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How can the meta-ecosystem approach improve the management of large river networks?

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Abstract River networks are harbouring a unique biodiversity and contribute to global ecosystem functions; they exchange with terrestrial system and connect to marine systems. Furthermore, they are a critical infrastructure for human development and provide a multitude of ecosystem services. Conservation and restoration of ecosystem functions, biodiversity and service provisioning is an urgent task, as ongoing multiple stressors impact ecosystems and may interact with legacies of past intervention, which often require management measures and determine possible options for the future. We build on different concepts by combining a meta-ecosystem framework with hydro-morphological development (also including major human interventions) and integrate these with ecosystem services as an essential link to human society. The meta-ecosystem framework incorporates metacommunity aspects and food web structures. It describes how spatial flows of energy, materials (abiotic and biotic transport of resources), organisms (dispersal, life-cycle migrations, and movements) and environmental conditions between and within different spatial units determine ecosystem services, ecosystem functioning, community composition and biodiversity, also considering the temporal dynamics. Such a riverine meta-ecosystem framework will complement current assessment approaches with a more process-oriented perspective. Studying the role of spatial flows at several scales provides tools to understand the spatial dynamics of regional biodiversity patterns and ecosystem service provision. This article, therefore, explores the potential of the meta-ecosystem approach to understand the dynamic interactions and the effects of past interventions to project the future development of connected river networks and guide future management interventions.

Keywords: Danube River, aquatic biodiversity, ecosystem services

1 Introduction

Different river engineering measures have transformed the riverine landscape of the Austrian Danube River. Consequently, the former habitat and aquatic species diversity have been altered to a large extent. Although measures for ecological restoration and, thus, improvements are continuously being implemented (e.g., floodplain restoration, fish migration facilities, habitat improvements), there is still a significant lack of knowledge about the long-lasting effects of regulation measures and their interactions with the overall effects of the individual restoration measures. It is also necessary to clarify/work out which types of measures will be needed in the future to regain a valuable Danube River ecosystem.

To analyse the interplay between aquatic ecology, human activities and ES provision at different spatial and temporal scales - especially in a highly modified river system such as the Danube - relevant scientific concepts need to be combined and new targeted management approaches need to be formulated (Lago et al., 2019). This emphasises that ecological and socially oriented theories need to be integrated together to create improved management frameworks (Truchy et al., 2015). A key ecologically orientated theory is that of meta-ecosystems.

The meta-ecosystem approach encompasses meta-community aspects and food web structures. It explains how spatial flows of energy, resources (abiotic and biotic), organisms (dispersal, life cycle migrations and movements) and environmental conditions between and within different spatial units determine ecosystem functioning, species community composition and biodiversity considering different spatial scales and temporal dynamics (Gounand et al., 2018a). Current frameworks also focus the coupling between nature and society within a socio-ecohydrological systems view (Hein et al., 2021). Furthermore, Gounand et al. (2018a) emphasized the potential of meta-ecosystem theory to integrate human interventions to obtain a holistic picture of ecosystem functioning. We apply these concepts by combining a meta-ecosystem framework with hydromorphological components (considering key human interventions in the Austrian Danube) and integrating these with selected ecosystem services as a fundamental link to human society. Such an integrated framework for river systems will complement current assessment approaches with a more process-orientated perspective (Hein et al., 2022).

The Christian Doppler Laboratory for Dynamics of **M**eta-**E**cosystems in Regulated **R**iverine Landscapes (MERI - https://cdl-meri.boku.ac.at), which was launched in October 2021, has work together with three partners viadonau (österreichische Wasserstraßen-Gesellschaft mbH), Verbund Hydro Power GmbH and Österreichische Bundesforste AG (ÖBF) for seven years within the laboratory. MERI applies the meta-ecosystem approach and transfers it into practice in order to analyse the current ecological conditions at the level of the Danube River network, to investigate the effects of restoration measures already implemented and to predict future scenarios of changes and measures for the best possible mitigation of ecologically detrimental changes (Bondar-Kunze et al., 2022). The CD-Laboratory MERI consists of four scientific work packages (Figure 1) that deal with the following overarching research questions:

- How do the quality, configuration and connectivity relationships of different river sections with different hydromorphological characteristics change in different temporal steps (historically, after river regulation, partial restoration), and how has the meta-ecosystem and its biodiversity changed as a result?
- How do changes in hydromorphological features influence the ecological patterns, processes and scale relationships (meta-ecosystem approach)
- How have biodiversity (e.g., river fish) and ecosystem functions responded to these past changes, and how have restoration measures changed/influenced these responses so far?
- How can a better understanding of scale-dependent patterns and processes improve management decisions for sustainable use and the provision of ecosystem services?

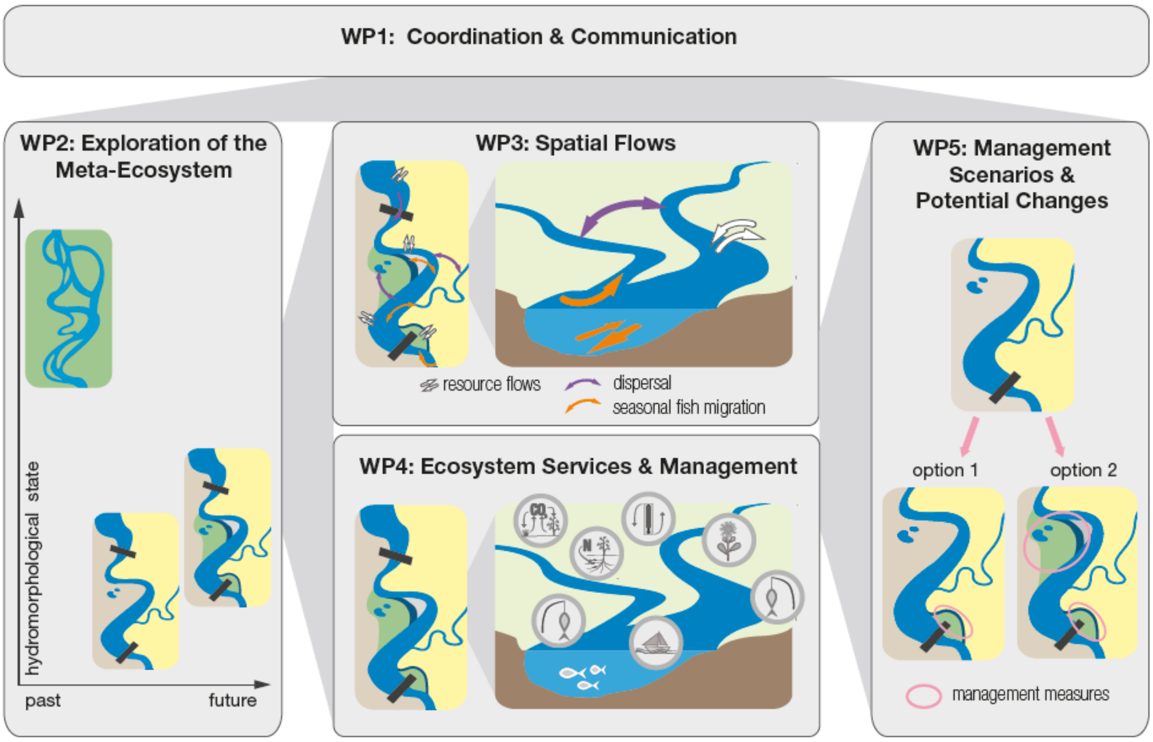

Figure 1: Work packages (WP) of the CD Laboratory MERI, © Astrid Schmidt-Kloiber

2 Methodological aspects

To address the five questions mentioned before, the CD Laboratory MERI is divided into five work packages (WP). WP1 coordinates all research efforts and guarantees communication with partners and stakeholders as well as international cooperation. Furthermore, a meta-database has been developed in turn of WP1 to homogeneously collect and update the information on existing and newly generated data sets describing the Danube system for all other WPs.

WP2 explores the meta-ecosystem Danube based on existing data. Firstly, we collected biotic and environmental data along the Austrian Danube and its tributaries and developed tools (e.g., riverconn – Baldan et al., 2022) and methods to describe the spatial component of this meta-ecosystem based on a graph theory approach (Funk et al., 2023). Secondly, the tools are used to explore and quantify spatial flows of energy, material and organisms in the meta-ecosystem. Within WP2, we further analysed historical river uses (change of fisheries management) and hydro-morphological changes and their consequences for the meta-ecosystem of the Austrian Danube. A comparative study (comparison of maps from 1959 and 2021) investigated the changes in habitat composition and wave action and confirmed that large parts of the banks of the study area were already fortified with riprap and groynes in 1959. By 2021, the gravel banks and areas continued to decrease, especially in the dammed sections, which had an impact on the fish habitats of rheophilic juvenile fish (Perle, 2023).

WP3 and WP4 assess the impact of network and hydrological connectivity and environmental conditions on a more detailed level. Comprehensive field studies are ongoing and enhance our understanding of meta-community and ecosystem service patterns within selected ecosystems of the Austrian Danube, characterized by specific network connectivity and habitat properties. As tributaries and adjacent water bodies constitute an essential part of the meta-ecosystem by providing seasonal habitats for reproduction, foraging, and refuge, it is central to investigate the full range of exchange processes between the main channel, its side channels, floodplains, and the major tributaries (WP3). In focus are investigations of riverine fish populations and their habitat use in riparian and deeper zones of the river, their migration behaviour by applying the Passive Integrated Transponder (PIT) technology (Conner et al., 2020) and further to analyse the effects of wave action on riverine food webs. WP4 focuses on the availability and quality of cultural ecosystem services (CES) and their link to different ecosystems of the Austrian Danube. The first task investigates a variety of different CES for selected impoundments and free-flowing sections of the Danube. The second task is dedicated to an in-depth study of recreational fishery. It will build on the results of WP2 (historical fisheries management) and investigates the development and current status of fisheries management in the Austrian Danube since the construction of the hydropower plants. This research combined with a stakeholder survey will establish the basis for developing scenarios for a sustainable recreational fishery.

WP5 will take up the tools, data and findings from WP2 to WP4 and will model and predict future scenarios considering various management strategies and climate change impacts.

3 Outlook

Numerous human interventions on and around rivers have resulted in ecological processes and human activities being closely intertwined - a connection that is referred to as a socio-ecological system (Hein et al., 2021). Human interventions have led to dramatic losses of river habitats and thus to a functional degradation of riverine landscapes. At the same time, the ecosystem services provided by riverine landscapes are widely recognised (e.g., Sanon et al., 2012; Schindler et al., 2014), and thus have prompted numerous restoration initiatives. These projects employ diverse measures to enhance biodiversity and improve ecosystem process-es (Jungwirth et al., 2014), and, more recently, also to increase the provision of ecosystem services (Funk et al., 2021). In order to create a solid basis for decision-making processes, it is necessary to jointly analyse ecosystem functions and their dynamics, the exchange of organisms, substances and resources and the associated interactions between society and river networks (Bondar-Kunze et al., 2022). Here, the understanding of how humans drive ecosystem change - also taking into account the interactions between individual ecosystems at larger scales with different levels of connectivity (Gounand et al., 2018b; Renaud et al., 2018) - can be translated into new management approaches. Therefore, such a research approach will provide a promising basis for deciding on optimal and sustainable ecosystem management and restoration strategies (Vermaat et al., 2016).

Traditionally, restoration projects and their monitoring have focused on small-scale stretches and have accordingly focused on the local level, i.e. on the importance of local habitats and their restoration. Since the fragmentation of the longitudinal course of rivers, i.e., the loss of connectivity due to barriers such as hydropower plants, and the lateral fragmentation of the river system, e.g., due to flood protection dams or bank stabilisation, have a cumulative effect over large spatial units (e.g., the entire Austrian Danube and its tributaries) and thus pose a threat to biodiversity. A management and restoration practice that focuses exclusively on the local habitat aspect, however, could fail to achieve the expected ecological results. The aim of the CD Laboratory MERI is therefore to develop and to assess a set of highly effective measures for the Danube meta-ecosystem that supports the required multifunctionality, i.e. integrating multiple species, multiple functions (biodiversity, hydropower, navigation) and multiple ecosystem services. By integrating trophic interactions (May, 1972), connectivity, and species migration behaviour (Williams et al., 2006; Vander Vorste et al., 2017) into our analysis, we can formulate management strategies that enhance the stability, including resilience and robustness, of the meta-ecosystem and its sub-areas (such as Danube River sections, tributaries, and floodplain systems). This approach considers local habitat characteristics, connectivity aspects, and long-term trends. In the course of MERI, forecasting models will therefore be developed to predict the effects of various management measures and to take future climate change impacts into account. Furthermore, future management alternatives and climate change scenarios will be used to analyse potential development paths for the meta-ecosystem.

4 Conclusions

Using multi-criteria analysis tools, we will be able to propose optimised management measures that can enable consideration of multiple objectives, including biodiversity and ecosystem functions, legal requirements for nature conservation and water status (e.g., EU Habitats Directive, EU Water Framework Directive), recreational use and other ecosystem services, as well as navigation and hydropower. The CD Laboratory MERI can serve as a crucial framework illustrating how meta-ecosystem thinking can steer European initiatives to restore free-flowing rivers. This can facilitate extensive planning and collaboration, ideally on a landscape and catchment scale (Stoffers et al., 2024). Within the context of the CD Laboratory MERI, these objectives are attained through national and international scientific collaborations, working closely with our company partners.

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