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The coupled socio-ecohydrological evolution of river systems: Towards an integrative perspective of river systems in the 21st century

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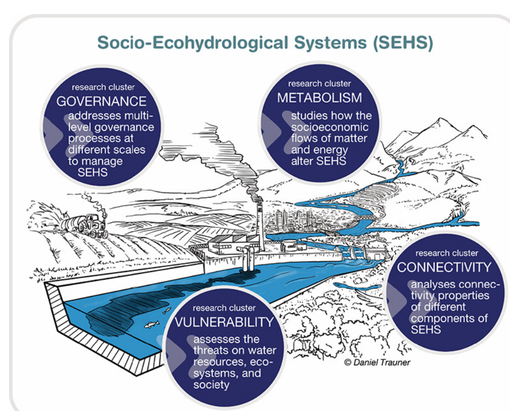
HIGHLIGHTS

- River systems have been massively transformed and are socio-ecohydrological systems.
- A socio-ecohydrologically driven approach provides insights into coevolutionary processes.
- Social metabolism and the colonisation of natural systems are underlying concepts.
- Four research clusters analyse the transformation and coupling of society and nature.
- Interdisciplinary and transdisciplinary approaches support the operationalization of the research agenda.

GRAPHICAL ABSTRACT



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ABSTRACT

River systems have undergone a massive transformation since the Anthropocene. The natural properties of river systems have been drastically altered and reshaped, limiting the use of management frameworks, their scientific knowledge base and their ability to provide adequate solutions for current problems and those of the future, such

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as climate change, biodiversity crisis and increased demands for water resources. To address these challenges, a socioecologically driven research agenda for river systems that complements current approaches is needed and proposed. The implementation of the concepts of social metabolism and the colonisation of natural systems into existing concepts can provide a new basis to analyse the coevolutionary coupling of social systems with ecological and hydrological (i.e., 'socio-ecohydrological') systems within rivers. To operationalize this research agenda, we highlight four initial core topics defined as research clusters (RCs) to address specific system properties in an integrative manner. The colonisation of natural systems by social systems is seen as a significant driver of the transformation processes in river systems. These transformation processes are influenced by connectivity (RC 1), which primarily addresses biophysical aspects and governance (RC 2), which focuses on the changes in social systems. The metabolism (RC 3) and vulnerability (RC 4) of the social and natural systems are significant aspects of the coupling of social systems and ecohydrological systems with investments, energy, resources, services and associated risks and impacts. This socio-ecohydrological research agenda complements other recent approaches, such as 'socio-ecological', 'socio-hydrological' or 'socio-geomorphological' systems, by focusing on the coupling of social systems with natural systems in rivers and thus, by viewing the socioeconomic features of river systems as being just as important as their natural characteristics. The proposed research agenda builds on interdisciplinarity and transdisciplinarity and requires the implementation of such programmes into the education of a new generation of river system scientists, managers and engineers who are aware of the transformation processes and the coupling between systems.

1. Introduction

The management of water has been pivotal in human evolution and fundamental in societal advancement, e.g., the development of agriculture and the establishment of permanent settlements. However, with increasing economic and social demands, river systems have undergone dramatic, worldwide and often irreversible transformations in geomorphic and ecohydrological properties (Hossain et al., 2020), culminating in the era of the Anthropocene (Waters et al., 2016). These transformations have been driven by a shift from agrarian (solar-energy-based) to an industrialised (fossil-fuel-based) sociometabolic regimes (Fischer-Kowalski and Haberl, 2007; Krausmann et al., 2008). The industrialisation of riverine landscapes has led to multifaceted alterations with a profound impact on the ecosystems' integrity, the availability and quality of water, and the provision of ecosystem services (Borgwardt et al., 2019; Culhane et al., 2019). In this paper, we argue that the coupling between natural and societal systems is crucial to gain a problem – appropriate understanding of the current transformation processes in rivers. This question of coupling, is specifically addressed by the Viennese Social Ecology (Haberl et al., 2016) approach which offers conceptual tools, that are utilised here for the first time in interdisciplinary research on riverine landscapes; in doing so we recognise and are aware of alternative approaches (Folke, 2006), including those dealing with the resilience of social-ecological systems (Berkes and Colding, 2003).

As the fundamental properties and interactions within riverine landscapes have changed, e.g., the connectivity patterns, the majority of large river systems can no longer be considered natural (Crook et al., 2015). These industrialised rivers have not only been moulded by humans but their further development will be a subject to the reciprocal interactions between society and the ecosystem (DeBoer et al., 2020), resulting in new emergent properties. The novel state of rivers in the Anthropocene has already been addressed by many concepts including, socio-ecological rivers, river basins (Brierley, 2020; Cabello et al., 2015; Dunham et al., 2018) and socio-geomorphology (Ashmore, 2015). The multiple interacting pressures on such river systems, for example, energy production, transport and resource utilization, have led to the loss of biodiversity (Dudgeon, 2019), the loss of productive soils in favour of settlements and infrastructure (Davies, 2017), the deterioration of water quality (Hofstra et al., 2019) diminished water security (de Graaf et al., 2019; Vörösmarty et al., 2010)· and alterations in global biogeochemical cycles and sediment dynamics (Best, 2019; Habersack et al., 2016; Hauer et al., 2018). It is these pressures that are manifesting themselves in conflicting or nonharmonised policies, challenging river basin governance, and rendering conventional environmental protection unsuccessful.

To tackle current and future pressures, the holistic approach of integrated water resource management (IWRM) was developed (GWP, 2000; Molle, 2006; Savenije and Van der Zaag, 2008; Warner et al., 2008) with the aim of "*the coordinated development and management of water, land and related resources in order to maximise the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems*" (GWP, 2000). In the context of IWRM, a scientific community effort highlighted the need to consider these ever-increasing interactions between human and natural systems, for example by announcing the Scientific Decade of Panta Rhei in 2013-2022 (Montanari et al., 2013). Concepts and research questions were developed (Montanari et al., 2013) from this stance, and pressing unsolved problems were highlighted (Blöschl et al., 2019) aiming to capture all human – nature interactions in contrast to IWRM focussing only on specific interactions. Despite this a limitation of the sociohydrological approach is that it reduces the whole complexity of interactions to fit in a quantitative model (Wesselink et al., 2017). IWRM is also faced with criticism in regard to the unclear definitions and breadth of the challenges or how to include the dynamic role of social influences on management (Cook and Spray, 2012). Furthermore, social-hydrological concepts still lack the integration of ecological and economic perspectives into their research framework and need to be extended to social-ecohydrological systems (Cabello et al., 2015).

To connect the natural and societal system, the 'ecosystem services' (ESS) concept links the biophysical state of ecosystems to societal needs (Daily et al., 1997), this concept highlights that all socioeconomic activities depend on the integrity, functionality and resilience of ecosystems (McCluney et al., 2014). The ESS concept focuses on the complexity of functions, services and processes provided by ecosystems for human societies. As a conceptual framework, however, it still tends to ignore the complexity of societal change and thus, undervalues the role of societal interventions in shaping ecosystems (Schröter et al., 2014). The hydrosocial approach offers a focus on actor coalitions and their power relations to explain water-related issues, but it does not comprehensively consider physical elements (Wesselink et al., 2017). The lack of a water-function-based framework considering hydro-ecological, hydro-social and hydroclimatic interactions has also been identified (Falkenmark and Wang-Erlandsson, 2021). Furthermore, current studies applying the water-energy-food nexus concept highlight the significance of new interdisciplinary approaches and the need for analytical tools to understand the effects of multiple human interventions (Albrecht et al., 2018).

While the majority of studies stress the central role of water in various societal processes, the socio-ecohydrological ontogeny of river systems is often neglected. Societies and currently applied technical management approaches are ill-equipped to cope with the drastic modifications and accelerated rates of change in industrialised river systems. They depend on the integrity of the ecological and social functionality of rivers, while they are faced with the urgent need for both immediate and long-term, sustainable management actions addressing pressing topics, such as, the freshwater biodiversity crisis, climate change mitigation and adaptation and sediment management. Translating research into policies is challenging (Tickner et al., 2020). The uncertainties of human interventions (Darby and Sear, 2008) and time lags between management actions and ecosystem responses (Wachniew et al., 2016) are still often ignored. Existing and foreseen demands challenge social and economic decision-making capacities, often resulting, if measures are taken at all, in fragmented or inappropriate, poorly coordinated actions (Cosgrove and Loucks, 2015). Even well thought-out and coordinated efforts, such as the EU Water Framework Directive, have to face deficits in the efficient implementation and evaluation of management actions (Carvalho et al., 2019).

The proposed research agenda aims to take a next step in the research of industrialised river systems by proposing a novel socio-ecohydrological approach, especially focusing on the coupling of the natural and social systems within riverine landscapes. We see the coupling of socioeconomic and ecohydrological processes as the main driver of river transformations and suggest to highlight this coupling by making it the focus of an integrative river research agenda by considering rivers as socio-ecohydrological systems. Using a socioecological foundation for future river research might close critical gaps in understanding the coupling in transformed river systems by analysing the causes and effects of transformation processes and their complex interactions. In the following chapters, we present the underlying concepts of this research agenda, argue for four research clusters, and conclude with an outlook on how this research agenda considers transdisciplinary aspects and informs the training of future experts in river research, management and engineering.

2. Conceptual foundation of a novel research agenda for river science

We suggest viewing rivers as "socio-ecohydrological systems" (SEHS), based on the analytical distinction between "natural systems", including ecological, hydrological and morphological aspects and "social systems", including socioeconomic and cultural aspects. Natural and social systems are coupled by coevolution and reciprocal dependencies (Fischer-Kowalski and Weisz, 1999; Haberl et al., 2016; Weisz and Clark, 2011). Analysing the coupling of the natural and social systems across both space and time facilitates the understanding of transformation and feedback processes within the overarching SEHS and is, thus, central in our SEHS approach. Furthermore, the SEHS approach aims to offer an interdisciplinary framework to integrate disciplinary expertise considering different types of interdisciplinarity as defined by (Max-Neef, 2005). From a natural science perspective, riverine landscapes encompass hydrological, energy and biogeochemical fluxes, hydro-, sediment- and morphodynamics, biodiversity and ecosystem functions at different spatiotemporal scales. Together they form the metabolism of the natural systems, i.e., the production and degradation of biomass to gain energy, grow and live. From a social science perspective, riverine landscapes can be viewed in terms of their role in a society's metabolism, encompassing the construction of sociocultural infrastructures based on time-dependent engineering knowledge and technologies to, e.g., extract resources (water, sediment, biomass), generate energy, build waterways and dispose of wastewater (Cabello et al., 2015). The tight coupling via reciprocal interactions between the natural and social systems results in the transformation of SEHS, and a better understanding of this coupling is the central idea of the proposed research agenda.

Social ecology (in the Viennese variant we follow, cp. (Haberl et al., 2016)) offers two key concepts to understand how social and natural systems are coupled, how interactions can be understood, and how this coupling results in sustainable or unsustainable developments: "social metabolism" and "colonisation of natural systems" (Fischer-Kowalski and Erb, 2016; Schmid, 2016). Here, we take up these socioecological concepts and use them for the first time for river research, by explicitly including the hydrological perspective.

"Social metabolism" can be seen as a functional equivalent of an organism's biological metabolism and is defined by the continuous throughput of materials and energy all human societies require to build, maintain and operate their material stocks and to reproduce their population (Haberl et al., 2016). The metabolism of a society is connected to the biological metabolism of rivers and to the individual metabolism of the aquatic organisms living there, but the systematic study of this linkage between social and biological metabolism is still in its infancy (Cabello et al., 2015 as an exception). The introduction of fossil fuels into the social metabolism, a major feature of industrialisation, has led to, amongst other effects, the current climate crisis. River systems are not only subject to climate and land use change, they also play a role in necessary mitigation measures and are a major conduit in the global carbon cycle, releasing carbon dioxide, supporting carbon savings and fostering carbon sequestration (Raymond, 2013).

The second key concept, 'colonisation', captures 'the intended and sustained transformation of natural systems, by means of organised social interventions, for the purpose of improving their utility for society as a whole' (Fischer-Kowalski and Erb, 2016). A colonising intervention must be causally effective in changing biophysical conditions (e.g., the riverine ecosystem, its biodiversity, hydromorphology), and it must make sense in the world of human communication, otherwise it would not be undertaken (Fischer-Kowalski and Erb, 2016). In the industrial socio-metabolic regime, colonising interventions into the nature of rivers encompass societal activities as diverse as, e.g., systematic river regulation for navigation, land reclamation for flood protection, dam construction for electricity generation, drinking water supply and other purposes, or the intentional introduction of fish species. Colonising interventions suffer from side-effects, unintended consequences, that again necessitate further remedial interventions, examples of such interventions include: soil salinization from irrigation, bed erosion from damming and biodiversity loss from habitat destruction or introduced alien species. Industrialisation, specifically the introduction of fossil fuels, has changed the spatial scale, frequency and intensity of colonising interventions in riverine systems, accelerating the rate of coevolutionary change and inducing a 'risk spiral' of unintended consequences (Sieferle and Müller-Herold, 1997).

The two concepts together allow us to study the coupling of social and natural systems in SEHS, from a systemic (metabolism-focus) and an actor-centred approach (colonisation-perspective). The latter is particularly important to attract more social scientists into the interdisciplinary field of river science.

3. Research agenda for SEHS

We need to understand in more detail how the SEHS will react to future changes in environmental, social, cultural and economic drivers, such as climate change, demographic shifts, new disaster patterns, different energy and agricultural policies, technological development, and land use. Based on the outlined concepts of metabolism and colonisation, we present a research agenda aiming to describe the coupling of riverine landscapes with social systems and their coevolutionary transformation (Fig. 1). Max-Neef (2005), suggested this can be characterised as a higher-level concept for the coordination of what he calls a 'purposive or pragmatic interdisciplinarity'.

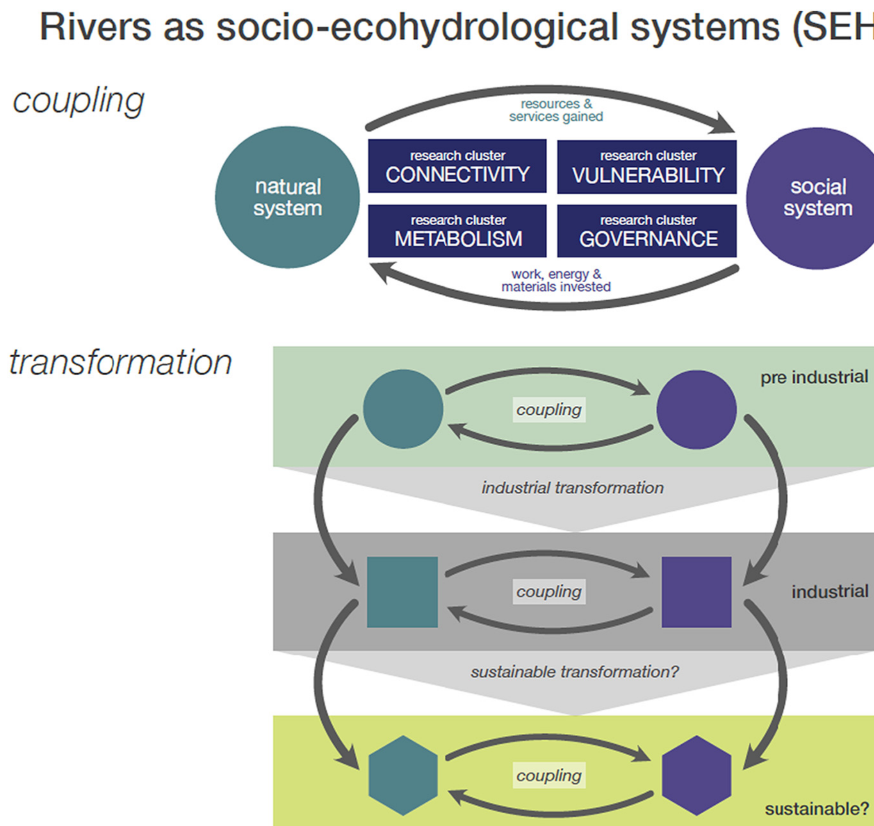

Fig. 1. The upper scheme depicts the coupling of natural and social systems through colonisation, and the four research clusters to study this coupling in socio-ecohydrological systems (SEHS). Social systems colonise natural systems by investing work, energy and materials (symbolised by the lower coupling arrow) to gain resources and services (upper coupling arrow). This coupling through colonisation not only transforms natural river systems into industrialised river systems, but also drives the coevolutionary transformation of the SEHS. The lower scheme depicts three crucial stages in this transformation of SEHS, from preindustrial to the current dominant industrial situation and a future envisaged, but by no means certain, sustainable coupling for which integrated river research must provide foundations. The upper scheme is based on Fischer-Kowalski and Haberl (2007) and Fischer-Kowalski and Weisz, 1999, but is specifically adapted for river systems here.

To structure the socio-ecohydrological research agenda in river science, we propose four basic research clusters (RCs) as starting points to investigate the coupling of society and ecohydrology in SEHS (see Fig. 1): (i) connectivity, addressing the transformation processes in riverine landscapes based on changes in ecological, hydrological and landscape connectivity,; (ii) governance, examining the transformation processes within social systems, iii) metabolism of both social and natural systems, including riverine landscapes as sources and sinks of resource flows (matter and energy) into, through and out of society; and iv) vulnerability to impacts, risks and shifting baselines.

This research agenda takes the conceptual basis from Vienna Social Ecology (Fischer-Kowalski and Haberl, 2007; Fischer-Kowalski and Weisz, 1999; Haberl et al., 2016) and further develops it explicitly for river systems and their transformations by stressing hydrology and focusing on coupled SEHS.

As a result of sociometabolic requirements (e.g. for so-called carbon neutral energy), a social system colonises a natural system and thus, transforms a river into an industrialised system; the latter substantially alters connectivity patterns, create a novel biological metabolism and lead to new types of vulnerability. In the short- or long-term, the social system not only gains resources and services from these industrialised systems, but also faces unintended consequences, with new types of risk and uncertainty that stipulate a transformation process within the social system interacting with the river. In the most favourable cases, learning processes in the social system lead to a better governance and planning regime guiding the next round of colonising interventions, leading to a potentially more sustainable transformation (as depicted in the lower scheme of Fig. 1). In any case, the social and the ecohydrological systems are coupled in their future development through colonisation and constitute rivers as coevolving SEHS.

Within this socio-ecohydrological framework, it is important to consider that social interventions often take place at one location and time point, while their consequences are observed and the decisions are made in another place and time. Thus, sustainable SEHS management needs to consider linkages between interventions and process changes, their consequences for the natural and social systems and the operational sphere of decision-making institutions and authorities across both temporally and spatially varying scales.

3.1. Connectivity

The concept of connectivity aims to understand and analyse the properties of complex systems, and is commonly applied in riverine landscapes (Turnbull et al., 2018). Here, connectivity in riverine landscapes describes the fundamental exchange processes of water, matter and organisms while considering the landscape context (Wohl, 2017). The transformation of riverine landscapes into industrialised systems affects connectivity properties by changing the spatial arrangement of landscape characteristics (habitat types, land use) and exchange processes. Colonising interventions such as hydraulic engineering or urbanization lead to changes in connectivity properties at local and regional scales; for example, promoting land use change in former floodplain areas limits the availability of floodplain habitats for riverine communities and impacts floodwater retention and recreational uses. Conceptualizing and analysing cross-scaling aspects linked to the downstream effects of these human interventions, could provide new insights in

SEHS and identify new emergent properties of the resulting industrialised system.

Furthermore, the connectivity concept considers geomorphic, hydrological, ecological and societal dimensions not only as nodes within SEHS and also facilitates the analyses of the linkages between these nodes (Bracken et al., 2015; Kondolf and Pinto, 2017; Mahoney et al., 2020), thus providing new insights into local and regional effects of restoration measures (Baldan et al., 2020) as one example of interactions at multiple scales. In network analyses, connectivity is, thus, differentiated in structural (e.g. habitats, resource stocks) and functional (e.g., matter fluxes and migrating organisms) components to analyse their relationship (Eros et al., 2012). Considering the structural and functional connectivity enables the quantification of changes in SEHS properties, as a result of societal activities.

Flows of matter and energy in rivers are available resources for social metabolism, but are simultaneously profoundly affected by the output flows of social metabolism. A further development of connectivity based analyses allows for the assessment of the linkages between societal dynamics (Kondolf and Pinto, 2017) and environmental dynamics, such as the modification of navigation channel geometry, promoting transport capacities in river corridors, while impacting the availability of the ecological corridor connecting protected areas. Furthermore, changes in social metabolism in response to changing regional and global drivers (e.g., climate change, economic development) will affect connectivity patterns in industrialised river systems (Winiwarter et al., 2016) requiring more attention in SEHS management in the future.

3.2. Governance and planning

To enhance the resilience and diversity of rivers as living spaces for human society and the attendant flora and fauna, an alternative colonisation strategy for riverine landscapes is needed, reconsidering the use of SEHS resources (landscape, soil, water, air, energy, biodiversity etc.). This need requires innovative approaches for strategic planning and governance and urges proactive and reactive management processes that promotes sustainability. Therefore, this research cluster addresses the interplay of formal planning and informal multilevel governance decisions at the international, national, regional and local scales to manage SEHS across territorial borders, scientific disciplines and administrative units. In this way, governance and planning are raised to the same scale as catchment-based approaches as requested e.g. by the EU WFD (EC, 2000).

As stated above, the transformation of SEHS not only disrupts the natural system but also changes the way society values, appropriates and uses riverine landscapes. Planning decisions have to be transparent and comprehensible, based on sound facts and a negotiated, societally agreed upon value base (Stöglehner, 2019). These need to be based on trade-offs amongst nature conservation, agricultural or silvicultural production, energy generation, recreation, infrastructure development and flood protection. The sound factual base forms the foundation of the value base as only what is known can be valued. Therefore, governance and planning for the sustainable development of the SEHS need to be supported by science-based approaches dealing with the interactions between the natural and social systems.

The implementation of the SEHS concept in governance and planning requires the coordination of top-down and bottom-up management and governance decisions with respect to regulatory frameworks, financial incentive systems, public infrastructure investments, administrative practices, public participation, awareness raising and private sector investments.

For the design of planning and governance processes, the following approaches have to be contextualized into already-existing and future steering and management mechanisms for SEHS, but also integrated with each other including: planning cultures (Levin-Keitel and Othengrafen, 2016); regional governance (Beutl, 2010); the strategic role of planning and management processes (Faludi, 2000; Stoeglehner, 2020); the quality of planning, management and governance processes (Roux et al., 2016); societal learning in and through planning and governance processes (Innes and Booher, 2000; Stoeglehner, 2010); and resilience in spatial development (Erker et al., 2017a; Godschalk, 2003). New theories and methodologies not only have to be tested and evaluated, but also have to be transferred beyond the scientific world and made accessible, comprehensible and applicable for political decision-makers, economic leaders and civil society at all governance and planning levels.

3.3. Metabolism

The RC metabolism investigates the role of rivers in a society's metabolism (cp. chapter 2.1) and asks how material and energy fluxes from, through and out of river systems are connected to biological and social metabolic processes in riverine landscapes and organisms. Riverine landscapes are sources of material and energy for society, they provide space for infrastructure ('stocks'), and they receive output flows from society in the form of waste(water), pollutants, heat and emissions (Fig. 1). Industrialisation resulted in the construction of infrastructure such as dams, fortified banks, shipping canals, ports and other facilities, that are often not or only poorly adapted to the dynamics of an earth and climate system in the Anthropocene (Palmer et al., 2009; Syvitski et al., 2009).

Changes in social metabolism are intricately linked to changes in the metabolic patterns of a riverine landscape (Rodríguez-Castillo et al., 2019; Cabello et al., 2015). Riverine landscapes, for example, play a crucial role in climate change mitigation, as they can act as sources and sinks of greenhouse gas emissions. However, this sink function depends on, amongst other things, on the connectivity within river systems (RC 1) and is altered by dam constructions and other infrastructure (Burgos et al., 2015). The decarbonisation of societal metabolism to reduce climate change impacts will very likely result in further transformation of riverine landscapes. There is an urgent need to conceptualize and plan for these transformations to be sustainable. Substituting coal-burning power plants, for example, with hydropower plants (seen as green-energy), has dramatically changed the hydrodynamics of large rivers, thereby, contributing to the decline in aquatic biodiversity (Winemiller et al., 2016). Other factors that change the metabolism of riverine communities are altered sediment balances and the oversupply of nutrients from settlements and intensive agriculture. The development of an increasing number of pharmaceutical and cosmetic products exemplifies how social change influences rivers' metabolism and challenges both science and management to find mitigation or compensation strategies. Although in some countries we see an influence of societal change, for example in agriculture, we observe a societal value shift from production-focused to more sustainable business-farming practices and landscape management, new challenges and legacy issues will arise that can be addressed effectively only using the holistic approach proposed herein.

3.4. Vulnerability

Assessing the vulnerability of water bodies and ecosystems to human impacts and climate change is key for developing sustainable solutions for water security and ecosystem health. Vulnerability as a component of risk assessment is often considered in the context of the source-pathway-receptor paradigm (EC, 2003; EC, 2010), with vulnerability linked to the pathway. Vulnerability has also been applied to integrate the social and environmental aspects in sustainability assessments (Bottero, 2011; Eakin and Luers, 2006). These assessments mainly use the DPSIR (Driving forces, Pressures, States, Impacts, Responses) framework adapted by the European Environment Agency. In the past, the impacts of single pressure–response processes were assessed (Adger et al., 2004). However, network theory and recent developments have shown that responses are greater than the sum of their parts (e.g., Graf, 2006). Thus, the consideration of only single pressures instead of multiple concurrent pressures can lead to unclear baseline conditions, with unpredictable consequences for riverine processes, aquatic organisms, and ultimately human society (Field et al., 2014). The main challenge of a vulnerability assessment is to adequately capture and describe the dynamic state of river systems, as even baselines are dynamic, due to the networked nature of several pressure-response relationships.

Accelerated transformation processes have led to secondary habitat types and even 'novel ecosystems' (Hobbs et al., 2006; Jackson and Hobbs, 2009). However, we need to advance our understanding of what constitutes 'novel', how vulnerable they are, what the critical tipping points are (Clements and Ozgul, 2018), and how they are triggered. Furthermore, it remains to be studied which changes are (ir)reversible and how new states can be determined for both, social and natural systems. This approach entails examining whether (static) indicators are appropriate to assess and manage different states of SEHS and whether industrialised rivers are systems with shifting baselines exhibiting dynamic, reversible or irreversible states (Humphries and Winemiller, 2009). A key requirement for future vulnerability assessment methods, for both natural and social systems and the connections between them, is to understand the main physical, chemical, and biological processes, including a sufficient appraisal of the natural and social effects of river engineering interventions and opportunities for future nature-based solutions (e.g., Wesselink et al., 2020). These key drivers need to be further embedded in a socioeconomic risk assessment, which would allow for the implementation of mitigation strategies and the prediction of their consequences for the natural and social system.

4. Important steps towards the implementation of the research agenda

The four research clusters allow us to analyse specific research questions related to the transformation of the SEHS and the coupling of the natural and social systems within the SEHS. The suggested research clusters are seen as a starting point to implement this holistic research agenda by targeting specific problems, using specific methodological approaches and considering the hierarchically structured spatiotemporal variability of structures, fluxes and processes within river systems. Furthermore, we consider the following aspects crucial for a successful implementation of the socio-ecohydrological research agenda presented: (1) the development of analytical approaches to predict transformation across these hierarchies; (2) the integration of experts from different disciplines such as ecology, social sciences and engineering; and (3) the communication and cooperation with various nonscientific stakeholders.

Understanding how industrialised rivers react to drivers of change requires the generation of new data (e.g., by environmental monitoring or local population surveys) and the development and application of models and tools that allow predicting processes and feedback mechanisms at different spatiotemporal scales. The spectrum of methods should include, amongst others, the analysis of past governance schemes and ensuing conflicts, the critical examination of failed interventions, the development and application of coupled socio-ecohydrological models of different complexity and statistical or machine learning approaches to analyse big data sets (Lin et al., 2020). One of the key challenges is the consideration and quantification of the full "chain of uncertainty" within the cycle of socio-ecohydrological scenarios relevant to industrialised rivers, their regional projections, subsequent impact analysis, the realisation of adaptation measures and possible feedbacks of these measures (Schürz et al., 2019).

For the research agenda we propose, it is important that the single disciplinary competences are not just added, but that interdisciplinarity is implemented by starting with the joint problem definition and formulation of research questions and ending with the joint elaboration of discussion and conclusions in interdisciplinary teams. For this purpose, universities need to orient higher education in a new way (Max-Neef, 2005). Natural scientists contribute their understanding of physical, chemical and biological processes. They study changes in the metabolism of the industrialised river system and how these changes are driven by natural processes following human interventions. Social scientists provide information, e.g., on motivations for interventions, changes in behaviour responding to transformations in SEHS, economic (ir)rationalities and contested political decision processes that precede colonising interventions. They analyse the long-term repercussions of colonising interventions of rivers back into society and identify perceived or ignored risks, vulnerabilities and opportunities in river management. Engineering sciences contribute their expertise on technology-based modifications of ecosystems and technical innovations for a more sustainable and efficient use of natural systems. Their knowledge helps to react adequately and compensate for the unforeseen consequences of colonising interventions.

Furthermore, we propose to make the knowledge generated under this research agenda relevant and operational for the sustainable development of SEHS by addressing universities' third mission and integrating knowledge from nonscientific interest groups in transdisciplinary approaches (Lozano, 2006; Trencher et al., 2014). Within the third mission of universities, knowledge is transferred to target groups, such as political decision-makers, the economic sector, planners and the civil society, by a bandwidth of integrative actions. Amongst these are the informal provision of knowledge (via public presentations, workshops, etc.), customised education programmes tailored to the specific knowledge demands of the target groups and co-research approaches to gain the full benefit of transdisciplinarity (Peer and Stoeglehner, 2013). While facts should be generated based on scientific research, the weighting of values in SEHS is always subject to negotiation (Stoeglehner, 2010). The perception of facts viewed by decision-makers and by society may differ from actual scientifically proven facts and might guide actions (Erker et al., 2017b). Therefore, the scientific knowledge generated about the metabolism, connectivity and vulnerability of SEHS should inform decision-making in governance and planning.

The development of new research programmes (e.g., the currently developed new European research programmes such Horizon Europe starting in 2021) can efficiently support interdisciplinary cooperation well-rooted in social-ecohydrological theory, targeted transdisciplinary activities and the establishment of new educational programmes. In the recent past, an international doctoral programme, Science for the Management of Rivers and their Tidal Systems (SMART), has proven that interdisciplinary and management-oriented research can provide significant contributions to science-based solutions for rivers (Serlet et al., 2020).

Transdisciplinary coproduction of knowledge supporting sustainable development can be provided within new educational PhD programmes to train a new generation of scientists capable of integrating and transferring knowledge more efficiently (Enengel et al., 2012). In addition to providing courses on interdisciplinarity and transdisciplinarity within the curriculum, the establishment of mentoring teams for specific PhD projects, consisting of experts from different disciplines and societal sectors, can stimulate joint research activities and the transfer of results into implementation. One example is the recently established doctoral school "Human River Systems of the 21st century" at the University of Natural Resources and Life Sciences in Vienna (hr21.boku.ac.at). Based on the proposed SEHS research agenda for rivers, we aim to inspire further discussion on that knowledge is needed for the sustainable development of rivers and how this knowledge can be delivered to and exchanged with decision-makers in river management.

5. Conclusions

Managing SEHS strategically and holistically to proceed towards sustainable development is highly complex and therefore requires a conceptual framework providing a holistic overview and ensuring that the interacting issues and processes are not overlooked. It thus calls for a scientific community effort to address these complex problems and engage in interdisciplinary and transdisciplinary research, including a broad spectrum of scientific disciplines and the societal actors connected to the respective river. These activities will support achieving the sustainable development goals and environmental issues, such as biodiversity targets. To spur further change towards sustainable development, research designs should not be limited to knowledge provision within the scientific community and traditional university teaching, but should also take the third mission of universities into account.

The proposed research agenda for sustainable development draws on the concept of SEHS that integrates different disciplinary approaches (interdisciplinarity) and captures the various drivers of change. The coupling of natural and social systems in SEHS is the clear focus of this research agenda, because industrialised river systems need to be conceptualized as social, ecological and hydrological systems to lay the groundwork for their sustainable transformation. Furthermore, transdisciplinary approaches are proposed to implement the research agenda and efficiently transfer the knowledge gained. The proposed research agenda is based on a deeper understanding of SEHS metabolism and connectivity, in doing so examines their vulnerability to different changing situations or disruptions, and explicitly addresses governance and planning regimes to direct ecological, societal, and economic developments towards a more sustainable SEHS. Furthermore, the research addresses different forms of knowledge diffusion to and through society.

CRediT authorship contribution statement

TH, CH, MS, GS and CS developed the basic concept with input from all authors. ASK developed the visualization of the scheme. All authors provided input to the manuscript and agree on this version.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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