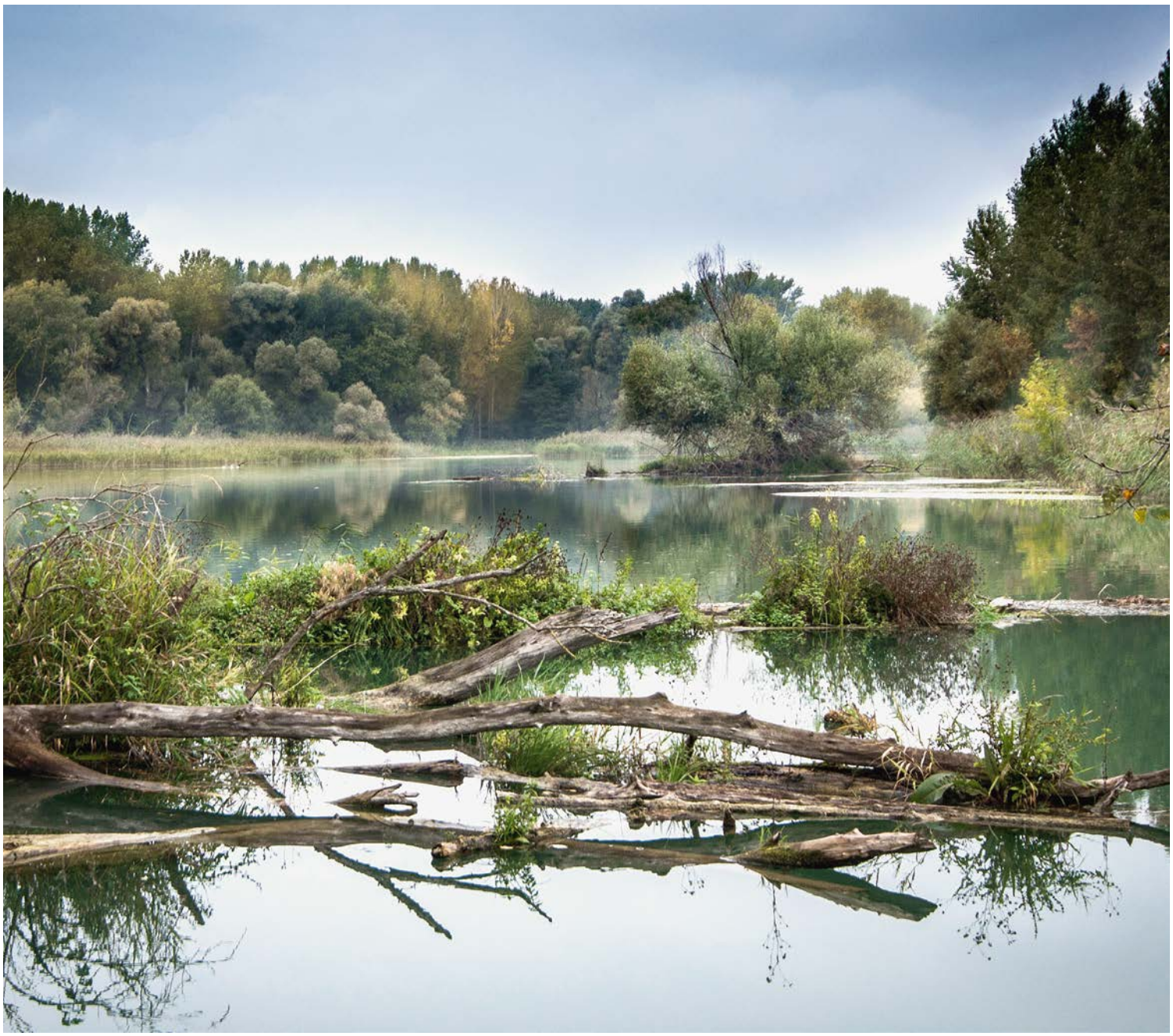
Living Waters:

A Research Agenda for the Biodiversity of Inland and Coastal Waters



Summary

Freshwaters including adjacent floodplains, as well as coastal waters are among the global hotspots of biological diversity. They are also among the most threatened ecosystems on Earth, and yet receive much less attention than terrestrial and marine ecosystems. Not only does the dramatic decline in freshwater biodiversity affect all levels of biological diversity (genotypes, species, populations, communities, habitats and ecosystems), it also compromises the ecosystem functions and services upon which humans rely. This loss of function has direct consequences for human livelihoods and quality of life, as well as for our capacity to mitigate the effects of climate change. Legislative and other measures to preserve and promote freshwater biodiversity have to date fallen short of stopping the decline of freshwater biodiversity and associated functions. In order to comprehensively protect freshwater biodiversity, new approaches must be developed and implemented.

Bearing this in mind, biodiversity research is called upon to provide workable approaches, appropriate methods and detailed information. A number of scientists engaged in aquatic biodiversity research in Germany have prepared this Research Agenda "Living Waters", in an intense process of exchange. The overarching objectives proposed in "Living Waters" are: to document the status and trends of freshwater biodiversity; to achieve a mechanistic understanding of how natural and anthropogenic factors influence freshwater biodiversity; to derive forecasts of future developments; and to develop approaches, strategies and measures for managing biodiversity sustainably and for achieving national, European and global targets. Such an ambitious agenda requires expertise from the natural, engineering and social sciences. The Research Agenda must, at its core, take account of society's perception of aquatic biological diversity, and of social and technological developments. The agenda must also integrate the whole range of actors and levels of action.

The sustainable management of freshwaters and coastal waters and effective conservation approaches require the integration of spatially and temporally explicit knowledge regarding the occurrence and development of freshwater biodiversity. To achieve this, monitoring data must be systematically exploited and made available digitally and free of charge. Data include those collected under the Water Framework Directive and the Habitats Directive, as well as those from other, hitherto underutilised sources.

The core elements underpinning the proposed Research Agenda are:

Monitoring: Establishment of a national aquatic biodiversity monitoring scheme; development and application of new methods – including environmental DNA (eDNA), remote sensing and citizen science – for the recording of biodiversity and of ecosystem processes; an understanding of the spread of invasive alien species including parasites; deepening of knowledge on taxonomy and ecology.

Ecology: Synthesis of controlling factors and cause-and-effect relationships with freshwater biodiversity, including ecosystem functions and services; quantification of interactions in ecosystems; predictions of the effects of extreme events; an understanding of the key role of invasive alien species; development of process-based models and their integration with experiments; establishment of large-scale research on restoration.

Society: Integration and consideration of human objectives and actions; clarification and transparency of social motives and norms; methods for the presentation and weighing of environmental, economic and societal needs; development of new approaches to integrate citizen science, raise awareness, improve education and incentivise public participation.

Options for action: Evaluation of environmental policy measures and water management options in terms of biodiversity conservation and presentation of alternative options; development of innovative solutions to conflicts of interests; development of mitigation and adaptation measures for freshwater biodiversity; evaluation of the importance of constructed ecosystems; scenario framework for biodiversity predictions.

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Biological diversity.
also biodiversity; the diversity of species, genetic diversity, the composition of communities, interactions within and between communities, and the diversity of habitats and ecosystems.

BMBF (2019): Forschungsinitiative zum Erhalt der Artenvielfalt (Research Initiative for the Conservation of Biodiversity); mirrors the definition by the Convention on Biological Diversity (CBD)
https://www.bmbf.de/upload_filestore/pub/Forschungsinitiative_zum_Erhalt_der_Artenvielfalt.pdf
[1 May 2019]

Preamble

Conserving biodiversity and its wide range of ecosystem functions is one of the biggest challenges of our time. It is against this backdrop that the **Research Initiative for the Conservation of Biodiversity** of the German Federal Ministry of Education and Research (BMBF) seeks to facilitate research on the systemic interrelationships associated with the loss of biodiversity and to help develop effective options for action in a rapidly changing world – as a potential flagship initiative of the "**Research for Sustainable Development (*Forschung für Nachhaltige Entwicklung*; FONA)" framework programme**.

This "Living Waters" Research Agenda makes a direct reference to this research policy framework, and focuses on Germany's and Europe's most species-rich habitats, which are also under the most pressure: **freshwaters** (groundwater, springs, brooks, rivers, small water bodies, lakes and wetlands) **and their adjacent floodplains and coastal waters**[1]. These freshwaters are global hotspots of biodiversity, and yet they are strongly impacted by numerous human activities. To assess the extent, causes and consequences of the loss of biodiversity in and along freshwater and coastal waters, a **holistic approach must be taken, an approach "from source to mouth" that also encompasses the entire catchment area of water bodies across administrative boundaries and that understands these waters and their adjacent floodplains as social-ecologically linked systems**. Building on this approach, biodiversity management can then be developed in the context of general resource and environmental management. This Research Agenda expands and furnishes the BMBF research initiative, and supports any government programmes that may be planned on research topics concerning the biodiversity of freshwater and coastal waters.

Excellent science in the various disciplines of biodiversity research is an integral part of making fundamental progress in the assessment, understanding and prediction of biodiversity. At the same time, however, **interdisciplinary research networks** and **collaborative transdisciplinary research among science, policy, administration, associations, industry and civil society** are needed to grasp the complexity of biodiversity management in its social context. Such collaboration includes exchange and cooperation on the part of the actors involved in this initiative with other initiatives, e.g. in the context of the Water Science Alliance, National Water Dialogue, international networks such as the Alliance for Freshwater Life, or potential accompanying research for the "Blue Ribbon" federal programme (*Blau-*

1 The terms "freshwater and coastal waters" and/or "aquatic biodiversity" are also used below for better legibility; both terms expressly include biological diversity in freshwater and coastal waters and in adjacent floodplains.

es Band Deutschland). When considering freshwater biodiversity in its entirety, it is important to overcome the disciplinary boundaries between freshwater and marine research, which continue to run through the scientific community and environmental legislation alike (e.g. the Marine Strategy Framework Directive versus the Water Framework Directive). Specifically, the task is to intensify exchange between different actors, e.g. with the "Coastal Research Strategy Group" of the "German Marine Research Consortium". Integrative concepts with terrestrial habitats are likewise necessary, due to the interconnectedness of freshwaters and their terrestrial surroundings. Recognising catchment areas as natural units of management would be a major step forward in crossing the disciplinary boundaries. This is now widespread practice in water management, particularly since the Water Framework Directive entered into force in 2000; however, the consideration of aquatic biodiversity remains very rare in terrestrial biodiversity monitoring and in many conservation approaches.

Challenges and objectives

Freshwaters including their adjacent floodplains and coastal waters are among the most **diverse, dynamic** and **complex** habitats on Earth[1]. Being **hotspots** of biological diversity, and owing to the essential **ecosystem services** they provide, freshwaters and coastal waters **need special protection**. To give an example, 8,500 animal and plant species have been recorded to date from the natural area of the Middle Elbe in Germany alone[2]. However, only less than one per cent of all running waters and floodplains in Germany are considered to be natural. Estuaries and coastal waters, being transitional waters between freshwater and marine ecosystems, also exhibit a species-rich blend of flora and fauna. Freshwaters and coastal waters also provide essential ecosystem services, such as the provision of **drinking water** in sufficient quality and quantity, **flood control**, **fishery resources**, and the **retention and conversion of nutrients**; they also provide space for **leisure** and **recreation**[3]. Coastal waters buffer land-based nutrient emissions, offering protection against marine **eutrophication** (nutrient enrichment); they are used as **spawning and rearing habitats** for many aquatic organisms of economic importance (fish and shellfish); and they provide shelter and food for many species of **shorebirds**. Coastal and freshwater fishing, including aquaculture, produces a significant proportion of the **animal protein** that feeds the world's population[4]; in Germany, recreational angling generates by far the largest fish yield[5]. Moreover, freshwaters and their floodplains play a central role in the **regional water cycle** and play a key role in organic matter processing and energy flow in the landscape. If freshwaters and their floodplains are no longer able to provide these natural functions due to **extensive human use** (e.g. problems with water quality and flood control), not only significant environmental, but also economic consequences arise. Finally, it has largely been overlooked that intact freshwater ecosystems have a high **cultural and aesthetic value**, with importance for quality of life generally accepted but little explored in detail.

Freshwaters and their floodplains are topographic sinks in the landscape that often exhibit the effects of chemical, physical, climatic and biological stressors. Coastal waters and estuaries are influenced directly by high nutrient and pollutant inputs from the catchment areas of the rivers that drain into them[6]. These ecosystems are also particularly susceptible to the intrusion of invasive species. One reason for this susceptibility is the large volume of shipping they sustain, another reason is the creation of new limnetic migration routes via artificial canal systems that link up different river regions and facilitate the immigration of alien species (e.g. numerous Ponto-Caspian species in the southeastern part of the Baltic Sea). Agriculture, industry, shipping, drinking water production, energy generation, wastewater disposal and recreational activities all use growing amounts of water, increasing the pressure exerted on **water as a limited resource**[7]. The anthropogenic pressure on water as a resource is exacerbated by the predicted impacts of climate change, as well as pathogens, parasites and other invasive alien species that have been introduced[8]. The rapid global change from the local to the global level substantially changes both phylogenetic and functional biodiversity. In coastal waters and estuaries, for example, a wide range of ecosystem functions are endangered by the decline of many structure-forming species, in combination with the immigration of new species – without having been systematically recorded to date. All these factors lead to a decrease in

the naturally high resilience and regenerative capacity of these systems and, ultimately, to the loss of biodiversity in our freshwaters.

Freshwater and coastal waters are among the most endangered habitats in the world: Globally, the loss of freshwater biodiversity is more than twice as high than in marine or terrestrial areas (WWF's Living Planet Index: a 83 % loss in selected vertebrate populations compared with 1970)[9]. Freshwater organisms and their habitats also top Red Lists at the national level[5]. Apart from a few exceptions, the current situation is presumably even more serious, because the extent of changes in many groups of organisms, types of aquatic ecosystems, and regions is presently unknown. This is particularly the case for changes in **groundwater communities,** which are strongly affected by heat input, groundwater depletion, construction projects and pollutant inputs, but which are little known and have not yet been systematically recorded[10]. No Red Lists exist for groundwater, and there are virtually no official monitoring programmes. No other freshwater habitat exhibits such major deficits when it comes to the implementation of legal requirements[11].

The loss of biodiversity has direct and indirect effects on **ecosystem functions,** such as productivity, self-cleaning and nutrient cycles, as well as the **ecosystem services** that depend on them[12]. This has a wide range of implications for human well-being, some of which are often unknown. The natural sustained benefits that society and industry gain from the ecosystem functions of freshwaters, their floodplains and coastal waters are **under severe threat throughout the world.** If tipping points in anthropogenic pressure are exceeded beyond the natural resilience of freshwater ecosystems, we may find ourselves without access to freshwater resources altogether.

Despite their importance, the endangerment of freshwaters is a **hidden crisis**. Whereas forests and oceans are discussed in day-to-day politics and have a (media) presence, freshwater species are disappearing and the ecological status of freshwaters are deteriorating without even drawing **public attention**[13]. In addition, the fact that freshwaters are habitats, sources of food and biodiversity hotspots does not enter into discussions on the distribution of water, such as the discussions held around the "food-water-energy nexus". **However, a reliable supply of water, food and energy and the conservation and promotion freshwater biodiversity are not mutually exclusive, because in fact they are interdependent**.

Several pieces of European legislation are intended to conserve and promote biodiversity, independently of the water bodies involved. The **Habitats Directive (HD),** the **Wild Birds Directive,** the **Water Framework Directive (WFD)** and the **Blueprint to Safeguard Europe's Water Resources** have led to great efforts and investments being made to halt the loss of biodiversity and ecosystem functions, and to reverse this trend. Germany is committed to the United Nations **Sustainable Development Goals (SDGs)**, has signed the **Convention on Biological Diversity (CBD)** and the **Ramsar Convention**. Germany also supported the **EU Biodiversity Strategy** and has implemented it nationally as the **National Strategy on Biological Diversity**. Germany is also strongly committed to the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (**IPBES**). Nevertheless, we are still a long way from halting the loss of aquatic biodiversity in Germany.

It is important to establish contemporary management for **competing demands on freshwater and coastal waters and their adjacent floodplains**, which result from different exploitation interests. Continuing agricultural practices in their current form, the pressures of tourism, shipping traffic, infrastructure works, fisheries and stocking, as well as the promotion of renewable energies by cultivating biomass and expanding the use of wind and hydropower often conflict with protection of aquatic biodiversity. This is compounded by the fact that legislation does not dovetail effectively with practices for managing freshwaters and their catchment areas. Although legal frameworks such as the WFD call for a different approach, most **measures occur in isolation**, and are thought out and implemented with too little consideration for the landscape context ("from source to mouth"). **A lack of coordination** between authorities and administrative boundaries within and between federal states often prevent whole catchment areas from being considered in the planning of measures. For this reason, positive individual measures, e.g. river system restorations, often have no impact.

A Research Agenda for the Biodiversity of Inland and Coastal Waters

The Research Agenda presented here proposes the further development of aquatic biodiversity research in order to help overcome the biodiversity crisis in freshwaters and their adjacent floodplains and coastal waters, whilst supporting sustainable development. This particularly relates to research foci on agriculture, climate change adaptation, infrastructure development, bioeconomy, the use of biomass, technological development, the exploitation of genetic resources and knowledge transfer in the area of integrated water management.

The overarching objectives of this Research Agenda are to document the status and development of aquatic biodiversity; to achieve a mechanistic understanding of factors influencing biodiversity, particularly anthropogenic pressures; to derive forecasts of multiple future scenarios; and to develop approaches, strategies and measures for sustainable biodiversity management in Germany that facilitate achieving national, European and global biodiversity targets. Besides drawing on expertise from the natural sciences, it is essential to include engineering and social science in the process. This requires incorporating society's perception of biological diversity, and of social and technological developments, and to integrate the whole range of actors and levels of action. Another main focus is on defining competencies and facilitating transdisciplinary networking among actors who benefit directly from biological diversity in freshwaters and are involved in shaping water landscapes by managing them.

Four major areas of research for freshwater biodiversity are explained below. **Key topics are identified for each of these four research areas.** These topics serve the purpose of providing decision support in environmental policy (e.g. implementation of the WFD, improvement of ecological status, insect decline, implementation of the Common Agricultural Policy, implementation of ecosystem-based management). They are also important for conserving and improving freshwater biodiversity and its use. Robust data on the status and changes in biodiversity are used as a basis for all of these, and as such is a cross-cutting issue.

Interdisciplinary cross-cutting issue: data collection, mobilisation, integration and provision

|| Overview of data sources and their structure || Mobilisation and digitalisation of WFD, HD and other data || Development of freely accessible digital infrastructures

Numerous biodiversity-related data, tools and reports are created not only within scientific projects on the assessment, management and restoration of freshwater and coastal waters, but also in the course of monitoring activities for implementing regulations. However, the current practice of the decentralised collection of data by different institutions, based on individual requirements, drastically restricts root cause analysis, prediction options, and drawing up recommendations for action. It also contradicts the principles of open data and the FAIR Data Principles, according to which data should be findable, accessible, interoperable and reusable. Besides the improved collection, mobilisation and integration of biodiversity data, it is therefore necessary to considerably enhance data availability and data provision. The following tasks are particularly pressing:

- Developing and establishing **freely accessible (open access) digital infrastructures,** such as databases, to enable freshwater biodiversity data to be used according to **FAIR Principles**: This includes developing an infrastructure for creating distribution maps, possibly in cooperation with European or global portals (e.g. GBIF) and voluntary activities. By linking up with related initiatives such as the NFDI4Earth or NFDI4BioDiversity initiatives coherence is to be ensured in the case of deliberations on the part of data management and/or the development of software and other tools.

- Creating an overview of **data sources on freshwater biodiversity** (metadata): Which monitoring data (both biotic and abiotic) are currently being collected in a systematic, long-term way? Which ongoing (long-term) series of measurements can be combined to generate an understanding of a given social-ecological system? What untapped historical data inventories exist, e.g. from field stations? Such data should be linked to the long-term development of key stressors relating to biodiversity in order to improve knowl-

edge of cause-and-effect relationships. Gaps can be identified and improved monitoring approaches derived from such knowledge.

- **Mobilisation and digitalisation** of water-dependent biodiversity data: Besides numerous biodiversity datasets from the literature, a wide range of data sources remain virtually untapped, e.g. data from angling associations, amateur naturalists or from unpublished environmental studies. A lot of effort is required to mobilise such data.

- It is also necessary to **merge and provide WFD and HD data for the purpose of research**. The two most extensive, spatially distributed datasets on aquatic biodiversity in Germany originate from state monitoring programmes relating to the Water Framework Directive and the Habitats Directive. These two programmes are mainly implemented by the federal states in Germany, but only highly aggregated data are reported centrally to the Federal Environment Agency (UBA) or to the German Federal Agency for Nature Conservation (BfN). On top of this, the federal states undertake additional monitoring activities, especially on pollutants in freshwaters. The aim is to systematically compile the original data that has been – and will be – collected in the context of monitoring for the WFD and the HD, as a foundation for analysing many of the issues described here.

1. Monitoring: recording of biodiversity, ecosystem services and potential pollution sources

|| Establishment of a central biodiversity monitoring system || Development of new methods – from environmental DNA (eDNA), remote sensing and citizen science for recording of biodiversity and of ecosystem processes || Spread of invasive alien species || Deepening of knowledge on taxonomy and ecology

- Closing of **gaps in knowledge on biological diversity**: Despite some very extensive monitoring data on selected groups of organisms, little is known about the occurrence and exact distribution of many **aquatic insect species**, in part because immature stages can often only be identified to the genus level. The taxonomy and ecology of many less accessible groups, such as parasites, meiofauna, protists, fungi and bacteria, have been very poorly explored. The biodiversity of numerous **habitats** that are not considered in routine monitoring programmes can often only be accessed on the basis of single, often historical, case studies. These include springs, small streams, small standing water bodies such as ponds, the hyporheic interstitial, bogs and other wetlands. Knowledge of **species diversity in groundwater** is particularly rudimentary. This concerns the lack of knowledge about species composition, as well as a lack of long-term studies, Red List assessments, indicator organisms for assessing risk in groundwater and drinking water protection or schemes for concrete conservation measures that takes into account progress in the recording of groundwater fauna and in the development of biological assessment methods.

- The **further development of molecular methods** for routine applications harbours great potential to reduce the large gaps in our knowledge of freshwater biodiversity. DNA-based methods, such as environmental DNA (eDNA) and DNA metabarcoding, are increasingly used for monitoring biodiversity and for recording biodiversity components that are functionally relevant, but have received little or no consideration to date. The aim of this research area is, among other things, to develop applicable monitoring methods (e.g., for implementation of the WFD) by calibrating DNA-based methods with traditional methods and by closing gaps in the knowledge, including creation of reference DNA barcode sequence databases of all freshwater species in Germany. In addition, molecular methods could enable easier monitoring of invasive alien species (neobiota) and identify cryptic species and would enable researchers to determine ecological functions and relationships in food webs.

- Establishment of a monitoring system for the **intraspecific diversity** of selected indicator species from all groups of organisms using population genetic approaches: This could lead to the registration of demographic trends on the one hand (fragmentation, evolutionary bottlenecks) and adaptations due to changing environmental conditions on the other. The phenotypic plasticity of many organisms, about which only very little is known at present, is important. Experimental approaches can mechanistically clarify not only species' physiological limits, but also their evolutionary adaptability to changing environmental conditions.

- Investigation of the **spread of invasive alien species and their impact**: This involves adding invasive alien species to ongoing monitoring programmes, developing new methods for detecting invasive alien species, their introduction and distribution routes, and the transfer of invasive alien species from freshwaters to coastal waters and *vice versa*. This knowledge is need-

ed to be able to assess impacts on natural communities and to take countermeasures accordingly. This is not only the case for plants and animals, but also for microorganisms. The spread of invasive freshwater species is critical for the coastal area of the Baltic Sea because it exhibits very few natural barriers, owing to the low or non-existent salinity gradients. Knowledge of introduced species is often only anecdotal, especially for the pelagic zone, since no systematic records are taken at present. A reliable monitoring programme also requires the development and application of new methods (e.g. eDNA investigations of ballast water, monitoring in the context of citizen science, the further development of visual surveillance).

- Development and establishment of a monitoring system on **ecosystem processes** for deriving ecosystem services: Such a monitoring system is particularly important in order to make connections between biodiversity and ecosystem functions and services, making it easier to illustrate to different stakeholders the environmental impairments caused by various user groups. In addition, recording all national ecosystem services helps to achieve the EU Biodiversity Strategy. New molecular methods ("omics" approaches) may provide extensive information on current processes (particularly microbial processes), enabling researchers to gain a better understanding of functional diversity. Such methods supplement established approaches, such as are established for lakes (assessment of primary production) and have been proposed for running waters, for example for studies of nutrient retention, litter decomposition and carbon cycling.

- The impacts of **matter and energy flows** in freshwaters on adjacent coastal areas undergo natural and anthropogenic changes. The recording, assessment and management of such flows, and the resulting consequences for ecosystem functions, are of great important to the achievement of development and environmental objectives for coastal waters. Unlike in terrestrial ecosystems, functional interactions between biodiversity, matter and energy flows, system compartments and trophic layers in freshwater and coastal waters remain poorly understood.

- **Further development of the national monitoring programme**: Several official monitoring programmes are being run at present, both at the national level (WFD, HD) and in individual federal states (e.g. KLIWA monitoring in Bavaria, Baden-Württemberg, Rhineland Palatinate and Hesse), which take into account different groups of organisms and environmental variables (e.g. monitoring of priority substances and river basin-specific pollutants). In addition, there are numerous monitoring points operated by research institutes, e.g. in areas within the German Long-Term Ecological Research Network (LTER). Since all of these programmes evolved for a particular reason, they are too poorly integrated to map short-term and long-term changes in freshwater biodiversity, and to identify drivers of change. The aim is to develop and implement a scheme for a comprehensive biodiversity monitoring system for freshwater and coastal waters throughout Germany that can incorporate existing long-term measurements. As such, the monitoring network should be able to meet requirements applying to statistically robust analyses and be in a position to represent the impacts of current stressors (e.g. climate change, chemical input, sedimentation input, invasive alien species) and future stressors. This involves striking a balance between representative and risk-related monitoring networks, and between temporally harmonised monitoring and the quantitative recording of communities at the level of the landscape or catchment area.

- The results of innovative biodiversity research **offer commercial potential**: It is essential to develop freshwater monitoring technologies and data analysis methods that can be exported (e.g. flow-through sequencing, DNA/RNA chip technologies, measurement of pollutants, acoustic monitoring). Sustainable technologies offer a wide range of options for regional development in Germany, and transfer to other countries and regions.

2. Analysis of ecological components

|| Synthesis of developing control factors and cause-and-effect relationships with aquatic biodiversity, including ecosystem functions and services || Quantification of interactions in ecosystems || Predictions of the effects of extreme events || Key position of invasive alien species || Development of process-based models and their integration with experiments || Establishment of large-scale research on restoration

- **Systematisation of the state of knowledge on the development of freshwater biodiversity** in Germany: To date, fundamental questions on the development of protection and management measures for freshwater biodiversity have been answered inadequately or not at all. One such question is whether the abundance and diversity of freshwater species is declining in the long term. There is a considerable deficit of data compared

to knowledge on terrestrial populations, with the exception of a few selected fish species. Despite a wide range of individual studies, the necessary synthesis has been lacking to date. Such synthesis necessitates the mobilisation of data (see above), as well as the systematic compilation and analysis of specialist literature and unpublished studies and the integrated assessment of the compiled data. This also includes the quantification of the contribution that different habitat types and regions make to freshwater biodiversity in Germany.

- **Cause-and-effect relationships** associated with changes in biodiversity in freshwater and coastal waters: The aim of the **integrative consideration of a wide range of influencing factors such as** urbanisation, agricultural practices and climate change and the resulting **stressors**, e.g. nutrient input (eutrophication), sedimentation input (colmation: clogging of the river bed), water pollution (pesticides, biocides, pharmaceutical products, hormone-active substances, heavy metals, microplastics, nanoparticles), hydrological and morphological changes, as well as light and noise pollution, is to mechanically understand **causal chains** and to derive predictions from them. A profound understanding of the interactions between organisms under the impact of stress plays an important role in this respect. Approaches for management measures can be derived from such understanding. Irrespective of the influencing factors, it is important to consider freshwater and coastal waters as an **integral part of the landscape**, rather than as isolated ecosystems, and to consider their interconnections and links to the terrestrial surroundings, paying great attention to **transition zones**, which are considered to be biodiversity hotspots. **Key topics** include: (1) the impact of agricultural practices; (2) point sources of substances from households and industry via wastewater treatment plants and the impact of many chemicals and mixtures of chemicals; (3) recording, assessment and avoidance of colmation due to sedimentation input from terrestrial surroundings, which are likely to be a main reason for the "failure to achieve good ecological status under the WFD"; (4) hydromorphological changes, as brought about by the development of hydropower and other river engineering and water utilisation measures; and (5) the impacts of urbanisation.

- **An integrative consideration of interactions within ecosystems** follows, because diversity and factors influencing change are often considered separately for individual groups of organisms (e.g. for fish, macrozoobenthos, phytoplankton, phytobenthos). And yet the individual components of an ecosystem are nearly always interacting, influencing diversity either directly (e.g. grazing pressure of fish communities on the macrozoobenthos) or indirectly (e.g. changes in the habitat due to macrophytes). Although parasitism and diseases have received little attention, they may play a major role, e.g. global amphibian declines resulting from multiple stressors and fungal infections. It is essential to analyse these pathways because they have a major impact on the effects of stressors, and knowledge of such pathways enables the development and implementation of sustainable and integrative protection strategies.

- **Improvement of the knowledge base on the role of climatic and hydrological extreme events (magnitude, duration, point in time, frequency, shift between extremes)** and their significance for the short-term and long-term development of aquatic biodiversity: This is particularly critical to understand how ecosystems will react to climate change. Special phases of extreme low water or even of drying up pose a great challenge to freshwater biodiversity. Thus far, only isolated pockets of information exist on how species respond to such hydrological change. Altered material flows in drying up systems (CO_2 emissions) have also been investigated inadequately in Germany. Conversely, intense rainfall events result in flooding and the substantial input of matter from terrestrial surroundings, which may lead to eutrophication, browning, oxygen depletion and other negative phenomena. It is urgently necessary to acquire a detailed understanding of the underlying processes and impacts on freshwater biodiversity, not only in freshwaters, but also in coastal waters.

- **Invasive alien species take on key positions in ecosystems** and may contribute to changes in diversity themselves or pave the way for other species to bring about change. In the process, they may endanger native species, e.g. through competition or grazing pressure, or they spread diseases, and have enormous ecosystem and socio-economic impacts. It is often unclear why particular alien species take on certain roles. Consequently, it is difficult to predict which specific effects they have on freshwater biodiversity and on ecosystem functions and services. This is particularly the case for many inconspicuous species that often receive little public attention, such as prokaryotic and eukaryotic microbiota.

- **Development and improvement of process-based models**: Large parts of contemporary knowledge are correlative and not causal, and now need to be supplemented step by step with a mechanistic understanding of the

underlying processes. This covers not only the joint effect of different stressors, but also mechanisms such as responses to environmental changes, the consideration of distribution and settlement processes, or interactions between species. The development of **experimental approaches** under realistic environmental conditions plays a central role in achieving this.

- There is considerable need for research in the **quantitative analysis** (e.g. models interconnected with experiments) of the adaptation potential of organisms and ecological systems. Central questions include: 1) How does adaptation potential to changed abiotic and biotic conditions increase with phenotypic diversity and with intraspecific and interspecific diversity, 2) how does the existing adaptation potential influence the dynamics of food webs and their responses to environmental changes, and 3) what feedback effects do the changed dynamics have on the conservation of biodiversity, and hence on the potential to adapt to future disturbances. Building on a better understanding of these interconnections, measures can be developed to break out of the downward spiral of declining biodiversity, reduced adaptation potential, further declining biodiversity and, as a result, increasingly variable ecosystem functions and services.

- A **mechanistic understanding** must be developed that condenses the complexity and context dependence of ecological systems into manageable units. In addition, it would enable the quantification of the **interrelation of the changes in communities and the associated consequences for ecosystem functions** and **services**. The aim is to predict the impacts of (biotic and abiotic) stressors on ecosystem functions and services on the basis of these relationships. This would enable decision-makers and citizens to grasp the loss of biodiversity, supporting decision-making in the case of competing interests.

3. Analysis of the social components of social-ecological systems

|| Integration and consideration of human objectives and actions || Clarification and transparency of social motives and norms || Methods for the presentation and weighing of environmental, economic and social needs || Development of new citizen science approaches, awareness raising, education formats and new incentive schemes

- **Perception, conflicts of interests, acceptance of and social handling of biodiversity** and other non-economic concepts are central future fields of activity in biodiversity management that have received little consideration to date. Effective and efficient biodiversity conservation can only be ensured if human objectives and actions are taken into consideration. Bearing this in mind, it is necessary to develop interdisciplinary and transdisciplinary research approaches that broach the human dimensions of biodiversity conservation alongside natural science perspectives in integrated projects.

- To achieve this, it is fundamental to clarify how citizens perceive freshwater biodiversity, and what role it plays for human well-being. It is essential to document and understand these interconnections in order to ensure that potential changes are comprehensible and to have an impact on the **social motives and norms** for protecting freshwater biodiversity.

- To optimise biodiversity management in an integrative manner, the next step must be to **analyse economic and social conflicts of interests**. An important principle is that biodiversity protection and the use of ecosystems are not mutually exclusive. To achieve this, principles need to be drawn up governing where and when recreational and other uses have relevant effects on freshwater biodiversity.

- The **communication and participation** of civil society is critical. Possibilities for engagement include the presentation of ecosystem services, the fascination of charismatic species (e.g. otter, beaver, sturgeon, salmon, freshwater pearl mussel, dragonflies, etc.) and the structured **development of citizen science**. Citizen science may benefit from the preparation of accessible training material, open access databases or specific contact persons for actors enabling citizen science to generate optimally usable and available data.

- After all, it is important to reinforce the **competencies** of those actors, who actively shape freshwaters, through own actions or by legislation. There is scope for transdisciplinary approaches, where local water recreation users such as angling clubs, research institutions, associations and administrative bodies carry out joint investigations into the protection and promotion of local freshwater biodiversity. The **environmental educational and ecological effectiveness** of these approaches need to be scientifically analysed. It is equally important to undertake the systematic environmental/economic analysis of **various incentive schemes for promoting the independent actions of water users and managers**.

4. Social-ecological integration, development of options for action and scenarios

|| Evaluation and optimisation of environmental policy measures and water management options in terms of biodiversity conservation || Innovative solutions to conflicts of interests || Mitigation and adaptation measures for freshwater biodiversity || Evaluation of the importance of man-made ecosystems || Development of a scenario framework for biodiversity predictions

- Compilation of existing knowledge on the **impact of adaptation and restoration measures**: Agricultural practices have been identified as an important driving force behind the loss of freshwater biodiversity in numerous studies. National implementation of the new Common Agricultural Policy (second pillar of EU funding) offers the possibility to specifically induce change. This requires insights into the impact of different **agri-environmental measures**. At the same time, measures must be found to reduce **point sources of substances** originating from industry and households. The global expansion of hydropower calls for investigations into environmentally compatible **hydropower development**, with minimal adverse impact on the local habitat and connectivity of freshwaters.

- There is also considerable need for **large-scale experimental studies** on the impact of **restoration measures** to identify and test science-based restoration. These approaches must encompass robust and replicated **before and after intervention control (BACI) with post-monitoring phases spanning several years**. It is also important to create cross-taxa studies on appropriate scales, that reflect the dispersal processes and life histories of target species and communities.

- Two questions therefore arise: 1) What **framework conditions** need to be met to achieve an enhancement of biodiversity and 2) under which **management strategies** can local ecosystems be optimised more sustainably and effectively for the provision of multiple ecosystem services? Ways of doing this include improving established wastewater treatment technologies, retaining water in the landscape, and combining measures for promoting recreation, climate adaptation, drinking water production, transport and energy.

- **Clear rules for resolving conflicts of interests,** resulting from the different legal guidelines (e.g. the Renewable Energy Sources Act (EEG) versus the Water Framework Directive) must be developed as a matter of urgency. Beyond the difficult financial situation at the municipal level, this is therefore linked to the development of methods, e.g. to facilitate political decision-making paths and priority setting for the optimal implementation of measures or to drive forward the development of strategies on implementing measures that have come to a standstill.

- **Impacts of national mitigation and adaptation measures on global freshwater biodiversity**: In a globalised world, national measures will inevitably have an impact elsewhere, e.g. due to the increased import of agricultural products, the production of which in other regions of the world also has an impact on freshwater biodiversity. With this in mind, it would make sense to develop standardised analyses of an extended **water footprint** that not only reflects water consumption, but is also capable of analysing local and regional impacts of human activities as well as global remote effects on freshwaters and their biodiversity, i.e. considers entire supply chains.

- Investigations into the **significance of new ecosystems** (i.e. freshwaters created and modified by humans, such as dams, residual lakes, dredging pools, ponds, quarry lakes, etc.) for biodiversity conservation, recreation and resource conservation are also of relevance. This also includes the impact of blue-green infrastructure networks and their significance for dispersal processes to counteract landscape fragmentation and the consequences of climate change.

- Studies on **future models** that enable economic use of freshwaters in harmony with biodiversity conservation (see IPBES scenarios, green infrastructure, ecosystem-based management): At present, there is a lack of overall concepts (models and case studies) and objectives for water management that are more closely oriented to the targets of the Convention on Biological Diversity, that help implement the UN Agenda 2030, and integrate climate change and future changes. The basis for this is a coordinated **scenario framework for biodiversity predictions** that are, e.g. regionally or temporally comparable.

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Background

On the occasion of the 15th BMBF Forum for Sustainability (13-14 May 2019) on "Maintaining Biodiversity – Researching for our Future" and the "Research Initiative for the Conservation of Biodiversity", the authors of this Research Agenda underwent an intensive exchange process to identify and coordinate the most important research needs in and on inland waters. The exchange with the "Coastal Research Strategy Group" of the "German Marine Research Consortium" reflects the (original) connectedness of inland and coastal waters.
This Research Agenda, presented by the authors, marks the start of a consultation process on the need to conduct research on freshwaters, and at the same time supports the development of the agenda of the BMBF Framework Programme "Research for Sustainable Development (FONA)".

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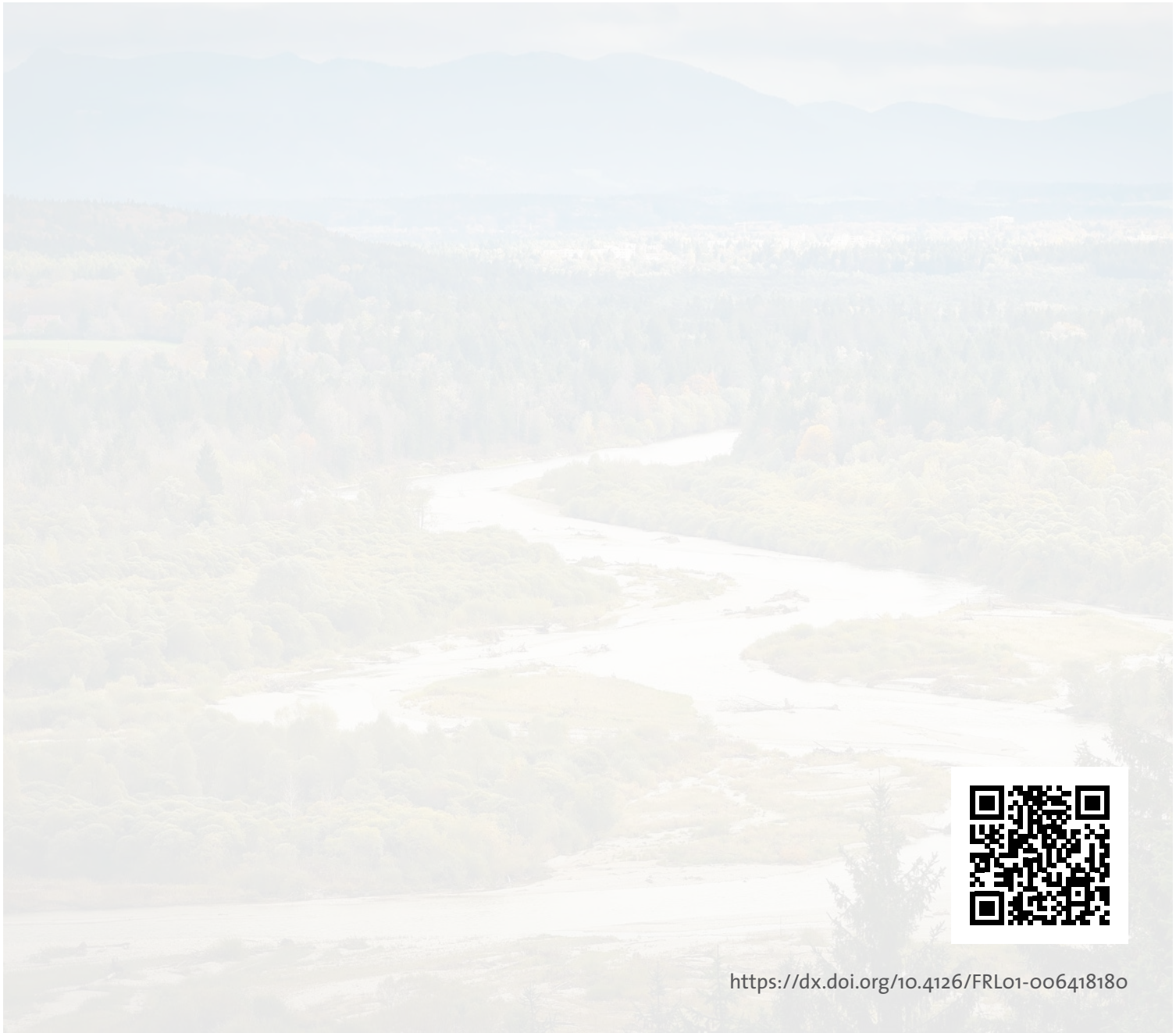

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