – also in the context of ecosystem goods and services – in line with the EU Water Framework Directive	Groundwater status/trends objectives and impacts on associated surface waters and groundwater-dependent ecosystems were included in two of the river basin case studies (WP4) and into the large-scale data analysis (WP5).	D4.1, D4.2, D5.1, D8.2

4.2 Main dissemination activities and exploitation of results

Advising river basin managers and sectors for the 3rd RBMPs

The MARS Deliverable D8.2: 'Guiding principles for River Basin Managers and other sectors (energy, water industry, agriculture) on how to best assess and mitigate impacts of multiple stressors' includes recommendations on the general approach of MARS on how to handle multiple stressors in River Basin Management. The contents comprise flow-charts, figures, tables and short texts providing recommendations, overview of multiple stressors in European waters, consistent interaction effects on biological quality elements of commonly occurring pairs of stressors, data sources, various modelling techniques, tools, and concrete examples. The intention is to help river basin managers to assess and improve their programme of mitigation measures to reduce the impacts of multiple stressors on the ecological status in their rivers, lakes and estuaries. The guidance has been produced after a close dialogue with WFD authorities at the national and regional level (see Second Project Periodic Report), to maximize usefulness and support for management. For convenience and better readability, this document uses hyperlinks to relevant MARS results, models and tools to enable readers to directly access the respective products.

Interaction with WFD-CIS working groups and MAES freshwater group

The activities under this task aimed at providing appropriate inputs to selected WFD-CIS (Water Framework Directive – Common Implementation Strategy) working groups and the working group MAES (Mapping and Assessment of Ecosystems and their Services), and were structured according to the topics addressed by these groups.

A work plan for the task was developed immediately after the project's kick-off and included 1) a plan for attending selected workshops of the relevant WFD-CIS groups and MAES subgroup; 2) a cross-cutting meeting with all relevant WFD-CIS groups leads and 3) the provision of MARS inputs to the relevant WFD-CIS and MAES documents. During the project the focus has shifted towards streamlining the MARS presentations to the work programmes of the WFD-CIS groups ECOSTAT, FLOODS, GROUNDWATER and MAES, by selecting the MARS products that were of highest relevance to their current main activities (Table 4.2). The CIS workshops in which MARS products were presented and discussed are given in Table 4.3.

Table 4.2: Links between WFD-CIS working groups main activities and MARS products

<table>
<tr><th>WFD CIS groups main activities</th><th>Relevant MARS products/activities</th></tr>
<tr><td colspan="2">ECOSTAT</td></tr>
<tr><td colspan="2">Overview:
A presentation on behalf of the ECOSTAT coordinators on the possible interactions and synergies between ECOSTAT and the project MARS was given by JRC at the MARS mid-term meeting in Fulda, Germany in March 2016.</td></tr>
<tr><td>Intercalibration:
Large rivers and transitional waters</td><td>D4.3 Manuscripts on river basin management. D4.3-1: Management of complex multi-stressor hierarchies in time and space; D4.3-2: Emergent lessons for the diagnosis, detection and management of multiple stressors using static, functional and dynamic indicators
D6.1 D6.1-2: Synthesis of stressor interactions and indicators: Manuscript on evaluation of methods for diagnosing cause of deteriorations in ecological status; D6.1-3: Synthesis of stressor interactions and indicators: Recommendations for more integrated river basin management and gaps in tools
D6.2 Synthesis report describing potential risks to status and services in relation to future scenarios of land-use change in combination with extreme climate events and possible mitigation options
D7.1 D7.1-3 MARS suite of tools I: Guidance document on the use of models in River Basin Management
D7.2 MARS suite of tools II: European scale scenario analysis tool</td></tr>
</table>

Table 4.2 (cont.): Links between WFD-CIS working groups main activities and MARS products

WFD CIS groups main activities	Relevant MARS products/activities
Hydromorphology: GEP harmonisation, E-flows, CEN HyMo standard	MARS addressed various hymo-pressures in experiments, case studies, and at European scale and produces multi-stressor maps and multistressor-impact relationships. **D3.2** Manuscripts on experimental results: D3.2-5 Impacts on river biota caused by extreme flows caused by hydropeaking and climate change in combination with eutrophication in Nordic rivers; D3.2-6 How extreme flows caused by hydropeaking and climate change affect river biota in combination with altered morphology and temperature in Alpine rivers; D3.2-7 How low flows affect river biota in combination with fine sediment dynamics and nutrients in Nordic rivers; D3.2-8 How low flows affect river biota in combination with organic load and varied temperature in Nordic and Mediterranean rivers **D4.3** D4.3.2 Manuscripts on river basin management: Emergent lessons for the diagnosis, detection and management of multiple stressors using static, functional and dynamic indicators **D5.1** D5.1-1 Reports on stressor classification and effects at the European scale: EU-wide multi-stressors classification and large scale causal analysis; D5.1-2 Reports on stressor classification and effects at the European scale: Relation of low flows, E-Flows, and Ecological Status
Nutrient standards: Guidance under development on how to set and use nutrient standards compatible with good ecological status.	How to set single stressor boundaries in multiple stressor environment? MARS studies the interaction of nutrients and other pressures, e.g. climate change, identifying whether interaction is present: if additive or synergistic: boundaries need to be more stringent, if antagonistic, then boundaries can be more relaxed. How to use these boundaries in ecological assessment and management now and in the future? MARS case study models assess distance to nutrient targets and links management measures needed to achieve the target under various land use and climate change scenarios, also considering upstream/downstream linkages. **D3.2** Manuscripts on experimental results: D3.2-1 Extreme rainfall and nutrients effects on shallow lakes; D3.2-2 Heat-wave and nutrients effects on shallow lakes, D3.2-3 Effects of nutrients, brownification by humic substances and extreme mixing (summer storms) in a deep stratified lake; D3.2-4 Interactive effects of climate, water quality and land use on river structure, function and ecosystem services; D3.2-5 Impacts on river biota caused by extreme flows caused by hydropeaking affect in combination with eutrophication in Nordic rivers; D3.2-7 How low flows affect river biota in combination with fine sediment dynamics and nutrients in Nordic rivers; D3.2-8 How low flows affect river biota in combination with organic load and varied temperature in Nordic and Mediterranean rivers **D4.2** D4.2.3 Manuscripts on stressor effects at the river basin level: Stressor propagation through inland/ transitional linkages and management consequences **D8.3** MARS synthesis paper including a collection of major inputs from the scientific community to WFD revision focusing on integrated status assessment, links between water status and ecosystem services and optimization of PoMs to mitigate the most common combinations of multiple stressors Furthermore, direct collaboration between MARS scientists and the ECOSTAT task group on nutrient standards has been carried out.

Table 4.2 (cont.): Links between WFD CIS working groups main activities and MARS products

FLOODS	
Main activities	**Relevant MARS products/activities**
Extracted from the Work Programme 2016-2018: Workshops on many topics, e.g.: - Pluvial floods, flash floods - Economic assessments of floods damage and measures - Effectiveness of measures - Science-policy interface - Climate change adaptation in flood risk management - Civil protection, critical infrastructure and cascading events - Coordination of FD & WFD & HD implementation - Green infrastructure and Natural Water Retention Measures - Spatial planning and non-structural preventive measures Resource documents on: - WFD & FD synergies - Habitats Directive and FD - Conducting PFRAs	**D2.1, D6.1, D7.1** Application of scenarios on the future of Europe's water resources testing impacts of extreme events on these assessment tools and which management measures would be best to counteract and mitigate impacts of such events (e.g. floodplains, green corridors along rivers). **D3.2** Manuscripts on experimental results: D3.2-1 Extreme rainfall and nutrients effects on shallow lakes; D3.2-5 Impacts on river biota caused by extreme flows caused by hydropeaking in combination with eutrophication in Nordic rivers; D3.2-6 How extreme flows caused by hydropeaking and climate change affect river biota in combination with altered morphology and temperature in Alpine rivers **D4.2** D4.2-3 Manuscripts on stressor effects at the river basin level: Stressor propagation through inland/ transitional linkages and management consequences; **D4.3** Testing effects of various flood risk reduction measures (e.g. restoration of riparian zones) in case study catchments
MAES	
Main activities	**Relevant MARS products/activities**
Action 5. Promote integration into accounting & reporting at EU & national level by 2020 **Action 6a.** Develop strategic framework to set priorities for ecosystem restoration at EU level	**D2.1** D2.1-2 Development of a methodology for the biophysical assessment and economic valuation of water ecosystem services, relevant for water resource management and river basin management plans of the WFD. **D4.1** Analysis of ecosystem services provided by aquatic ecosystem in 16 European catchments by research teams of different countries across Europe **D5.1** D5.1-3 Mapping and assessment of major services of rivers, lakes and coastal water ecosystems at the European scale, linking them to the multiple pressures and ecological status of water bodies **D5.1** D5.1-3 Economic valuation of ecosystem services provided by European lakes and reservoirs The research published by MARS was disseminated to JRC colleagues coordinating the MAES pilots (Urban: Joachim Maes; Forest: Jose Barroso; Agri-ecosystem: Maria Luisa Paracchini) and to DG ENV. MAES is currently working on the development of an analytical framework for mapping and assessment of ecosystem condition. The work developed by MARS for freshwater (Deliverable D2.1-2 and D5.1-3) has been considered relevant both for the methodological approach and the relationship between ecosystem services and conditions. JRC has also assured dissemination of the MARS research in the EU FP7 projects GLOBAQUA and OpenNESS, as it is actively involved in these projects. In addition, the results of MARS were communicated to JRC colleagues working on the project KIP-INCA (collaboration between DG ENV, EUROSTAT, DG JRC and EEA, on the accounting of ecosystem services).

Table 4.3: WFD-CIS workshops attended with MARS presentations

Working Group	Workshops with MARS presentations
ECOSTAT	**March 2016 in Warsaw, Poland** – MARS activities and products and how they could link to the different ECOSTAT activities were presented by Anne Lyche Solheim, NIVA. **October 2016 in den Helder, the Netherlands** – A whole day was devoted to a joint ECOSTAT-MARS workshop. The following presentations were given: 1. MARS overview was presented by Sebastian Birk, UDE. 2. MARS tools were presented by Tom Buijse, Deltares (MARS Information System), Christian Feld, UDE (MARS diagnostic tool), Gerben van Geest, Deltares (MARS framework for combining abiotic and biotic models), Markus Venohr, IGB (MARS Scenario Analysis Tool). 3. Output from stakeholder workshop on MARS tools and progress in other MARS activities were presented by Anne Lyche Solheim, NIVA. **April 2017 in Berlin, Germany** – MARS activities, including announcement of the MARS e-Conference on 'The Future of Water Management in Europe', were presented by Anne Lyche Solheim, NIVA. **October 2017 in Ispra, Italy** – a brief account of the outputs from this e-Conference were presented by Ana Cristina Cardoso, JRC.
Floods	**October 2016 in Berlin, Germany** – MARS activities with relevance for the Floods working group programme were presented by Lidija Globevnik, University of Ljubljana **November 2017 in Tallinn, Estonia** – A presentation on impacts on ecological status from multiple pressures including floods was presented by Lidija Globevnik, University of Ljubljana, Slovenia.
MAES	The research activities developed in the MARS on mapping and assessment of water ecosystem services were communicated to the MAES Working Group before their regular meetings. In particular: • 10th MAES Meeting, 17-18 September 2015, Brussels. Information note to MAES Working Group. • 11th MAES Meeting, 8 March 2016, Brussels. Information note to MAES Working Group. • 12th MAES Meeting, 19 September 2016, Brussels. Personal communication to JRC colleagues attending the meeting. The assessment of ecosystem services at the European scale (MARS Deliverable D5.1-3) was presented to the MAES WG coordinator (DG ENV) and key partners (JRC, EEA and Topic Centres) at the meeting 'Preparation for the EU MAES Workshop on Ecosystem Condition' that took place on 27-28 June 2017 in Brussels (Belgium), gathering representatives from Member States, DG ENV, DG AGRI, DG JRC and EEA. The research contributed to the development of methodology and indicators to assess ecosystem condition, with a focus on the freshwater ecosystems (MAES Freshwater Pilot).

Scientific inputs to WFD revision

A successful three-day MARS Web Conference on the theme of 'The Future of Water Management in Europe: an e-Conference reviewing WFD implementation' was held in September 2017. 249 people attended from 27 European countries. Talks and panel discussions reviewed strengths, weaknesses, innovation and best practice in WFD monitoring, management and policy integration. The talks and panel discussions are available to view online: https://www.ceh.ac.uk/get-involved/events/future-water-management-europe-econference. A post-conference questionnaire was completed by 95 attendees.

The e-Conference was advertised through relevant EU project coordinators and social media (Twitter and Facebook) and attracted 249 attendees from 27 European countries and ten countries outside Europe (including USA, Canada, India, China, Brazil, Australia and New Zealand). The e-Conference centred around twelve talks given by expert speakers on a range of topics reviewing strengths, weaknesses, innovation and best practice. Additionally, there were six panel discussions with two speakers and two additional expert panellists (chair & guest panellist). In addition to representatives from MARS, speakers and panellists were invited from a range of other relevant EU projects (AQUACROSS, OpenNESS, GlobAqua, FAIRWAY) and relevant bodies (e.g. ECOSTAT and EEA). An anonymous online post-conference questionnaire was then circulated to all registered attendees, collating the views of attendees on a number of the key topics related to WFD revision. There were over 13,000 Twitter 'impressions' during the e-Conference and over 450 video views since the e-Conference. The background of the 95 respondents to the questionnaire was predominantly from 23 countries across Europe representing scientific research (53 %) or River Basin manager/ regulatory agency (33 %). A few respondents were from water, energy and agricultural policy, consultancy and (hydropower) business backgrounds. When asked to rate their knowledge of the Water Framework Directive implementation, 78 % of questionnaire respondents assessed it to be either good or high, suggesting the questionnaire responses were based largely on a thorough understanding of the WFD implementation.

The opinions from the e-Conference have since been summarised in Deliverable D8.3 and will be finalised as a paper publication over the next few months followed by a policy brief to be circulated and presented by members of the MARS project team to DG ENV and ECOSTAT.

The recommendations cover three main themes addressed in the e-Conference:

1. Monitoring & Assessment Systems
2. Managing water resources impacted by multiple stressors
3. Integration across policy sectors

One key conclusion was that there is an urgent need to develop processes and targets for the WFD beyond 2027. These need to recognise the reality that long negotiation and planning periods are needed to implement many catchment measures and recovery times may span decades once measures have been implemented. Social acceptance of wide-scale catchment measures and agreement over potentially conflicting policy demands may drive the success or failure of the ambitious WFD target of good status in all waters.

There was strong support across speakers and respondents that we should not lose the positive momentum the WFD has created. The WFD focus on ecosystem health is even more understood and accepted today and fits closely with the EU Biodiversity Strategy 2020 and the global goals of the UN Intergovernmental Panel on Biodiversity and Ecosystem Services (IPBES) and the UN Sustainable Development Goals. In short, it was concluded that the WFD's framework and approach on ecosystem health was ambitious and ground-breaking.

Progress with management measures and improving quality has not been rapid, and certainly slower than originally envisaged, but this progress needs to be built upon stronger policy integration across sectors and maintaining resourcing for effective evidence-based decisions in both monitoring and management. Integrated water resource management is never going to be easy to achieve, but successful examples at local and river basin scales demonstrate that real progress can be made. To further facilitate enhanced WFD implementation there is a great need to more widely share these experiences and knowledge. Since its inception, the WFD has inspired other water policies around the world. After >15 years of implementation it now needs to evolve to address the weaknesses in implementation. It envisioned an integrated monitoring, management and policy framework that operates at a landscape scale, the sustainable development challenge is to now deliver that more effectively.

Cross-cutting communication, including policy briefs and other external content of the MARS website

The MARS web-site (http://www.mars-project.eu) was maintained and regularly updated during the entire project's duration, to communicate the objectives, approaches, events and results to the external target groups.

The Freshwater Blog (http://freshwaterblog.net/) was fed with weekly posts, directly communicating and profiling the work of the MARS project and individual scientists; or of related EU projects such as GLOBAQUA, AQUACROSS and SOLUTIONS. The blog provided an in-depth and engaging look 'behind the scenes' of the project, and provided simple explanations of the project's key (and often complex) focuses.

The blog also continued to invite debate on new and important scientific publications and policy topics relating to freshwaters. These are designed to attract an interested audience of freshwater scientists, water managers and policy makers, thereby also raising the visibility of the MARS project, and providing a growing open-access resource of engaging, accessible material on the science, policy and management of aquatic multiple stressors.

The first Freshwater Blog post under MARS editorial was on 17.02.14 – since then 231 blog posts have been published (58 in 2014, 56 in 2015, 54 in 2016, 53 in 2017, 10 in 2018), including:

- Visualising multiple stressors on European river catchments: the MARS Scenario Analysis Tool (March 2018)
- Messages from MARS (February 2018)
- Sketching another world: Stephen Thackeray's aquatic art/science drawings (November 2017)
- The politics of biodiversity and hydropower on 'Europe's last wild river' (July 2017)
- Managing multiple stressors in European water bodies: reporting on MARS progress (October 2016)
- Freshwater species populations fall by 81% between 1970 and 2012 (October 2016)
- Ecological surprises: why multiple stressors in freshwaters may cancel each other out (September 2015)
- MARS Podcast: an interview with Professor Steve Ormerod (March 2015)
- Key Biodiversity Areas: new IUCN report finds that Mediterranean freshwater ecosystems are inadequately protected (November 2014)
- Introducing the MARS river and lake experiments (September 2014)

The popularity of the blog has grown significantly since MARS took editorial responsibility in February 2014, totalling 402,016 views between its establishment and March 2018. There were 68,873 views in 2014, 104,672 views in 2015, 107,468 views in 2016, and 102,575 views in 2017. Between January and March 2018 there were 18,428 views. The most popular month was June 2015 (16,214 views) and most popular day 15.06.15 (1,575 views). The blog posts published between February 2014 and March 2018 total 190,003 words.

The Freshwater Blog has 327 followers who automatically receive each post in their email inbox, and 268 who receive them in their Wordpress inbox.

As of March 2018, the MARS Blog social media communication metrics are:

- Twitter: https://twitter.com/freshwaterblog, The Freshwater Blog twitter is predominantly followed by water scientists, conservationists, managers and other professionals around the world, and has 3,794 followers who receive each post.
- LinkedIn: https://www.linkedin.com/grp/home?gid=4148402. The Freshwater Blog LinkedIn group has 344 members, largely drawn from water scientists, researchers and managers. It is used to post updates from the Freshwater Blog, and to facilitate discussions amongst members.
- Facebook: https://www.facebook.com/TheFreshwaterBlog The Freshwater Blog facebook page was transitioned from the BioFresh Cabinet of Freshwater Curiosities page, and has 980 followers. It is used to share Freshwater Blog posts, and to facilitate discussion, amongst an audience of predominantly freshwater and conservation students, researchers and professionals.

Policy briefs represent an important element in the MARS communication and dissemination strategy. They allow for translating the project's evidence into tangible policy recommendations. The policy briefs mainly target the audiences engaged with river basin management. Deliverable D8.1 includes the policy briefs 'Relevance of multiple pressures, related stressors and their interactions in European River Basin Management' and 'Protecting and restoring Europe's waters: The current state and future evolution of the Water Framework Directive'. The first brief advocates tailor-made management strategies for multiply-stressed water bodies and asks for riparian management as a key to success. The second brief highlights the issues in relation to monitoring and assessment systems, management measures, policy integration and WFD continuation beyond 2027.

Professional video-clips on MARS outline and results

Main achievement of this task was the production of the video 'The good ecological status of rivers and lakes' (Figure 4.1). The video aims at communicating the key-objective of the Water Framework Directive to a wider audience (including stakeholders broadly concerned with river basin management). It is publicly available at https://www.youtube.com/watch?v=xOExg4B9tRY and already received 2,330 views (last accessed on 17 April 2018). A German version was also produced (1,080 views). The video was generally well received, with requests from several national and regional water administrations for presenting it at stakeholder meetings to inform about the objectives of the European Water Framework Directive.

Figure 4.1: Thumbnail of the video 'The good ecological status of rivers and lakes' produced by the MARS project.

The first video-clip providing an overview of multiple pressures, the problems they cause, the challenges on how the could be managed, and how MARS will contribute has been published at VIMEO: https://vimeo.com/137474377. We furthermore published a summary of results and impressions of the MARS Vienna workshop at VIMEO: https://vimeo.com/163431149. In addition, several interviews of scientist from MARS and related projects have been published as videos (https://www.youtube.com/user/AquatischeOekologie; http://www.mars-project.eu/index.php/what-is-mars.html).

The Freshwater Information Platform

A main obstacle for disseminating results of EU-funded projects is the lack of maintenance of products, such as databases, models or tools, once a project has ended. To overcome this problem, MARS (in collaboration with other projects) has launched the Freshwater Information Platform (http://www.freshwaterplatform.eu/), on which results of several projects are combined, disseminated on maintained. Currently, four institutes are committed to maintain the platform independently from project cycles.

The MARS consortium has agreed to make available major parts of the results obtained in the project through the FIP. This concerns all metadata, parts of the original data, the tools generated in WP7, and all maps resulting from WPs 4 and 5. Furthermore, MARS maintained and extensively used the Freshwater Blog (www.freshwaterblog.eu), which is part of the FIP.

The FIP was launched in May 2015. It is partly based on previous projects (in particular BioFresh), and was step by step extended with MARS results, but also with results of related projects such as GLOBAQUA and SOLUTIONS. The FIP is an interactive website integrating results and original data stemming from finished, on-going, and future freshwater research projects. The platform contains several complementary sections, either providing access to original data or summarising research results in an easily digestible way. All sections are composed as 'living documents' that will be continuously improved and updated.

The 'Freshwater Biodiversity Data Portal' provides access to data on the distribution of freshwater organisms (such as fishes, insects and algae), both in Europe and worldwide, whilst the 'Global Freshwater Biodiversity Atlas' provides a series of maps on freshwater biodiversity richness, threats to freshwaters (or 'stressors') and the effects of global change on freshwater ecosystems.

The 'Freshwater Species Traits Database' integrates the knowledge on the ecology of around 20,000 species inhabiting European freshwater ecosystems, including information about where species live, what they feed on or how tolerant they are to pollution.

The 'Freshwater Metadata' section provides an overview of hundreds of major data sources related to freshwater research and management and offers the option to publish such data in the Freshwater Metadata Journal.

The vibrant and widely-read 'Freshwater Blog' publishes features, research highlights, interviews and podcasts on freshwater science, policy and conservation. The Freshwater Information Platform also provides a collection of research tools, information about freshwater-related policies and relevant European and global networks relating to freshwater science and policy.

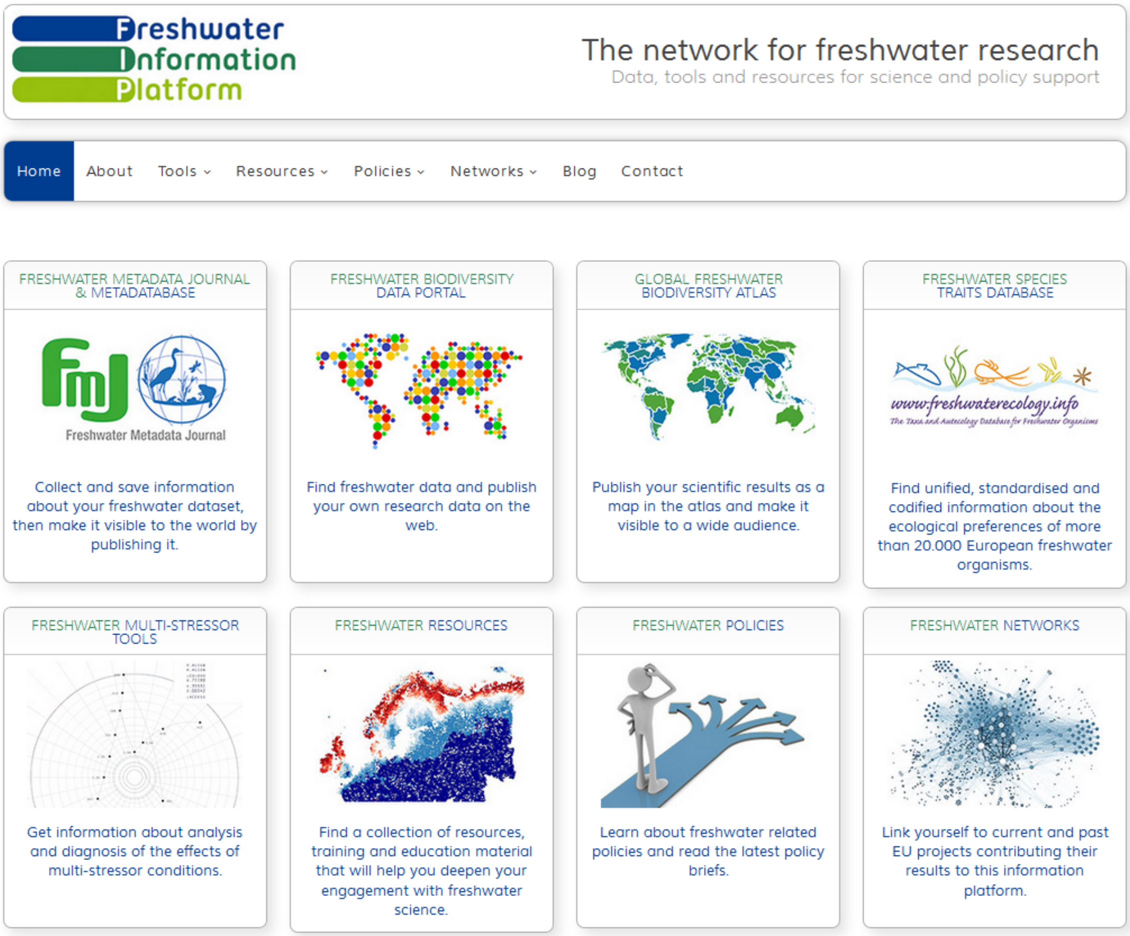


Figure 4.2: Screenshot of the FIP start page.

Deliverables

The main dissemination outcomes are documented in the following deliverables:

- D8.1 Policy briefs containing recommendations in the form of key messages
- D8.2 Guidance document for river basin managers and other sectors (energy, water industry, agriculture) on how to best assess and mitigate impacts of multiple pressures
- D8.3 MARS synthesis paper including a collection of major inputs from the scientific community to WFD revision focusing on integrated status assessment, links between water status and ecosystem services and optimization of PoMs to mitigate the most common combinations of multiple stressors
- D8.4 Factsheets including a set of illustrations

List of beneficiaries

No	Name	Short name	Country	Leader	
1	UNIVERSITAET DUISBURG-ESSEN	UDE	Germany	Daniel Hering	daniel.hering@uni-due.de
2	AARHUS UNIVERSITET	AU	Denmark	Erik Jeppesen	ej@dmu.dk
3	FUNDACION AZTI/AZTI FUNDAZIOA	AZTI	Spain	Angel Borja	aborja@azti.es
4	UNIVERSITAET FUER BODENKULTUR WIEN	BOKU	Austria	Stefan Schmutz	stefan.schmutz@boku.ac.at
5	CESKY HYDROMETEOROLOGICKY USTAV	CHMI	Czech Republic	Vít Kodeš	kodes@chmi.cz
6	CARDIFF UNIVERSITY	CU	United Kingdom	Steve Ormerod	ormerod@cardiff.ac.uk
7	INSTITUTUL NATIONAL DE CERCETARE-DEZVOLTARE DELTA DUNARII	DDNI	Romania	Jenica Hanganu	hanganu@ddni.ro
8	STICHTING DELTARES	DELTARES	The Netherlands	Marijn Kuijper	Marijn.Kuijper@deltares.nl
9	EESTI MAAULIKOOL	EMU	Estonia	Tiina Nõges	tiina.noges@emu.ee
10	FORSCHUNGSVERBUND BERLIN E.V.	FVB-IGB	Germany	Markus Venohr	m.venohr@igb-berlin.de
11	INSTITUT NATIONAL DE RECHERCHE EN SCIENCES ET TECHNOLOGIES POUR L'ENVIRONNEMENT ET L'AGRICULTURE	IRSTEA	France	Christine Argillier	christine.argillier@irstea.fr
12	JOINT RESEARCH CENTRE- EUROPEAN COMMISSION	JRC	Belgium	Ana-Cristina Cardoso	ana-cristina.cardoso@ec.europa.eu
13	MIDDLE EAST TECHNICAL UNIVERSITY	METU	Turkey	Meryem Beklioglu	meryem@metu.edu.tr
14	NATURAL ENVIRONMENT RESEARCH COUNCIL	NERC	United Kingdom	Laurence Carvalho	laca@ceh.ac.uk
15	NORSK INSTITUTT FOR VANNFORSKNING	NIVA	Norway	Anne Lyche Solheim	als@niva.no
16	NATIONAL TECHNICAL UNIVERSITY OF ATHENS	NTUA	Greece	Yiannis Panagopoulos	ypanag@chi.civil.ntua.gr
17	SUOMEN YMPARISTOKESKUS	SYKE	Finland	Marko Järvinen	marko.jarvinen@ymparisto.fi
18	UNIVERZA V LJUBLJANI	UL	Slovenia	Lidija Globevnik	lidija.globevnik@tcvode.si
19	UNIVERSIDADE TECNICA DE LISBOA	ULisboa	Portugal	Teresa Ferreira	terferreira@isa.utl.pt
20	AGENCIA PORTUGUESA DO AMBIENTE	APA	Portugal	Helena Alves	helena.alves@apambiente.pt
21	BUNDESMINISTERIUM FÜR LAND- UND FORSTWIRTSCHAFT, UMWELT UND WASSERWIRTSCHAFT	BMLFUW	Austria	Helena Mühlmann	helena.muehlmann@lebensministerium.at
22	ENVIRONMENT AGENCY	EA	United Kingdom	Jo-Ann Pitt	jo-anne.pitt@environment-agency.gov.uk
23	INTERNATIONAL COMMISSION FOR THE PROTECTION OF THE DANUBE RIVER	ICPDR	Austria	Adam Kovacs	adam.kovacs@icpdr.org
24	NATIONAL ADMINISTRATION APELE ROMANE	NARW	Romania	Corina Boscornea	corina.boscornea@rowater.ro

References

Alahuhta, J., Aroviita, J., 2016. Quantifying the relative importance of natural variables, human disturbance and spatial processes in ecological status indicators of boreal lakes. Ecol. Indic. 63, 240-248.

Bækkelie, K.A.E., Schneider, S.C., Hagmann, C.H.C., Petrin, Z., 2017. Effects of flow events and nutrient addition on stream periphyton and macroinvertebrates: an experimental study using flumes. Knowledge and management of aquatic ecosystems 418 (article no. 47).

Birk, S., W. Bonne, A. Borja, S. Brucet, A. Courrat, S. Poikane, A. Solimini et al., 2012. Three hundred ways to assess Europe's surface waters: An almost complete overview of biological methods to implement the Water Framework Directive. Ecol. Indic. 18, 31-41.

Birk, S, Böhmer, J., Schöll, F., 2017. Intercalibrating the national classifications of ecological status for very large rivers in Europe – Biological Quality Element: Benthic Invertebrates. JRC Technical Reports. Luxembourg: Publications Office of the European Union. 255 p.

Birk, S., Böhmer, J., Schöll F., 2018. XGIG Large River Intercalibration Exercise - Fish Fauna: Summary of the achievements and open issues. 37 p.

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. Sci. Total Environ. 573, 594-602.

Bowes, M.J., Loewenthal, M., Read, D.S., Hutchins, M.G., Prudhomme, C., Armstrong, L.K., Harman, S.A., Wickham, H.D., Gozzard, E., Carvalho, L., 2016. Identifying multiple stressor controls on phytoplankton dynamics in the River Thames (UK) using high-frequency water quality data. Sci. Total Environ. 569–570, 1489-1499.

Branco, P., Boavida, I., Santos, J.M., Pinheiro, A., Ferreira, M.T., 2013. Boulders as building blocks: Improving habitat and river connectivity for stream fish. Ecohydrology 6, 627-634.

Bucak, T., Trolle, D., Tavşanoğlu, N., Çakıroğlu, A.İ., 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. Sci. Total Environ. 621, 802-816.

Bussi, G., Whitehead, P.G., Bowes, M.J., Read, D.S., Prudhomme, C., Dadson, S.J., 2016. Impacts of climate change, land-use change and phosphorus reduction on phytoplankton in the River Thames (UK). Sci. Total Environ. 572, 1507-1519.

Bussi, G., Whitehead, P.G., Gutiérrez-Cánovas, C., Ledesma, J.L.J., Ormerod, S.J., Couture, R.M., 2018. Modelling the effects of climate and land-use change on the hydrochemistry and ecology of the River Wye (Wales). Sci. Total Environ. 627, 733-743.

Carvalho, L., C. McDonald, C. De Hoyos, U. Mischke, G. Phillips, C. Borics, S. Poikane et al., 2013. Sustaining recreational quality of European lakes: minimising the health risks from algal blooms through phosphorus control. J. Appl. Ecol. 50, 315-323.

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. Sci. Total Environ. 621, 713-724.

Crane, M., C. Watts & T. Boucard, 2006. Chronic aquatic environmental risks from exposure to human pharmaceuticals. Sci. Total Environ. 367: 23-41.

Duethmann, D., S. Anthony, L. Carvalho & B.M. Spears, 2009. A model-based assessment of non-compliance of phosphorus standards for England and Wales. International Journal of River Basin Management 7, 197-207.

EEA, 2012. European waters – assessment of status and pressures. EEA report 8/2012.

ETC-ICM, 2012. Hydromorphological alterations and pressures in European rivers, lakes, transitional and coastal waters. ETC- ICM Technical Report 2/2012. European Topic Centre on Inland, Coastal and Marine waters, Prague.

ETC-ICM, 2015. European Freshwater Ecosystem Assessment: Cross-walk between the Water Framework Directive and Habitats Directive types, status and pressures, ETC-ICM Technical Report 2/2015. European Topic Centre on Inland, Coastal and Marine waters, Magdeburg.

Feld, C K., S. Birk, D.C. Bradley, D. Hering, J. Kail, A. Marzin, A. Melcher, et al., 2011. From Natural to Degraded Rivers and Back Again: a test of restoration ecology theory and practice. Advances in Ecological Research 44, 119-209.

Feld, C.K., Fernandes, M. do R.P., Ferreira, M.T., Hering, D., Ormerod, S.J., Venohr, M., Gutiérrez-Cánovas, C., 2018. Evaluating riparian solutions to multiple stressor problems in river ecosystems — A conceptual study. Water Res. 139, 381-394.

Gieswein, A., Hering, D., Feld, C.K., 2017. Additive effects prevail: the response of biota to multiple stressors in an intensively monitored watershed. Sci. Total Environ. 593-594, 27-35.

Globevnik, L., Koprivsek, M., Snoj, L., 2017. Metadata to the MARS spatial database. Freshw. Metadata J. 21, 1-7.

Grizzetti, B., Pistocchi, A., Liquete, C., Udias, A., Bouraoui, F., Van De Bund, W., 2017. Human pressures and ecological status of European rivers. Sci. Rep. 7, 1-11.

Hering, D., A. Borja, J. Carstensen, L. Carvalho, M. Elliott, C.K. Feld, A.-S. Heiskanen, R.K. Johnson, J. Moe, D. Pont, A. Lyche Solheim & W. van de Bund, 2010. The European Water Framework Directive at the age of 10: A critical review of the achievements with recommendations for the future. Sci. Total Environ. 408, 4007-4019.

Hering, D., A. Borja, L. Carvalho & C.K. Feld, 2013. Assessment and recovery of European water bodies: key messages from the WISER project. Hydrobiologia 704, 1-9.

Jeppesen, E., M. Søndergaard, M. Meerhoff, T.L. Lauridsen & J.P. Jensen, 2007. Shallow lake restoration by nutrient loading reduction – some recent findings and challenges ahead. Hydrobiologia 584, 239-252.

Jöhnk, K.D., Huisman, J., Sharples, J., Sommeijer, B., Visser, P.M., Stroom, J.M., 2008. Summer heatwaves promote blooms of harmful cyanobacteria. Global Change Biology 14, 495-512.

Kaandorp, V.P., Molina-Navarro, E., Andersen, H.E., Bloomfield, J.P., Kuijper, M.J.M., de Louw, P.G.B., 2018. A conceptual model for the analysis of multi-stressors in linked groundwater–surface water systems. Sci. Total Environ. 627, 880-895.

Kail, J. & C. Wolter, 2011. Analysis and evaluation of large-scale river restoration planning in Germany to better link river research and management. River Research and Applications 27, 985-999.

Leung, B., D.M. Lodge, D. Finnoff, J.F. Shogren, M.A. Lewis & G. Lamberti, 2002. An ounce of prevention or a pound of cure: bioeconomic risk analysis of invasive species. Proceedings of the Royal Society: Biological Sciences 269, 2407-2413.

Moe, S.J., Haande, S., Couture, R.M., 2016. Climate change, cyanobacteria blooms and ecological status of lakes: A Bayesian network approach. Ecol. Modell. 337, 330-347.

Nõges, P., Argillier, C., Borja, Á., Mikel, J., Kode, V., Pletterbauer, F., Sagouis, A., Birk, S., 2016. Quantified biotic and abiotic responses to multiple stress in freshwater, marine and ground waters. Sci. Total Environ. 540, 43-52.

Nõges, T., Anneville, O., Guillard, J., Haberman, J., Järvalt, A., Manca, M., Morabito, G., Rogora, M., Thackeray, S.J., Volta, P., Winfield, I.J., Nõges, P., 2018. Fisheries impacts on lake ecosystem structure in the context of a changing climate and trophic state. J. Limnol. 77, 46-61.

Prudhomme, C., D. Jakob & C. Svensson, 2003. Uncertainty and climate change impact on the flood regime of small UK catchments. Journal of Hydrology 277, 1-23.

Rankinen, K., Butterfield, D., Faneca Sànchez, M., Grizzetti, B., Whitehead, P., Pitkänen, T., Uusi-Kämppä, J., Leckie, H., 2016. The INCA-Pathogens model: An application to the Loimijoki River basin in Finland. Sci. Total Environ. 572, 1611-1621.

Read, D. S., Bowes, M. J., Gweon, S., Oliver, A., Newbold, L., Rhodes, G., Carvalho. L., 2017. Pathogen dynamics in the river Thames (UK) over a two-year period. Deliverable 4.2-5: Multiple-stressor risks for pathogens. MARS Project.

Segurado, P., Almeida, C., Neves, R., Ferreira, M.T., Branco, P., 2018. Understanding multiple stressors in a Mediterranean basin: Combined effects of land use, water scarcity and nutrient enrichment. Sci. Total Environ. 624, 1221-1233.

Whitehead, P.G., Leckie, H., Rankinen, K., Butterfield, D., Futter, M.N., Bussi, G., 2016. An INCA model for pathogens in rivers and catchments: Model structure, sensitivity analysis and application to the River Thames catchment, UK. Sci. Total Environ. 572, 1601-1610.