Transformation towards resilient water landscapes

Scientific and societal challenges

Inland waters are unique ecosystems, which provide a large number of essential services to human societies including the provision of safe drinking water and a broad range of natural attenuation processes that can mitigate anthropogenic pressures and impacts on the water cycle. There is a strong coupling between ecosystem health and human needs, which is recognized in modern environmental management approaches, e.g. by the German National Water Strategy (BMUV 2023) and globally by the SDGs ("6 - Clean water …"/ "14 – life below water"). However, aquatic ecosystems experience diverse degradation trajectories due to anthropogenic pressures and impacts including nutrient pollution and corresponding eutrophication, chemical pollution and associated biodiversity loss, or hydromorphological degradation, which have caused significant overall impairment. Additionally, climate change effects, including hydrological extremes, become increasingly perceptible, and override management successes made in the past.

Future management of aquatic systems must thus target both - turning degradation pathways into recovery trajectories and at the same time adapting to ongoing climate and socio-economic change. So far management practices, connected e.g. with the EU-Water Framework Directive, have been weak in both aspects. We see three major shortcomings: First, today´s practices are not well suited to tackle shifting hydroclimatic and societal boundary conditions as they are oriented towards past reference states. Second, programs of measures often solely take a sectoral perspective on typically interconnected water problems, thereby ignoring synergies and trade-offs. And third, mitigation measures did not operate at appropriate spatial scales and often fail in considering constraints set by natural boundaries. In order to overcome these shortcomings, we proposed a resilience-oriented management. Resilience is defined here as the ability of a systems to resist, or recover from, disturbance and thereby persist (*sensu* Oliver et al., 2015). In a UFZ wide effort across different research units, we developed a novel framework for the operationalization of this resilience concept ("resiliencing", see Weise et al., 2020). This includes the focus on specific essential variables, which need to be "resilienced" (here: water quantity, water quality, key ecological processes and services) as well as their control and resilience mechanisms (including landscape configuration, network structures, functional architecture). Furthermore, the framework integrates the resilience mechanisms in three distinctive decision contexts and time-horizons: **reactive**, when a threat is immediate and severe, **adjustive**, when there is time to implement an adaptive management, and **provident**, when uncertainty is high and time horizons for interventions are long.

It is our mission to provide the science base for the necessary transformation of the vulnerable water systems of today towards resilient water landscapes of the future that sustainably serve all essential ecosystem and societal needs. In our efforts we will utilize the new quality of big monitoring data (in terms of temporal and spatial resolution), and will build on novel data-driven ecosystem analyses that link mutual interdependencies and feedbacks of water quality, water quantity and ecosystem attributes and inform a new generation of process based smart models. The **UFZ is in a unique position** to provide the required knowledge, tools and strategies, because it covers expertise on all components of the water cycle, which is needed for a truly cross-sectoral approach, has the necessary modelling and monitoring infrastructures and focusses research towards science-based management including real world transfer and applications.

Major scientific achievements

Our scientific activities are focused on providing the process understanding, which is needed for transforming vulnerable water landscapes of today into resilient water landscapes of the future. Specifically, this comprises the identification of resilience mechanisms for essential variables (water quantity, water quality, key ecological functions and services). On this scientific basis, we foster the transformation by developing tailored management strategies and demonstrating their application together with stakeholder (see *Outreach and impact*). The scientific achievements in more detail are:

1) Robust quantification of water fluxes across scales now and in the future under extremes. The development of a large-scale typology of hydrological processes leading to streamflow events (Tarasova et al., 2020) has supported understanding the role of events generated by different mechanisms on nutrient export patterns from local (Winter et al., 2022) to national scale (Saavedra et al., 2022) identifying the potentially hazardous types of events for maintaining water quality in the receiving water bodies. We could also show that in-depth understanding of physical processes generating streamflow events and controlling their dynamics have a potential to predict the emergence of extreme flood events and regional flood anomalies (Basso et al., 2023; Tarasova et al., 2023). The work on water quantity is conducted in strong collaboration with RU ModMon and included the implementation into the UFZ model infrastructure and within international collaborations (e.g., AG Blöschl, University of Vienna).

2) Mechanistic process understanding for quantification of matter fluxes within catchments. Major progress has been made in understanding matter input, transport and fate in catchments addressing the interplay of hydroclimatic variability and anthropogenic impacts in different landscape settings (Kumar et al., 2020, Keller et al., 2020, Ebeling et al., 2021, Musolff et al., 2021, Winter et al. 2023). Nutrient dynamics were analysed within a stoichiometric framework (Wachholz et al., 2023), linking catchment-scale processes with potential ecological effects (Graeber et al., 2021). In an across-RU collaboration (ModMon) we have put emphasis on the role of legacies of past nutrient inputs and their implementation into SMART catchment models (Lutz et al., 2022; Nguyen et al., 2022), and on network-scaling of instream nutrient uptake (Yang et al. 2021, Yang et al. 2023). For low water flows, across RU (esp. RU CITE) and across centre (AWI, HEREON) collaborations within the MOSES initiative quantify the effects of low water flow on water quality in a land-to-sea continuum (Kamjunke et al., 2021, 2022).

3) Identifying major controls of ecological functions and services and their feedback to water quality. In a global meta-analysis, we identified major drivers for the control of essential ecosystem functions (Brauns et al., 2022). Based on these drivers we continue to develop concepts to manage ecological functions within the EU project RESTOLINK. On a continental scale we could link catchment-wide matter fluxes with local ecology by showing that treated wastewater is responsible for the observed poor ecological status of many European streams (Büttner et al. 2022). Novel perspectives emerged from our work on eutrophication control, e.g. by analysing long-term patterns in eutrophication and their deviation from present text-book views (Iannino et al. 2023, Davidson et al. 2023), by identifying previously overlooked control mechanisms (Saha and Fink, 2022) or by analysing how global change may impact control mechanisms (Roggatz et al. 2022, Kong et al., 2023). Join and complementary work on ecological effects of chemicals (Weitere et al., 2021) and zero-pollution strategies for inland waters, which are closely coordinated with the work presented here, are performed within the RU CITE (see storyline "Toxic-free water resources").

Outreach and impact

The scientific process understanding is used to develop **transformation strategies** from current management practices towards future resilient-oriented management on the three time horizons of our framework (see above) and to demonstrate their implementation together with stakeholders. As an example of **reactive resiliencing**, we developed climate-proof management strategies, which have been provided to the operators of Germany's largest drinking water reservoir by real-time monitoring and process-based reservoir modelling (Mi et al. 2022, 2023, Rinke 2023). A key infrastructure and monitoring demonstration site is the Rappbode-Reservoir-Observatory, which was developed and established by UFZ scientists and since 2023 is operated by the reservoir managers. The system allows immediate responses of the reservoir operation to upcoming water quality problems. Another example is the development of a low water strategy to adapt to extreme droughts together with authorities from the federal state of Thuringia. This includes both short-term emergency action plans during droughts following scientifically justified ecosystem thresholds as well as longer-term adaptation strategies e.g. for temperature regulation as example for **adjustive resiliencing**. Finally, our system understanding was used to develop the German National Water Strategy with UFZ as main scientific advisor (BMUV 2023). The strategy is a blueprint for long-term transformation towards resilient water landscapes in Germany and thus for **provident resiliencing**. It is based on a national water dialogue with more than 200 stakeholders under advice of UFZ. On the international scale, UFZ supports the European Environmental Agency (EEA) through the European Topic Centre on Biodiversity and Ecosystems in the implementation of the range of EU directives, strategies and policies as well as the monitoring requirements and approaches for tracking progress towards the implementation of the European Green Deal.

Another important pillar for implementing our novel concepts for water management is **education,** particularly of doctoral researchers in three 'blue' PhD colleges, an EU ITN and through the successful establishment of a Helmholtz International Research School on Trajectories towards water security (TRACER). TRACER was developed together with national (TU Dresden, UBA) and international experts/partners (University of Florida, Purdue University, EEA, UNEP) to educate the next generation of water scientists and decision makers. The school received an excellent mid-term evaluation in December 2022 based on its transdisciplinary research (e.g. Wachholz et al., 2023).

UFZ scientists use their knowledge to **inform the public** about pressing water-related problems, consequences of droughts on water quality and quantity. This includes numerous representations of UFZ scientists in mass media including top-news-broadcast "heute" and "Tagesschau/ Tagesthemen" at the major channels ARD and ZDF as well as documentary and talk-show prime time formats.

Next steps and outlook

So far, we established ways for the operationalization of resilience concepts for management, provide the scientific background for the implementation along selected variables and demonstrate the applicability. With the long-term aim to achieve resilience in a multi-functional context considering synergies and trade-offs and to implement the concept broadly, we will integrate more essential variables and related resilience mechanisms. We will expand the applicability-demonstration by working on the implementation of the concepts into national and international frameworks.

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