Preparatory Phase for the pan-European Research Infrastructure DANUBIUS–RI
"The International Centre for advanced studies on river-sea systems"

Strategic Science & Innovation Agenda

Underpinning the Technical and Organisational Design of DANUBIUS-RI

Draft - Deliverable 2.5

European Commission

This project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No 739562

Project Full Title	Preparatory Phase for the pan-European Research Infrastructure DANUBIUS-RI “The International Centre for Advanced Studies on River-Sea Systems”
Project Acronym	DANUBIUS-PP
Grant Agreement No.	739562
Coordinator	Dr. Adrian Stanica
Project Start Date and Duration	1st December 2016, 36 months
Project Website	www.danubius-pp.eu

Deliverable Nr.	2.5	**Deliverable Date**	M24
Work Package No.	2		
Work Package Title	Science and Innovation Agenda		
Responsible	HZG		
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Status:	**Final (F)**	
	Draft (D)	●
	Revised draft (RV)	
Dissemination Level:	**Public (PU)**	
	Restricted to other program participants (PP)	
	Restricted to a group specified by the consortium (RE)	
	Confidential, only for members of the consortium (CO)	●

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EXECUTIVE SUMMARY

This document presents the Science and Innovation Agenda (SIA) for DANUBIUS-RI: a dedicated Research Infrastructure (RI) to advance interdisciplinary research (IDR) on River-Sea (RS) systems. The vision for the RI is to provide research facilities that spanning the freshwater and marine environments and hence 'make river – sea systems' work by drawing upon new developments in environmental analysis, observation, and modelling, to address current and emerging challenges that confront diverse RS systems across Europe. The intention is to maximise the benefit to society by enhancing resilience and enabling Europe to develop "the most competitive and dynamic knowledge-based economy in the world capable of sustainable economic growth with more and better jobs and greater social cohesion[1]". This is encapsulated in the "Europe 2020" strategy, which reflects the ambition to generate a "smart, sustainable and inclusive growth as a way to overcome the structural weaknesses in Europe's economy, improve its competitiveness and productivity and underpin a sustainable social market economy[2]".

DANUBIUS-RI is currently (2018/19) receiving preparatory phase funding support from the EU through a Coordination and Support Action (DANUBIUS-PP), drawing together contributions from 30 institutions in 16 countries. DANUBIUS-RI occupies a unique position in the European RI roadmap as it spans freshwater and marine environments and caters for a range of disciplines across these domains. DANUBIUS-RI will comprise both new and existing components and the intention is to bring these together under a single European Research Infrastructure Consortium (ERIC). It is hoped, subject to agreement and support of member states, to establish DANUBIUS-ERIC by 2022. This will be a legal entity offering facilities that breakdown the barriers to IDR on rivers and seas, offering the tools to enable mission-orientated research, enhance knowledge exchange and train new communities of users. DANUBIUS-ERIC will overcome the fragmentation of resources (facilities, data, expertise, equipment) devoted to research on European research on Rivers and Seas. It will enhance the mobility of European researchers and consolidate financial resources in national facilities that in some cases lack critical mass, suffer from underinvestment, and are hindered by limited cross-border collaborations. The potential added value of RIs of this nature is demonstrated by the ongoing success of CERN.

The motivation for DANUBIUS-RI is that globally rivers and seas have experienced widespread and pervasive changes in their environment, which threaten the continued provision of key ecosystem services. This requires novel approaches to Research and Innovation (R&I) that recognise the multi-faceted links within RS systems and offers enhanced interdisciplinary and holistic understanding. The vision is that DANUBIUS-RI will offer facilities for R&I that link freshwater, transitional water and coastal water environments to advance process and system

1 www.europarl.europa.eu/summits/lis1_en.html
2 https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2010:2020:FIN:EN:PDF

understanding, enhance stakeholder engagement, enable the development of informed environmental policies and regulations and thereby 'make River-Sea Systems work'. This will include promotion of the **DANUBIUS Commons**, a new approach to R&I with a common language and research toolbox that unites the communities involved in freshwater and marine environments.

The SIA identifies four key Research Priorities in RS systems that are being used to guide the development of the RI through the preparatory phase to implementation and operation: i. Climate Change; ii. Water Sufficiency; iii. Sediments and their Management; and iv. Ecosystem Health. These Research Priorities are open to revision as the RI matures, and the aspiration is that that DANUBIUS-RI will provide the facilities to advance IDR on RS systems. Hence, all the Research Priorities require collaboration between individual academic domains, ranging from the natural sciences to the social and economic sciences.

Climate Change is contributing to an intensification of the hydrological cycle and the increasing frequency of floods and droughts. The effects of these extreme events are exacerbated in coastal areas by sea level rise and land subsidence with significant social and economic impacts (for example, on agriculture, communications and transport and on industry and business). Hence, long-term mitigation and adaptation are crucial to maintaining key ecosystem services currently provided by RS systems. This, in turn, requires greater holistic understanding of RS systems, and recognition of how these systems are evolving at different spatial and temporal scales.

Water Sufficiency embraces the challenge of how to ensure continued water availability to satisfy both anthropogenic and environmental needs. It includes questions relating to both the quantity and quality of surface water and groundwater, along the continuum from catchment to coast. In this area, the difficulty is how to address problems, such as eutrophication and hypoxia, pollution, salinization, changes in river (and tidal river) regime and sea level, given increasing water abstraction, river regulation, and changing catchment land-use. Rivers have been increasingly isolated from their floodplains, and modified by extensive engineering with effects that propagate along the River Sea continuum.

Sediment is essential to the functioning of RS systems, which are characterised by sediment routing from source to sink through erosion, deposition and remobilisation. Catchment, river and coastal management has affected sediment availability, which is required to sustain farmland and enhance flood protection (e.g. via floodplain or estuarine aggradation). Erosion and sedimentation occur over different scales, and holistic approaches to research on RS systems are required to deliver integrated sediment management plans, which are supported by key stakeholders.

Ecosystem Health in RS systems focuses on the complex and diverse habitats in freshwater, semi-terrestrial and semi-aquatic (i.e. floodplains), transitional (deltas, estuaries) and coastal environments. Biodiversity is a key element for ecosystem structure and functioning, underpinning key ecosystem services (such as fish production, habitat provision, flood and storm protection). It is threatened by habitat fragmentation and loss, insufficient water and sediment quantity and quality, overfishing and invasive species. A key challenge is to determine how changing ecosystem structure and function will affect ecosystem health and the provision of ecosystem services in the future.

The four Research Priorities, *Climate Change*, *Water Sufficiency*, *Sediments and their Management*, and *Ecosystem Health* are interrelated and highlight the importance of interdisciplinary R&I across the RS continuum. As an environmental RI, the primary users of DANUBIUS-RI are anticipated to be from the academic community, however, the RI seeks to work with a wider community of users, including local and national governments, business, environmental agencies, both as potential beneficiaries and as funders. To date, a total approaching 200 specific services have been identified for five target user groups: research organisations (and staff); business and professional bodies; students; government bodies; and the general public. The vision of DANUBIUS-RI is to provide a distributed RI for observation, experimentation and modelling in a range of European RS systems that addresses this need by integrating existing knowledge and providing new interdisciplinary knowledge, using standardised methods and providing access to comparable data, and engaging decision makers, stakeholders and the public(s). This will avoid the classic European separation between research, education and innovation: the role of pan-European, modern RI is to constitute knowledge hubs that eventually foster the “knowledge-based economy” and “smart, sustainable and inclusive growth” sought after by the Lisbon Agenda and Europe 2020 strategy.

PREAMBLE

DANUBIUS-RI, the International Centre for Advanced Studies on River-Sea Systems, is being developed as a pan-European distributed research infrastructure (RI) to link and integrate research in rivers and seas; i.e. from the mountains to the sea. In 2016, DANUBIUS-RI entered the Roadmap of the European Strategy Forum on Research Infrastructures (ESFRI) in the category "Environment". It will be a "research infrastructure supporting research on transitional zones between freshwater and coastal marine areas to fulfil the need for a "holistic view on the water cycle that demands for integrated, interdisciplinary and trans-sectorial approaches, which will provide solutions to societal risks such as severe floods, landslides and droughts" (ESFRI-Roadmap, 2016). DANUBIUS-RI will build on existing expertise around Europe and aims at research using a systems-based approach to overcome disciplinary, regional and national boundaries, in order to better understand environmental processes and system dynamics, to maintain ecosystem functioning and thus to sustain valuable ecosystem services. The RI will provide access to a range of River-Sea (RS) systems, facilities, data and expertise, and will enable interdisciplinary research (IDR), knowledge exchange, education and training. DANUBIUS-PP (Preparatory Phase) is a three-year, European Commission funded H2020 project that seeks to achieve the legal, financial and technical maturity required for the successful implementation, operation and further development of DANUBIUS-RI (www.danubius-pp.eu, Grant Agreement No. 739562).

Purpose of the Science & Innovation Agenda (SIA)

The SIA describes our methodological approach to RS system research in subchapter 1.2, conveys the scientific focus in chapter 2, and provides the science-based framework for technical design of the RI in chapter 3 . Chapter 4 depicts how DANUBIUS-RI's performance will be monitored, while chapter 5 tells how our SIA will be updated as research needs in RS systems and requirements of stakeholders will change with time. In DANUBIUS-RI, we understand innovation as the application of novel solutions, methods and techniques to integrative, IDR. The SIA explains how DANUBIUS-RI translates its vision and mission into strategic research themes/topics, and implementation of the RI. The identified research needs will shape the infrastructure, to provide for the required capacities, tools, expertise and interdisciplinarity. In addition, the SIA represents an indispensable tool to highlight the infrastructure and its capabilities with to give the reasoning to policy makers and funding agencies to support DANUBIUS-RI, to foster stakeholder engagement, and to attract users from science, environmental agencies, policy making, industry and to inform the wider public.

1. INTRODUCTION

Jana Friedrich & Peter Heininger (HZG), Chris Bradley (UoB)

Why do we need research on the continuum of River and Sea?

Water on Earth is inter-linked with the atmosphere, cryosphere, soils, sediments and the rest of the geosphere, as well as with the entire biosphere, and therefore must be seen and studied in a holistic way (ESFRI-Roadmap, 2018). Water has a unique role as the essential ingredient for life, and for direct and indirect provision of ecosystem services (Pahl-Wostl et al., 2013). RS systems comprise whole river basins and coastal seas ('from the mountains to the sea', Figure 1). Rivers and their floodplains, lakes, groundwater, estuaries, deltas, coastal wetlands and adjacent coastal seas are the dynamic products of interacting environmental processes, and have been shaped progressively by humans since the beginning of the Holocene. RS systems are subject to continuous change at different spatial (local, national and global) and temporal (seasons to centuries) scales. Change originates from interacting driving forces such as geologic forces, global climate change and extreme events, and from human activities, such as urbanisation, water born transport, hydropower generation, industrial development, agriculture and changing land use. RS systems provide ecosystem services that are fundamental to societal wellbeing. Therefore, RS systems are considered as social-ecological systems (SES). Presently about 40% of the world's population lives within 100 kilometres of the coast (UN, 2007). 50% of the world's population lives closer than 3 km to a surface freshwater body, and only 10% of the population lives further than 10 km away (Kummu et al., 2011).

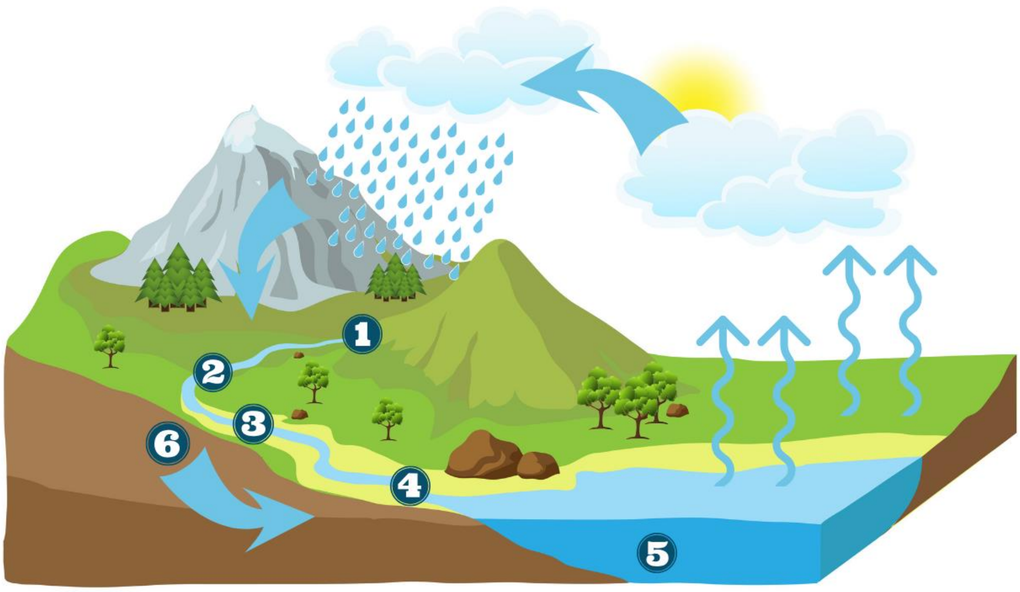

Figure 1 DANUBIUS-RI's conceptualized view of a RS continuum including (1) Headwaters, (2) Middle Waters, (3) Lower Waters, (4) Transitional Waters, (5) Coastal Waters and (6) Groundwater

However, human actions also jeopardise the continued provision of key ecosystem services and alter the capacity of RS systems to sustain societal development. For example, fundamental changes in the movement of water and sediment from catchments to coasts due to hydropower dam construction, river channelling and diffuse pollutant inputs result in widespread consequences, such as erosion of deltas, pollution and eutrophication. According to a recent assessment of European surface waters by the European Environment Agency (EEA) ca. 60% of the reported surface waters are not in good ecological or chemical status. The assessment attributes the main significant pressures to hydromorphological pressures (40%), diffuse sources (38%) mainly from agriculture, atmospheric deposition (38%), followed by point sources (18%) and water abstraction (7%) (EEA, 2018). According to a policy brief of the Source-to-Sea platform (SIWI, 2018), marine and coastal resources represent enormous assets for local and global economies, but they may be jeopardized by upstream activities on land and along rivers. Worldwide, approximately 8 million tons of plastic enter the ocean from land-based sources every year (SIWI, 2018). Nutrient loads from unmanaged agricultural runoff and inadequate wastewater treatment continue to cause eutrophication and spread of dead zones in our coastal and marine waters. Flows of some rivers are so highly diverted that little water reaches the sea, robbing coastal ecosystems of the water, sediment and nutrients they need. Fragmentation of rivers - from dams, weirs and other infrastructure – has radically reduced anadromous and migrating fish populations worldwide. All this leads to a water-food-energy-ecosystem nexus crisis, according to (SIWI, 2018). This illustrates that water is of enormous global geopolitical importance.

Without counteraction towards sustainable development, these pressures and respective ecosystem state changes are likely to increase in future with implications throughout the RS continuum, and with uncertain consequences for the resilience of RS systems. What will be the social and economic costs of human disturbance to rivers and coastal zones, e.g., the costs of lost floodplains and beaches, decline of deltas, hyper-turbid rivers, loss of fish stocks, polluted surface and groundwater, since they provide more valuable ecosystems than any other biome on the planet (Costanza et al., 1997)?

To date, an increasing number of international organisations, conventions and research frameworks have recognised the important connection between rivers and seas, e.g., ESFRI, UNECE Water Convention, the Stockholm International Water Institute (SIWI) with the Source – to – Sea platform (S2S), JPI Water, Future Earth – Coasts, Global Water Partnership. Given the global context of water problems and the need to identify solutions, Pahl-Wostl et al. (2013) advocate the setting of 'global water testbeds' for IDR, in which integrated methodologies can be developed to enhance interdisciplinary knowledge and build on new and emerging ideas in the environmental sciences. SIWI and S2S suggest, for tackling these challenges, that a source-to-sea transboundary perspective would be needed. This holistic approach considers the linkages across the full continuum from source to sea, i.e. from land to freshwater, delta, estuary, coastline, nearshore and ocean, and addresses six key flows that are defining attributes of transboundary rivers: water, sediment, biota, pollutants, materials and ecosystem services (Figure 2). The source-to-sea approach builds on the four areas of focus of the Water Convention – prevent, control and reduce pollution; promote ecologically sound and rational water management; share water in a reasonable and equitable way and conserve and/ or restore ecosystems (SIWI, 2018). As early as in 2000, the Global Water Partnership determined a general need for researching and promoting "the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems" (Global Water Partnership 2000).

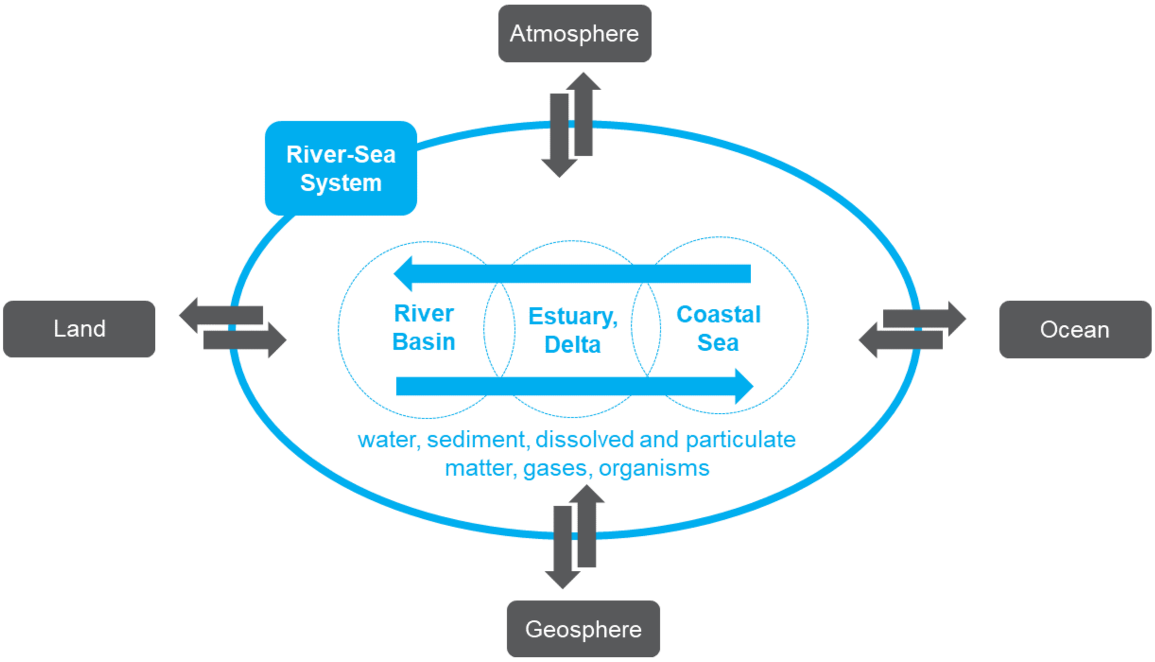

Figure 2 RS systems include the river basin, transitional waters, such as estuaries and deltas, as well as the adjacent coastal sea. Water, sediment, dissolved and particulate matter, gases and organisms are the connecting elements within the RS continuum. Thus, RS systems are located at the interface between land and ocean, as well as between geosphere and atmosphere.

DANUBIUS-RI is setting out to address these global challenges in RS systems. The basis ought to be improved scientific understanding so as to preserve our resource base and increase its resilience for life, nature, society and to protect human health in the changing climate (ESFRI-Roadmap, 2018). The gaps, challenges and future needs analysis related to water research in Europe performed by the ESFRI for its Roadmap 2018, states that Europe needs a highly instrumented Supersites network of observation, simulation and experimental platforms and ecosystem service modelling in fresh- and marine waters. For the comprehensive analysis of the changes in aquatic ecosystems an integrated basin approach is necessary to understand the impact of the different drivers and to find measures for sustainable water management (ESFRI-Roadmap, 2018). DANUBIUS-RI is considered by the ESFRI Roadmap 2018 as the only pan-European RI devoted to support research on transitional zones between coastal marine and freshwater areas, aiming to bridge the gaps mentioned above, at a basin-wide, river-to-sea approach.

At present, research facilities devoted to rivers and seas are fragmented with a paucity of R&I facilities spanning freshwater and marine systems. This is problematic given the scale of current and emerging environmental problems confronting RS systems that require: (1) new approaches to observe, understand, and model the environment; and (2) enhanced links between academic communities, policy, industry, business, and the public to improve the management of these vulnerable environments. A holistic and integrated approach is needed for effective implementation of key environmental policies and to address key current and emerging environmental and societal challenges. This is illustrated by the large number of sectorial European policies related to RS systems: the Water Framework Directive (WFD), the Flood Directive (FD), the Urban Waste Water Treatment Directive (UWWTD), the Marine Strategy Framework Directive (MSFD), the Maritime Spatial Planning Directive (MSPD), the Nitrate Directive (ND) and the Habitats Directive (HD).

1.1 Vision & Mission

Jana Friedrich & Peter Heininger (HZG), Chris Bradley (UoB)

DANUBIUS-RI's *vision* is "Making River-Sea Systems work". To achieve sustainable use of RS systems is in accord with the EU's vision to live well, within the planet's ecological limits, by 2050 (EU, 2013). It is key is to understand how to sustainably live with change both from the human and ecosystem perspective. How is the functioning of RS systems changing due to natural and anthropogenic drivers and pressures? Wise stewardship of the resources upon which we depend is critically dependent upon a continuing flow of information from observation to analysis, understanding, anticipation, and mitigation of future changes (Cloern et al., 2016) in RS systems.

How will DANUBIUS-RI address research on River-Sea Systems?

DANUBIUS-RI's *mission* is to deliver integrated knowledge for sustainable management, use and protection of RS systems. The UN 2030 SDGs, in particular SDG 6 'Clean Water & Sanitation' and SDG 14 and 'Life below Water', which explicitly emphasize the role of water for humans and nature (UN, 2015), provide guidance for defining the goals of DANUBIUS-RI. DANUBIUS-RI will contribute to the scientific basis for informed environmental policymaking and the EU's vision of sustainable blue growth and eco-innovation. A better scientific understanding of the functioning of RS systems will facilitate the joint implementation of existing European environmental policies, e.g. WFD, MSFD, FD and HD. Integrating a source-to-sea approach into transboundary water cooperation is needed to the meet the goals of the Water Convention (UNECE, 2018). DANUBIUS-RI addresses the need for environmental observation systems that are fit-for-purpose, integrated and interdisciplinary to address the global challenges of the 21st century, related to in RS systems. This thereby supports the implementation of the UN Sustainable Development Agenda and EU policies (WFD, MSFD).

What is DANUBIUS-RI?

DANUBIUS-RI, the International Centre for Advanced Studies on River-Sea Systems is being developed as a pan-European distributed RI to link and integrate research in rivers and seas; i.e. from the mountains to the sea. In 2016, DANUBIUS-RI entered the Roadmap of the ESFRI in the category "Environment". The RI will provide access to a range of RS systems, facilities, data and expertise, and will enable IDR, knowledge exchange, education and training. DANUBIUS-RI will enable effective collaboration between biological, physical, environmental and economic science research communities, usually working separately and on different environmental sectors, in an interdisciplinary and holistic scientific approach of RS systems, made possible through the adoption of scientific best practices, standards, methods, instruments, data acquisition, treatment, storage, and access. DANUBIUS-RI will provide an infrastructure for excellent IDR, education and training, and will develop into a 'one-stop shop' for knowledge exchange. DANUBIUS-RI will offer long-term provision of top-level research facilities, expertise and harmonised instrumentation, protocols and data to guarantee quality and consistency.

DANUBIUS-RI addresses six target groups: research institution staff, businesses and professionals, students, authorities, environmental policy makers and public at large. Services at DANUBIUS-RI will be provided as often as it is feasible on a competitive basis, on-demand otherwise. In compliance with the ESFRI philosophy, competitive access to the RI for research institution staff will be based on proposals, evaluated by a jury of independent experts against scientific excellence and social and economic relevance. Access to DANUBIUS-RI and its services are regulated by the European Research Infrastructure Consortium (ERIC) Statutes and Internal Rules. The "Access Policy Reference Document" (D4.4) provides a complete description of the DANUBIUS-RI access policy.

DANUBIUS-RI is composed of Hub, Nodes, Supersites, Data Centre and Technology Transfer Office (TTO). The **Hub**, as headquarters of DANUBIUS-RI, will provide leadership, management, administration and governance, coordination, communication and standardisation activities. It will be in charge of strategic planning, scientific evaluation, scientific endorsement, connectivity to the Data Centre, coordination with the TTO, Nodes and Supersites and dissemination of research outputs. The four **Nodes** “Observation”, “Analysis”, “Modelling” and “Impact” address major fields of expertise that are necessary for evaluating, understanding, and managing RS systems in change. In their specific areas, they provide methodological knowledge, facilities and services, data storage and provision, experimental and *in situ* measurements opportunities, state-of-the-art analytical capabilities and implementation of standardised procedures and quality control.

The **Supersites** provide natural laboratories for observation, research, modelling and innovation at locations of high scientific importance and opportunity, covering RS systems from headwaters to transitional waters and coastal seas. Ranging from the near pristine to the heavily impacted, the Supersites are selected to provide contrasting systems across environmental, social and economic gradients that have been impacted, to varying degrees either directly or indirectly, by industrialisation, urbanisation, population expansion, land use change and farming. They provide IDR platforms, identify, model, and define system states and conditions for naturally and anthropogenic triggered transitions in the physical, biogeochemical and biological states. They will provide excellent opportunities to undertake social and economic investigations in contrasting settings.

The **Data Centre** is responsible for data availability and processing. The data portal will provide access to a DANUBIUS-RI meta-database covering digital data from: remote sensing; automatic stations in real time and periodic downloading; cruises; computer models; and the results of other physical, sedimentological, chemical, and biological and ecotoxicological analyses. The primary role of the **TTO** will be to leverage the intellectual property rights and the infrastructural resources to successfully engage the range of end-users and stakeholders. Further details of the structure and functioning of DANUBIUS-RI will be provided in chapters 3, 4 and 5.

1.2 Methodological Approach

Peter Heininger, Jana Friedrich & Sina Bold (HZG), Chris Bradley (UoB), Henriette Otter & Gerald Jan Ellen (DLT)

RS systems are hot spots of interactions and dependencies between humans and nature, where ecosystems are shaped by humans while humans are depending on the ecosystems and the services they provide (Stockholm Resilience Centre; 2018). Due to this strong coupling, DANUBIUS-RI regards RS systems as **social-ecological systems** (Stockholm MISTRA Institute, 2006; Folke, 2006). DANUBIUS-RI will substantially contribute to overcome the dichotomy of nature and society, which are both “premature attempts to collect in two opposite assemblies the one common world” (Latour, 2005). To achieve societal impact, DANUBIUS-RI draws upon an integrated approach for advanced studies of RS systems across various spatial and temporal scales (Bradley et al., 2017).

Recognising the integrated nature of RS systems, their study needs to be interdisciplinary on many levels. Thus, DANUBIUS-RI enables IDR and innovation to enhance process and system understanding of RS systems so that environmental and socio-economic challenges related to RS systems can be mitigated. Furthermore, DANUBIUS-RI promotes a participatory approach including engaging various stakeholders and public(s) during and after the scientific process e.g. by giving stakeholders a strong voice in defining research priorities. In total, DANUBIUS-RI’s **mission-oriented**, **integrated, interdisciplinary and participatory** approach will initiate a **step change** in process and system understanding of RS systems and their respective management.

Addressing Change and Resilience

RS systems are the dynamic products of interacting biological, chemical, physical, geological, climatic as well as economic and social processes, and consequently are subject to continuous change. Therefore, the concept of variability around a quasi-equilibrium state may not apply to RS systems, and hence, may not be useful for guiding research or management (Cloern et al., 2016) of RS systems in a continuing state of change. Research and management towards protecting or restoring ecosystem functioning may be a more realistic goal than restoration towards an earlier, pristine state (Rosenzweig, 2003). Hence, DANUBIUS-RI considers change in and resilience of RS systems as key categories. In definitions of resilience, the threat to which the system should be resilient is often not specified and the focus is rather on general system characteristics. However, operational definitions are needed when resilience is to be quantified, monitored or addressed by policies (Biggs et al., 2012; De Bruijn 2005; Shaw 2012;

Wardekker et al., 2010). In those cases, both the system and the relevant disturbance should be clearly specified – "resilience of what to what?" (Carpenter et al., 2001). The co-construction of indicators of resilience from human and ecosystem perspectives will contribute to overcoming both the ignorance of the feedbacks and interactions between humans and ecosystems and the definition of conservation objectives in terms of reversion to a prior, pristine nature (Caillon et al. 2017).

In complex socio-ecological systems, adaptation and transformation take place at multiple scales. Dynamic interplay of persistence, adaptations and transformations at different scales contribute to the overall resilience of the larger system (Folke et al., 2010). Transformations may be deliberate or forced by crises and disasters, which form windows of opportunities for innovation and change. Deliberate transformation (and adaptation) follows from the ability of socio-ecological systems to incorporate learning (Biggs et al., 2012; Carpenter et al., 2001), or to timely foresee that change is needed because the current policy is bound to fail in the future (Klijn et al., 2015). DANUBIUS-RI addresses these two strategies by incorporating learning as a core principle. When resilience is used to analyse human-environment systems two questions are important: "resilience to what ends?" and "resilience for whom?" (Davoudi, 2012). Increasing resilience is expected to lead to a desirable outcome, but what is desirable in a social context is normative. Similarly, decisions on who should be resilient can involve value judgements about priorities and trade-offs (Berkes and Ross, 2016). De Bruijn et al. (2017) translated the scientific debate on resilience into five practical principles that can be used by policy makers and practitioners to develop strategies that enhance resilience. DANUBIUS-RI considers them as a core subject:

1. Adopt a system's approach: understanding of the entire system – including the physical, environmental and socio economical aspects – is required to define societal effective measures. The system is studied as a whole and the different subsystems areas and processes within the system are viewed as interlinked.
2. Look at beyond-design events: rare events with disastrous and lasting consequences may call for measures against higher costs than justified by standard cost-benefit analyses.
3. Build and prepare infrastructure according to 'remain functioning' principle: focus on ensuring infrastructure will remain functioning once a change/event occurs.
4. Increase recovery capacity by looking at social and financial capital; and remain resilient into the future: The capacity to recover depends on social capital (the individual ability of people), institutional capital (the ability to organize) and economic capital (the ability tot finance)
5. Remain resilient into the future: flexibility, the ability to learn, the capacity to adapt and the willingness to transform if necessary are crucial to cope with gradual but uncertain changes, it is important to realise that the current resilience of a system may be exhausted due to gradual geo-physical developments such as climate change or subsidence, and

socio-economic developments such as migration, conflicts, urbanization and economic growth.

Mission-oriented

Global challenges have been expressed as 17 Sustainable Development Goals (SDGs) in the United Nations' Agenda 2030 (United Nations, 2015). These include "Clean Water & Sanitation" (SDG 6), "Life below Water" (SDG 14), "Life on Land" (SDG 15) and "Climate Action" (SDG 13). RS systems are naturally linking several SDGs. DANUBIUS-RI believes that healthy RS systems are the basis for the fulfilment of these SDGs, which in turn are the basis for other SDGs and their fulfilment, since societies and economies are embedded parts of RS systems. As stated in the World Water Development Report, "water is at the core of sustainable development" (WWAP UN-Water 2018).

Above all, DANUBIUS-RI applies a mission-oriented approach by facilitating concrete projects, not in isolation, but interlinked within a long-term framework in order to achieve targeted missions and to address global challenges. According to Mazzucato (2018), missions "must be bold, activating innovation across sectors, across actors and across disciplines." Mission-oriented research enables bottom-up solutions and experimentation and represents a smart way to frame the conversations between applied R&I and basic fundamental research. It allows a new way of thinking about "the dynamic interactions between enabling horizontal policies (framework policies around e.g. education, skills, training, R&I) and more directed vertical policies (e.g. health, environment, energy)." The themes of this SIA (1) coping with climate change and extreme events, (2) having sufficient water in terms of quantity and quality, (3) ensuring balanced sediment conditions in terms of quantity and quality, (4) achieving and sustaining healthy ecosystems, and (5) living with change in RS systems fully comply with these claims (cf. Chapter 2 – Research Priorities).

Integrated

DANUBIUS-RI's studies strive for an integrated understanding of the natural system in terms of space and time, of biotic and abiotic factors, of water and material fluxes and cycling, of system processes, functioning and change. In the integrated understanding RS systems encompass (1) freshwater, transitional, e.g. estuaries and deltas, and marine ecosystems (longitudinal connectivity); (2) semi-aquatic and semi-terrestrial ecosystems, e.g. floodplains and wetlands (lateral connectivity); as well as (3) benthic and pelagic ecosystems (vertical connectivity). These three dimensions of connectivity can range from fully connected to disconnected over diverse temporal and spatial scales (Wohl, 2017). Furthermore, the connectivity between landscapes and riverscapes (Tetzlaff et al., 2007), as well as riverscapes and seascapes will be highlighted (Figure 3).

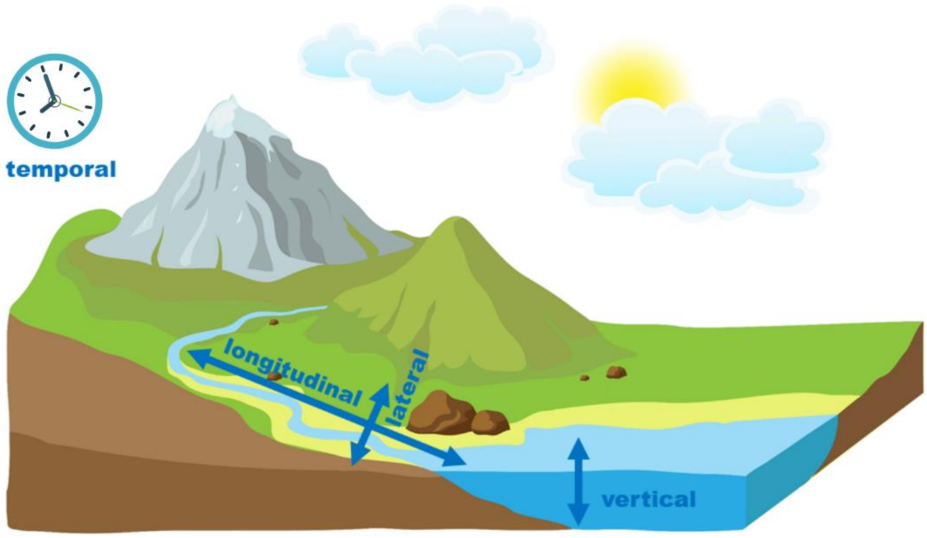

Figure 3 Four degrees of connectivity within RS systems, which include (1) freshwater, transitional, e.g. estuaries and deltas, and marine ecosystems (longitudinal connectivity); (2) semi-aquatic and semi-terrestrial ecosystems, e.g. floodplains and wetlands (lateral connectivity); as well as (3) hyporheic, benthic and pelagic ecosystems (vertical connectivity) over diverse temporal scales (temporal connectivity).

Given the inherent complexity of SES, we use a problem-based approach to identify, structure and assess the links between both human and natural forces and the resulting pressures and effects they exert on RS systems and hence, on human welfare. We apply the Driver – Pressure – State Change – Impact – Response (DPSIR) conceptual framework as problem structuring method. It links cause-effect relationships among the five categories of the framework and has proven in many studies a powerful means for analysing and assessing the social and ecological problems of aquatic systems subject to anthropogenic influence (Gari et al, 2015). The DPSIR framework is one of the original tools developed by the Organization of Economic Cooperation and Development (OECD, 1993) and the European Environment Agency (EEA, 1995) for the adaptive management of SES. It fulfils two important tasks by enabling a systemic, interdisciplinary and ecosystem-based approach to research needs and allowing identifying RS continuum-spanning research challenges.

RS systems provide ecosystem services that are fundamental to societal wellbeing. However, these systems face compounding pressures from climate change and from human drivers such as land use change, urbanisation, energy generation, waterborne transport, agriculture and fisheries at different spatial (local, national and global) and temporal (seasons to centuries) scales. The resulting changes in the status of RS systems lead to the decrease or loss of biodiversity and ecosystem functions, also affecting ecosystem services. An ecosystem services-based approach is a way of understanding the complex relationships between nature and humans to support decision-making, with the aim of reversing the declining status of ecosystems and ensuring the sustainable management of resources (Martin-Ortega et al., 2015). Such an approach entails the following core elements: (1) the focus on the status of ecosystems, and the recognition of its effects on human wellbeing; (2) the understanding of the biophysical underpinning of ecosystems in terms of service delivery; (3) the integration of natural and social sciences and other strands of knowledge for a comprehensive understanding of the service delivery process; and (4) the assessment of the services provided by ecosystems for its incorporation into decision-making (Martin-Ortega et al., 2015). In order to reconcile ecological and human wellbeing, DANUBIUS-RI's research on environmental protection and nature conservation will have social sciences integrated. In this respect, an important factor will be to develop indicators that integrate the specific well-being of ecosystems and the relationship between humans and nature that maintain these well-beings (Caillon et al., 2017). This may also be a way to embed the ecosystem services concept in the more comprehensive understanding of RS systems as SES.

Interdisciplinary

IDR has been defined by the US National Academy of Sciences as: "a mode of research by teams of individuals that integrates information, data, techniques, tools, perspectives, concepts, and/or theories from two or more disciplines or bodies of specialized knowledge to advance fundamental understanding or to solve problems whose solutions are beyond the scope of a single discipline or area of research practice" (National Academies, 2005). This definition gives two reasons for knowledge integration: (1) to advance fundamental understanding and (2) to solve problems. DANUBIUS-RI will satisfy both reasons, but will conform in such a way that four fundamental requirements defining knowledge production are also satisfied: (1) grasp the complexity of problems, (2) take into account the diversity of scientific and life-world perceptions of problems, (3) link abstract and case-specific knowledge, and (4) develop knowledge and practices that promote what is perceived to be a common good (Pohl and Hirsch Hadorn 2007). To make sure that interdisciplinarity is implemented DANUBIUS-RI will address the five principles that were described in nature to 'forge' interdisciplinarity (Brown et al., 2015):

1. Forge a shared mission. A shared mission provides a compelling account of the overall goal of the collaboration, including impact as a necessary outcome.
2. Develop 'T-shaped' researchers. Interdisciplinary collaborations have the greatest chance of success when researchers are 'T-shaped' — able to cultivate both their own discipline, and to look beyond it.
3. Nurture constructive dialogue creating the environment and informal rules that empower researchers across all sciences to engage effectively, despite their vastly different approaches to research design and methodology, and their differing technical vocabularies and communication cultures.
4. Give institutional support. Academic career pathways for IDR are essential if it is to attract and retain the brightest and best.

5. Bridge research, policy and practice. The establishment of enduring connections between researchers, policymakers and industry practitioners proves to be an important driver in growing interdisciplinary collaborations. Industry rarely thinks in disciplinary silos. They tend to tackle complex problems from a range of perspectives, thereby modelling integrated, solution-focused thinking.

In other words, DANUBIUS-RI strives for joint approaches of natural and social sciences on knowledge development and generating solutions for societal challenges related to the management and use of highly complex and dynamic RS systems. This can be described as ‘learning together, to increase impact together’ and leaving each other’s comfort zones (breaking the silos) as ‘doing what we did, gets us what we got’. An interdisciplinary approach is a prerequisite for achieving step changes in RS system science and innovation. Such research aims at achieving innovations to provide operational perspective, practical solutions, methods and tools for policy makers, managers and entrepreneurs.

Participatory

In recent decades, science has provided society with a valuable, basic understanding of the environment and human society as interconnected systems. Hence, DANUBIUS-RI considers RS systems as SES, as stated above. To address environmental change in the 21st century, DANUBIUS-RI aims to improve the understanding of the impacts, vulnerabilities and risks of environmental change, in order to enable society to develop adaptation and mitigation strategies as well as to benefit from opportunities in an environmentally sustainable manner. However, capturing the full complexity of these systems calls for combining scientific knowledge with local knowledge (Raymond et al., 2010), which calls for participatory methods for knowledge development and decision-making (Reed et al., 2009; Bäckstrand, 2003; Goodwin, 1998). To be most valuable, this knowledge will be provided on time, space and societal/institutional scales that enable effective decision-making and support equitable economic and social development.

In DANUBIUS-RI’s scientific understanding, IDR is conceived as a system where academic researchers and social actors closely interact for the benefit of shared aims, such as water sufficiency, balanced sediment conditions and environmental health in RS systems. A strong voice for users in defining the research priorities will be mandatory and DANUBIUS-RI will provide effective structures, forums and methods such as participatory monitoring/citizens science (Danielsen, 2009), but also participatory, or even collaborative modelling as described by Basco-Carrera et al (2017) to constitute and sustain the necessary recursive process between the essential academic disciplines, the civil society, public agencies and the private sector with respect to problem identification and structuring, problem analysis, and implementation of results.

DANUBIUS-RI stimulates the science-policy dialogue. Through its integrated IDR that addresses the global challenges of the 21st century in RS systems, DANUBIUS-RI supports the implementation of the UN Sustainable Development Agenda (United Nations, 2015), e.g. by connecting the SDGs to RS system management. Not least, DANUBIUS-RI provides scientific solutions for the implementation and deeper integration of the different EU water and environment directives, such as the WFD, MSFD, FD, Natura 2000/FFH Directive.

Step Change

Understanding the functioning and evolution of RS systems across their physical-chemical-biological-societal dimensions and across spatial and temporal scales, and leveraging this understanding to predict changes and inform behaviours and decisions (Belmont Forum, 2011), will require a step change in R&I through interdisciplinary collaboration across academic disciplines and social actors and across geographical areas. DANUBIUS-RI provides the scientific and practical ways and means to achieve this step change by:

- establishing a methodological and conceptual framework for R&I that is adequate to the enormous social-ecologic complexity of dynamically evolving RS systems;
- addressing in its scientific work all formative natural, societal and economic components and processes in RS systems;
- bringing together excellent scientists from all relevant academic disciplines;
- providing a unique infrastructure that (1) spans the whole range of knowledge generation and implementation: from analysis, observation and modelling to impact and implementation including adequate data management structures and processes and (2) enables both basic fundamental as well as applied R&I;
- providing with its components (Hub, Nodes, Supersites, TTO) science-economy interfaces for knowledge exchange, development and practical testing to promote innovation and sustainable growth;
- providing research opportunities both in excellent laboratories and in Supersites that represent the whole spectrum of real-world situations – from nearly pristine to heavily modified, from the inland until the coast;
- establishing the DANUBIUS Commons in all areas of activity, which will guarantee for the quality, consistency and applicability of the generated data and scientific solutions.
- offering the interactive communication tools that are necessary for an effective, pro-active stakeholder involvement;
- facilitating broad opportunities for training, education and public engagement such as citizen science as an essential part of DANUBIUS-RI.

Based on the step change in IDR, DANUBIUS-RI will develop the understanding of what environmental and social information is most crucial to know, and what data, methodologies, measurements, technologies, and models are necessary for this. Consequently, DANUBIUS-

RI’s scientific work addresses research fields and encompasses scientific results in different categories, at different levels of complexity and specialization:

- generic RS system problems of global dimension, such as managing water beyond Integrated Water Resources Management, the food-water nexus, mega-urbanization or the concepts of risk-vulnerability-resilience;
- methodological key competences, such as observation and analysis methods and sensors, consistency in data generation, integrated quantitative modelling of coupled SES, scenario modelling, socio-ecologic assessment;
- RS system management in sites of high scientific interest and opportunity, as represented by DANUBIUS-RI’s Supersites.

2. Research Priorities

Jana Friedrich & Peter Heininger (HZG), Chris Bradley (UoB)

This chapter presents the strategic research priorities for the starting phase of DANUBIUS-RI. The research priorities cover topics that are of importance, scientifically and socially, and which focus on the RS continuum. The research priorities illustrate how using DANUBIUS-RI will enable scientists and stakeholders to address the complex intertwined environmental and societal challenges in RS systems. Although solutions to individual research questions may not be available immediately, they illustrate the motivation and need for DANUBIUS-RI. In the following, we outline the current state of research in the DANUBIUS-RI core topics, highlight current knowledge gaps, summarise research needs, and formulate research questions addressing the causal chain of causes, effects and the human responses to environmental and societal challenges in RS systems.

DANUBIUS-RI understanding of River-Sea Systems

DANUBIUS-RI defines RS systems as encompassing whole river basins and coastal seas ('from the mountains to the sea', Figure 2). The extent of a RS system is delineated on land principally by the catchment. The marine boundary is more variable and determined by the extent (in the sea) of riverine influence of individual phenomena (parameters, processes) of interest. As such, RS systems encompass (1) freshwater, transitional, e.g. estuaries and deltas, and marine ecosystems (longitudinal connectivity); (2) semi-aquatic and semi-terrestrial ecosystems, e.g. floodplains and wetlands (lateral connectivity); and (3) benthic and pelagic ecosystems (vertical connectivity). RS systems are the dynamic products of interacting biological, chemical, physical, geological, climatic as well as economic and social processes. They have been further shaped by past human use and decision-making and are intertwined with recent human actions that alter their capacity to sustain societal development. This requires, *inter alia*, linking the understanding of natural and human processes, as well as linking freshwater, transitional water and coastal water processes to enhance process and system understanding, to provide the basis for sustainable adaptive management and to aid the development of informed environmental policies and regulations.

Overarching Challenges in RS Systems

Challenges and resulting research needs in European RS systems have been identified using the DPSIR conceptual framework (Eurostat, 1999, Gregory et al., 2013, Gari et al., 2015) applied to the DANUBIUS-RI Supersites. This conceptual framework permits a structured and interdisciplinary analysis of complex problems in SES (Binder et al., 2013), (Annex I, Figure 10). Details on the Supersite-specific DPSIR analysis can be found in "Working Document on Research Needs in River-Sea Systems" (D2.2)[3].

[3] danubius-pp.eu/www/wp-content/uploads/2018/06/2.2.-Working-Document-on-research-needs-in-river-sea-systems-actors-and-events-for-science-developments-relevant-for-the-innovation-process-of-DANUBIUS-RI-final-version.docx

Based on the DPSIR analysis, the challenges and research needs in RS systems are grouped into four overarching and closely interrelated topics, which will guide the development of DANUBIUS-RI through the PP towards implementation (
Figure **4**):

- Climate Change
- Water Sufficiency
- Sediments & their Management
- Ecosystem Health.

OVERARCHING QUESTIONS
ADDRESSING CHALLENGES IN RIVER-SEA SYSTEMS

- How can we discern the effects of natural variability, climate change and human drivers, driving altogether the evolution of RS systems?
- What determines the resilience of individual RS systems against natural and anthropogenic forcing? Why are some RS systems more resilient than others?
- Which pressures and related changes reduce the resilience of the RS SES?
- What are appropriate strategies to manage certain drivers of change in RS systems?
- How can existing and new, innovative components be integrated into a coherent infrastructure for observing and predicting RS system dynamics under global change?
- How can we harmonize ecosystem conservation, restoration, and intensive human use of RS systems and which new paradigms are needed in the management?
- How can we improve knowledge transfer regarding RS systems functioning to e.g., politicians, industry, and the wider public etc.?
- How can stakeholders be involved in RS systems management at the local, regional, national and transnational (full RS system) scale?
- How can we increase (public) awareness for sustainable use and protection of RS systems?

Climate Change, Climate Variability, Extreme Events, and human drivers resulting from basic human needs have a combined effect on the RS systems. The pressures resulting from these past and present human activities affect Water Sufficiency, Sediments and Ecosystem Health, and cause a wide range of ecosystem state changes, which have multiple and often compounding impacts on RS systems, and thus ecosystem services provision. Consequently, the four topics cover important challenges for society and the environment.

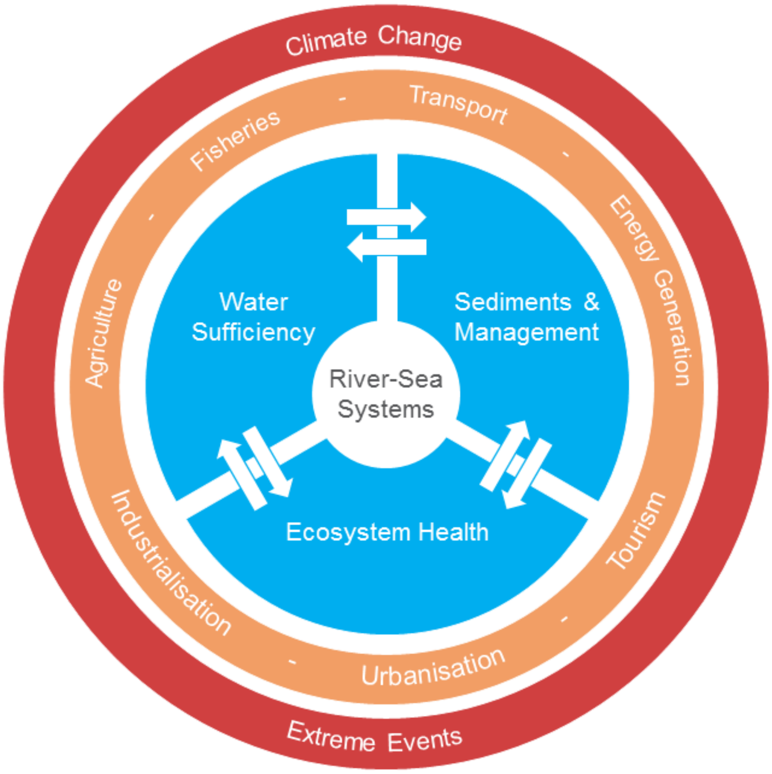

Figure 4 Climate drivers (Climate Change and Extreme Events) and human drivers (Fisheries, Tourism, Transport, Agriculture, Energy generation, Industry, Urbanisation, etc.) resulting from basic human needs are having combined effects on RS systems. DANUBIUS-RI identified overarching challenges related to Climate Change, Water Sufficiency, Sediments and their Management, and Ecosystem Health.

Climate change is contributing to an intensification of the hydrological cycle by increasing temperatures, melting polar ice, , increasing precipitation in certain regions, and an increasing frequency of extreme events (e.g. floods and droughts), with effects that are exacerbated in coastal areas by sea level rise, increase river discharge and land subsidence. Inevitably, there will be considerable social and economic impacts on agriculture, on urban and peri-urban areas, on communications and transport, as well as on industry and business. Hence, long-term mitigation and adaptation will be crucial to maintaining key ecosystem services currently provided by RS systems. This, in turn, requires greater holistic understanding of RS systems, particularly our ability to attribute ‘cause and effect’ in recognising how RS systems are responding to a variety of ‘drivers’ at different spatial and temporal scales.

DANUBIUS-RI conceives **Water Sufficiency** as the challenge of ensuring continued water availability for both human needs and nature, while guaranteeing good ecological status according to the WFD and MSFD. It includes water of sufficient quantity and quality of both surface waters and groundwater along the freshwater-marine continuum to maintain ecosystem functioning and to provide ecosystem services. The challenge of Water Sufficiency lies in addressing problems such as floods and draughts, eutrophication and hypoxia, pollution, salinization, changes in river (and tidal river) flow regimes, disrupted connectivity, and sea level rise in the context of climate change, increasing water and sand abstraction, river regulation, shipping, and changing catchment land-use. The task of users and political actors is to allocate sustainably the increasingly scarce resource water between the different groups of interest.

Good ecological status and the sustained provision of RS systems crucially depends upon maintaining **Sediment** balance and good sediment quality. RS systems are characterised by the routing of sediment from source to sink through erosion, deposition and remobilisation. Naturally, rivers persist in a state of permanent change, and hence dynamic equilibrium. However, current management practices in all parts of RS systems often conflict with the natural dynamic sediment conditions, e.g. by river regulation, fairway deepening, embankments, and the construction of dams and reservoirs. Furthermore, sediments in many European rivers and worldwide have a long pollution history and are further polluted from diffuse and point sources. This all threatens the sediment status and dynamics that are needed for RS system health and functioning. Holistic approaches are required both in research and in implementation to deliver integrated sediment management at RS system scale.

Healthy Ecosystems are resilient, stable in their community, structure and functioning and sustainably managed. They are able to maintain their organisation over time. Biodiversity in different spatial and temporal scales is the key to healthy ecosystems, and hence, to the provision of their services to humans (such as fish production or flood and storm protection). Ecosystem health is threatened e.g. by habitat fragmentation and loss, insufficient water and sediment quantity and quality, overfishing and invasive species. A key challenge is to determine what healthy ecosystems are under changed climate and how changing ecosystems will affect the future provision of ecosystem services.

Change is an intrinsic feature of SES and we must acknowledge and embrace it as challenge in research, sustainable management, use and protection of RS systems. Society needs to adapt to change, manage and mitigate unwanted effects. The subchapter **Living with Change** addresses the combined effects of climate change and intensive human activities in RS systems. It draws upon the effects of multiple pressures, the four-dimensional (space-time) context of RS systems: longitudinal (upstream-downstream); lateral (floodplain or coast); vertical (water-sediment, surface-groundwater); and time (short-term storm events and decadal changes). It highlights natural versus anthropogenic change: the difference in space- and timescales of response and consequences for management/mitigation measures, the urgency to act/respond to climate and human changes and the need to address the science-policy interface regarding knowledge transfer.

2.1 Climate Change

Stephen Flood, Jeremy Gault (UCC), Ole Rössler & Stephan Dietrich (BAFG)

The majority of nations recognizes human-driven climate change (Paris agreement, United Nations 2016). Currently, global temperatures are approximately 1°C above preindustrial levels and rising, and under business as usual are projected to further rise at a remarkable and worrying rate of an estimated 4°C above preindustrial levels by the end of the century (Marcott et al. 2013; IPCC, 2013). Until the mid-20th century, it was generally thought that significant large-scale global and regional climate change occurred at a gradual pace within a timescale of many centuries or millennia (Maslin et al., 2001). The Intergovernmental Panel on Climate Change (IPCC) 5th Assessment Report, however, states that the warming of the climate system is unequivocal, and since the 1950s many of the observed changes are unprecedented over decades to millennia (IPCC, 2013). The ocean and atmosphere have warmed, the amount of snow and ice has diminished, sea level has risen and concentrations of greenhouse gases have increased (Ibid). The science is clear that human influence on climate has been the dominant cause of observed warming since the mid-20th century, and global average surface temperature has warmed by 0.85^{o}C between 1880 and 2012 (Ibid). The latest IPCC special report, which assessed the knowledge base for a 1.5°C warmer world documents how the global temperature rise to date has already resulted in profound alterations to human and natural systems, bringing increases in extremes, some types of droughts, floods, sea level rise and biodiversity loss, and causing unprecedented risks to vulnerable persons and populations (IPCC, 2018). It is particularly this rate of change that places humans-environmental systems under pressure, as adaptation capacity – that in the past has always be a key feature of these systems – becomes critical due to time pressure.

2.1.1 Climate Change & Climate Variability

Climate change acts as a cross-cutting external driver for pressures, state changes and effects on the natural environment and human well-being not only in RS systems. The impact of climate change on rivers and flooding is considered in a range of literature applied to case study river systems. Climate change impacts directly linked with water availability are well documented (Schewe et al., 2013; Gosling and Arnell, 2016; Haddeland et al., 2014). Furthermore, climate change impacts on water availability for agricultural systems have received attention in the literature (Elliot et al., 2013; Iglesias and Garrote, 2015 Saadi et al., 2015). A trend analysis of extreme precipitation and flooding in Europe over a large number of studies in Europe was carried out by Madsen et al. (2014). Findings suggest that there is a general increase in extreme precipitation under a future climate and that, as of time of writing, only a few countries have developed guidelines that incorporate a consideration of climate change impacts on river systems. Donnelly et al. (2017) report that there are clear changes in local impacts on evapotranspiration, mean, low and high runoff and snow water equivalent between a 1.5, 2 and 3°C warmer world in European hydrological systems. In a warmer world, the hydrological impacts of climate change are more intense and spatially more extensive.

Research focused on deltas and estuaries profiles the risks they face in light of climate change (Tessler et al., 2015, Passeri et al. 2015). Both deltas and estuaries are highly sensitive to increasing risks arising from local human activities, land subsidence, regional water management, global sea-level rise, and climate extremes. Findings suggest that, although risks are distributed across all levels of economic development, wealthy countries can invest more in flood-protection infrastructure and coastal defense to control the risk. In an energy-constrained future. However, such protections will probably prove to be unsustainable, raising relative estimated risks by four to eight times e.g., in the Mississippi and Rhine deltas and by one-and-a-half to four times in the Chao Phraya and Yangtze deltas (Tessler et al., 2015). Another global study (that also covers some European river systems) exploring the interaction between sea levels rise, changes in sediment accretion, and biodiversity loss in deltas, suggests that majority of deltas are on course to drown (Giosan et al., 2014).

In summary, the effects of climate change on the water cycle in general and in RS systems in particular (Bates et al., 2008) are strong, e.g. due to sea level rise and land inundation, and increasing frequency and intensity of extreme events. Climate change in addition to land use changes is projected to cause higher and more frequent floods and longer and intensified droughts in southern regions of Europe, while decreasing flood frequencies are predicted for the North (Roudier et al., 2016). There will be considerable socio-economic impacts, for example on agriculture, communications, transport, utilities, infrastructures, industry and business (Field et al., 2014, Brown, 2016). Long-term mitigation of climate change and adaptation to climate change effects will be crucial to maintain RS systems as favourable settlement areas for human well-being. To this aim, an integrated view on water, ecosystem health and environmental flows is essential to devise sustainable agricultural and economic systems that will allow us to decelerate climate change, protect us from extremes whilst at the same time, adapting to the unavoidable (UN-Water, 2017a).

Thereby, a clear distinction between climate and human drivers is crucial for mitigation and adaption programmes to be effective, or to prevent unwanted effects, due to differences in control of the drivers and the efficacy of the measures adopted (KDM, 2007). The functioning of the RS systems is particularly defined by the interplay of these two big groups of drivers and their consequences: climate change and human needs that are defined by land use change, water consumption and human activities along water systems. Hence, the clear attribution of observed and projected changes to one of these drivers is of highest importance and yet a major challenge. The required clear distinction is further complicated by the fact that long-term climate change trends are superimposed by natural, low-frequency internal climate variability (e.g. decadal or multi-decadal climate oscillations like North Atlantic Oscillation), which makes a clear distinction difficult.

The detection and attribution of hydrological changes in a changing climate is based on objective statistical tests to assess whether observations contain evidence of the expected responses to external forcing that is distinct from variation generated within the climate system (IPCC, 2013). For several extreme events (heat waves, droughts, floods, rain) progress is observed (Otto et al., 2018) and it is noted that the pinning extreme weather on climate change is now routine and reliable science (Schiermeier, 2018). Rapid-attribution services are already being set up in Germany and elsewhere in Europe. However, the attribution of the climate change effect on longer timescales is still under discussion (Cheung et al., 2017). Climate change impact and attribution studies are currently based on model simulations only. Despite the great effort to elaborate and reduce the many uncertainty sources involved in these scenario simulations, uncertainties are often considerable. Therefore, it is of great importance to complement these modelling approaches by observations. Despite its high relevance to record the spatial temporal variability of the hydrological cycle and the parameters influenced by it, systematic studies on spatiotemporal variability and methodological implications are lacking. This represents a considerable challenge for the monitoring of river systems. The knowledge deficit includes data from national monitoring networks as well as from scientific projects and international initiatives under auspices of World Meteorological Organization (WMO) or the Global Climate Observing System (GCOS).

Although climate change impact assessment studies are numerous, research specifically looking at climate impacts on RS systems in a European context is much more limited and ranges across topics such as flood risk (Akter et al., 2018), impacts on fish populations (Pletterbauer et al., 2015), power generation (van Vliet et al., 2016), and aquatic ecosystems (Hering et al., 2015). Existing research often cites The European Water Framework Directive emphasises an integrated approach to water resource management at a basin scale. Existing research, which often cites this Directive, covers the use of decision-support tools in participatory river basin management (Welp, M., 2001), adaptive water management in a changing climate (Huntjens et al., 2011), and stakeholder-based policy design in the process of developing and adopting a river basin management plan (Pahl-Wostl, 2010).

DANUBIUS-RI can play a prominent role in strengthening and streamlining European research, contributing to monitoring and attribution of changes in the climate signal of the global, regional and local hydrology including changes in water quality or changes in sediment and nutrient fluxes. This knowledge will be necessary for future discussions of high-level panels, including the global stock-take conducted as part UNFCCC reporting.

CLIMATE CHANGE & VARIABILITY: Selected Research Questions

DRIVERS & PRESSURES

- How will sea level rise, warming, shifting seasons and changing precipitation patterns affect key environmental attributes (discharge regime, tidal patterns, suspended matter and sediment dynamics, benthic-pelagic coupling, biological productivity and biodiversity) and key socio-economic attributes (as land use patterns in relation to human production (agriculture, energy, industry) and waterborne transportation) of RS systems?
- How does climate change affect the frequency and magnitude of meteorological extreme events?
- How is climate variability (e.g., low and high discharges) influencing water-quality issues (e.g. eutrophication, hypoxia, and contaminants)?
- In which way, and to what extent are climate change induced pressures interacting with human pressures, such as pollution or nutrient loading?

STATE CHANGES & IMPACTS

- How are climate related changes in parts of the RS systems or in coastal seas affecting the other parts of the system?
- What are the combined effects of climate change, climate variability and human drivers in RS systems?

HUMAN RESPONSES

- How to deal with the inherent uncertainty associated to climate change regarding mitigating the impacts in RS systems?
- How can technical measures, changes in regulation, in human perception and in behaviour be effectively integrated in adaptive management strategies addressing climate change challenges in RS systems?
- How can conflicts between stakeholders for water (e.g., agriculture, drinking water supply, shipping, hydropower generation) be managed?

2.1.2 Extreme Events

Georg Umgiesser (ISMAR), Ole Rössler, Jörg Uwe Belz & Silke Rademacher (BAFG), Eva Feldbacher & Thomas Hein (WCL)

In the DANUBIUS-RI context, extreme events describe climate or weather events of high magnitude (a climate/weather variable above or below a critical threshold) leading to negative impacts on social, ecological, or physical systems (Seneviratne et al., 2012). Relevant to RS systems are hydrological extreme events such as intense rainfalls inducing landslides and/or high floods or long periods of droughts leading to extreme high or extreme low discharge in aquatic systems, respectively. Extreme events related to high precipitation lead to a very high hydrological connectivity between the catchment and riverine network and can be characterised by high surface flows leading to short, very intense erosion periods (massive rock and soil movements) and high sediment inputs into surface waters. This intensified transport can cause massive geomorphic dynamics in the riverine network. In mountainous regions massive precipitation events can trigger landslides and material input into aquatic systems, leading to massive changes in geomorphology of these reaches. Of high scientific relevance is in that context how the geomorphic conditions are changed, the long-term effect of these changes, the effects on adjacent landscape elements as well as downstream effects. Furthermore, these events can cause also changes in elemental cycles by providing new sources of matter to aquatic ecosystems (e.g. black carbon stocks) and can lead to changes in the turnover of these elemental cycles not only during these events, but also after these events (Yeh et al., 2018; Schomaker et al., 2018).

In contrast to high flow events, droughts may change local temperature regimes, disrupt longitudinal connectivity in riverine networks, and may even lead to drying of riverbeds and aquatic ecosystems. Changing land use change and increasing anthropogenic water consumption (Döll et al., 2009, Wisser et al., 2010) lead among other impacts to an intensification of droughts (Wada et al., 2013). Droughts can severely reduce the capabilities of shipping, power and industrial production, irrigation water amounts, and reduced groundwater renewal rate (Van Loon 2015). Consequences for aquatic ecosystems are far-reaching such as changes in biodiversity, ecosystem functions and ecosystem services due to the alteration in hydrology (Bunn et al., 2002, Jentsch et al., 2008). Lower groundwater levels may impair drinking-water supply; in coastal areas, they will enhance the risk of saltwater intrusion into the subterranean water bodies. Integrated water resource management in a RS continuum is thus challenged to answer how to protect human well-being and ecosystem functioning from this multitude of threads emerging during hydrological extremes.

In general, the prediction of the occurrence of extreme events driven by the weather conditions, and their effects on riverine networks and associated landscape elements inherits high uncertainties of its effects and magnitude, and hardly predictable system changes in the long term (ICPDR 2013, IPCC 2014, Mastrandrea et al., 2010, Garcia-Ruiz et al., 2000, Beniston et al., 2007). Understanding these dramatic changes and their long-term consequences is a major present and future challenge for RS systems.

Extreme events in one part of the RS system will inevitably influence the other parts. Strong river floods will have an impact on the coastal zone, and coastal flooding due to storm surge events will propagate some way up the river. Strong sea level oscillations, caused by storm surges or tsunamis, may propagate into the river, and due to morphological characteristics may be amplified, creating flooding events in the upper part of the river. During low river flows, because of prolonged draught events, salinity intrusion may occur in the river and into groundwater, creating a situation where river water will be unavailable for service or drinking water use. Polluting substances inserted in the upper river can travel a long distance down to the sea and pollute the coastal zone.

Hydrological extreme such as floods, storm surges and droughts are naturally occurring phenomena with irregular occurrence. Human behaviour, e.g. population settlement off floodplains ever closer to coasts, and hydromorphological interventions, may turn extreme events into disasters with high losses for humans and nature. Increasing socio-economic wealth and settlements along rivers and coasts exacerbate the damage exposure to floods (Barredo et al., 2009). Flood protection measures like channelization in turn may amplify flood magnitudes: Munoz et al., (2018) found evidence for a human-driven amplification in the Mississippi River; Belz et al. (2001) proved flood increase as a result of streambed shortening and time of flow (River Rhine, Germany); Promny et al. (2015) showed effects of man-made influence by (diking resp. re-diking) repeated embankments works (River Elbe/Germany) and Schuh and Hatz (2018) discuss suitable flood-protection measures against the background of anthropogenic river-training effects. Contrariwise Pinter et al. (2006) and Petrow and Merz (2009) attributed trends in flood occurrences of German rivers to climate only. Estimations of the multi-hazard related economic loss predict an increase of ten times the baseline loss from 1981-2010 by the end of the 21th century (Forzieri et al., 2018).

Primary effects of flooding like inundation are accompanied by secondary effects like sediment remobilization or water quality deterioration, e.g. in the Meuse River (van Vliet, 2008). Societal impacts of floods stretch from direct effects (e.g. damage to buildings, crops and infrastructure, loss of life and property) to indirect (e.g. losses in productivity and livelihoods, increased investment risk, indebtedness and human health impacts). Furthermore, water quality can be severely affected if floods release pollutants from infrastructures like wastewater treatment plants or mining subsidence reservoirs (Euripidou & Murray, 2004). Likewise, coastal lines are often polluted during storm surges, e.g. due to destroyed harbour infrastructures and shipwrecks, and related oil spills. Research on secondary effects of hydrological extremes provides new insights to the enduring impact of extremes on society and ecosystems. Yet comprehensive, unifying, IDR is missing that combines time-series observations and projections of hydrological extremes from different regions of Europe, quantifies their change, attributes the change to underlying drivers, and estimates their primary and secondary impacts on RS systems, ecosystems and societies.

Extreme hydrological events can cause massive system changes, leading to a complete system shift or system responses with a pronounced long phase influenced by the event and long-term effects (Seneviratne et al., 2012). A first challenge is the correct capture of the RS system state (flood level, velocities, sediment mobilization) and its change during an extreme event, as well as the quantification of pressures and impacts. Examples for geomorphic effects of intense flood events are, at smaller scales: changes in channel width and the structure and level of the riverbed; and at larger scales: changes in adjacent floodplains (erosion and reactivation of floodplain alluvia) and coastal areas including deltas (coastal retreat). Differentiating the resilience capacity against extreme events is a key challenge for RS system research.

Human response can be through both hard and soft interventions. Against increasing storm surge frequencies storm surge barriers can be helpful (e.g. London, Venice). These interventions can also effectively stop the flood wave at the lower river course. Similar barriers can also be used against saline intrusion, where only the bottom water is blocked from entering the rivers. Soft interventions would create larger floodplains able to accommodate higher amounts of water. This would guarantee less drastic change in ecosystem services than with hard interventions.

EXTREME EVENTS: Selected Research Questions

DRIVERS & PRESSURES

- What are the mechanisms triggering extreme events (e.g. floods, droughts, storm surges, tsunamis), which may develop into disasters at different scales?
- Which human activities in RS systems turn extreme events into disasters for humans and nature (increase of risk)?
- How are flood protection measures (e.g. dyke construction, reduction of floodplains) affecting flood regime (inland waters) and development of flooding (incl. coastal)?
- Can we quantify the influence of drivers (e.g. climate and human activity), and attribute these to observed changes in extreme event occurrence frequencies?

STATE CHANGES & IMPACTS

- How to define extreme events; how to distinguish them from natural variability?
- What is the impact of extreme events on the evolution of RS systems and the associated SES?
- How are extreme events changing the hydromorphological conditions of RS systems (reversibly/irreversibly)?
- For how long are “footprints” of extreme events visible (memory / legacy effects)? Which components return to pre-extreme event conditions? How long does it take? How are they influencing ecosystem functioning?
- How resilient are RS socio-ecological systems to extremes events? How can the resilience of the SES be increased?

HUMAN RESPONSES

- How effective are “nature-based solutions” in mitigating the impacts of extreme river flow events or storm surges for humans and nature?
- What are adequate management strategies against extreme droughts (e.g. considering the ambiguous effects of water storage in the headwaters)?
- How can salinity intrusion be mitigated through water management and artificial barriers?
- How to account for the uncertainty in magnitude of extreme events when designing mitigation measures?

2.2 Water Sufficiency

Chris Bradley (UoB), Jana Friedrich (HZG)

Water is a fundamental resource, which is globally impacted by changing patterns of land use (agriculture, urbanisation), utilisation (irrigation, abstraction for domestic, and industrial purposes), and climate (Grizzetti et al. 2017; Vörösmarty et al. 2018). These processes have substantially changed the ways in which water moves through catchments, from rivers to seas, presenting numerous problems including poor water quality (reflecting inadequate waste-water treatment, nutrient loading, emerging pollutants) changes in water availability (foods, droughts) and reduced ecosystem functioning (e.g., due to river fragmentation, channelization and wetland drainage). While the 'natural' chemical composition of surface water and groundwater is largely determined by catchment geology, in most cases, it has been substantially affected by anthropogenic activities. The challenge, with respect to water sufficiency, is to ensure continued water availability within the RS continuum to sustain key ecosystem services, reconcile different (and potentially competing) uses of water in the context of fast changing aquatic and terrestrial environments that are increasingly modified by anthropogenic processes. In many cases, it is difficult to attribute 'cause and effect', but recent work suggests that globally, river regulation, has a greater effect on riverflow on snow-fed rivers than changing climate (Arheimer, et al. 2018). This emphasises the ubiquity of human impact and the need to identify new inter-disciplinary approaches to understand the ways in which water moves through the RS continuum and resolve problems arising from changes in water quantity and quality.

In the following sections, key challenges and research gaps are identified related to problems in water quality (eutrophication and hypoxia, pollution by organic and inorganic contaminants) and quantity (changes in river and coastal flow regime) and inter-related problems with changes in sediment flux, and river and coastal morphology. These problems are due to complex interactions between water (its dissolved, colloidal and suspended matter), morphological structures (riverbed, banks/coasts, floodplains/marshes), sediment and biota. Together these threaten the continued provision of key ecosystem services, which require 'cross-cutting' tools, in observation, analysis, and modelling that are to be provided by DANUBIUS-RI (Bradley et al. 2018). These are needed to avoid increasing declines in ecosystem structure and functioning, which jeopardise key ecosystem services, such as nutrient and pollution retention and transformation capacity.

2.2.1 Changes in Hydromorphology

Chris Bradley (UoB), Christine Borgsmüller (BAFG), Istvan Forizs (SZE)

Hydrological and morphological dynamics of RS systems encompass the movement of water, dissolved and suspended matter, and sediment through catchment, river, estuary and coastal sea, as well as geomorphological processes in rivers, floodplains, transitional waters and seas at a multitude of different scales. Hydromorphological dynamics are the primary driver shaping the fluvial landscape, the diversity of aquatic ecosystems and coastline morphology. Hydrological extremes (droughts, fluvial and coastal floods, tidal storms) discussed in the previous section may lead to rapid changes in river and coastal morphology. Changing sedimentary balances (discussed below) also have a major influence on hydromorphological conditions in RS systems. Together hydro-morphological processes encompass the main abiotic characteristics of these environments, which are also shaped by biotic processes, and changes in water quality. The latter are covered in the following sections, and hence the focus here is on the underpinning interdisciplinary context for hydromorphological research on RS systems and the need for more integrated, and holistic, approaches to research and management.

The physical characteristics of freshwater, transitional and coastal marine environments have been universally impacted by anthropogenic activities including: river regulation and impoundment, channelization, fairway deepening, catchment management, floodplain and wetland drainage, flood protection and changes in the catchment water budget (Overeem, Kettner & Syvitski, 2013; Nilsson et al. 2005). The increasing disconnection of rivers from their floodplains and their catchment as a result of human activities has had multiple consequences: in some reaches leading to riverbed incision (Habersack et al. 2013) and in others to clogging of the streambed with sediment (Tiziano et al. 2007). The changes in hydromorphology, and in the structure and functioning of freshwater, transitional and coastal environments, extend through the RS continuum with wide-reaching societal and environmental consequences that propagate through the catchment to estuarine, costal and marine environments (Milliman & Farnsworth, 2011). They threaten key ecosystem services in areas with high (and increasing) population density, particularly in coastal areas with projected increases in flooding (Vitousek, et al. 2017). Hence the identification of how catchments can be managed in ways that reconcile competing demands (e.g. of navigation, hydropower, flood protection and environmental conservation) is a growing challenge of our time. A crucial challenge lies in identifying how the diverse hydrological characteristics of rivers and the physical structures that they create (i.e. their hydromorphology) can be improved and maintained. This is complicated by the difficulties in disentangling the compounding effects of climate change and land use on hydromorphology in the context of incomplete system understanding and changing ‘baselines’, such as the increasing frequency of extreme events. This emphasizes the importance of holistic perspectives to river basin management, with prioritized interventions to improve hydromorphological conditions.

It is estimated that 40% of Europe's water bodies are currently affected to varying degrees by hydromorphological pressures with significant consequences for the morphology and hydrology of rivers, and ecosystem health (EEA, 2018). In some cases, it may be possible to identify physical interventions to address these pressures (e.g. by restoring lateral and longitudinal continuity, enhancing natural water storage, and prescribing ecological flow requirements). However, some of the relationships between hydromorphological conditions and ecosystem functioning have yet to be fully quantified, given incomplete understanding of the interaction between physical, chemical and ecological process in RS systems and their social and economic significance. This has significant implications for European rivers and seas, such as the Danube (Habersack et al. 2016) and the Rhine (Uehlinger et al. 2009) particularly given the extent to which the effects of human interventions in different forms (changes in land use, impounded rivers, daming, water abstraction) magnify problems of water scarcity as they propagate downstream (Veldkamp et al., 2017). This requires detailed knowledge of the history of fluvial and coastal shaping processes that together account for the (current) hydromorphological state of a particular river, estuary or coast, an understanding of the timescales over which key processes predominate, and an appreciation of how the impacts of these interventions may vary between individual catchments and RS systems.

Increasingly the ways in which water moves through catchments and rivers to seas has been modified: as abstraction for agriculture, industry and domestic purposes have reduced river flows (Vorosmarty et al. 2010), and rivers have been regulated for navigation, flood control and hydropower. Flow manipulations affect channel morphology and the hydrology of floodplain wetlands, contribute to reductions in floodplain productivity and in the dynamics of deltaic systems, and may lead to the extensive modification of aquatic communities (Nilsson et al., 2005). Dam construction fragments aquatic habitats, impeding species movement and sediment and nutrient transport, as observed in the Nestos River – Kavala Bay system of Greece (Sylaios and Kamidis, 2018) and the Danube River – North Western Black Sea (Humborg et al., 1997; Friedl et al., 2004). The distribution and accumulation of contaminants in RS systems has also been extensively modified by dams, with the potential for significant contaminant retention in impounded river reaches and reservoirs (Lehner et al., 2011). These and other effects have been directly linked to the reduced abundance and diversity of freshwater fish populations (Nilsson et al., 2005). Hydromorphological modifications may lead to excess sedimentation (e.g. in artificial lakes or shallow water zones) or erosion (e.g. sediment starving rivers downstream of a dam and coastal beach erosion). This also causes degradation of aquatic habitat quality including: 1) changes in coarse material load/deposition needed for fish (e.g. salmon) spawning, applications to organism burrowing (fine vs coarse fractions); 2) changes in fine material load – i.e. decrease/increase of turbidity and related light availability and light quality, temperature, trapping/releasing of contaminants (cf. 2.4 Ecosystem Health).

Maintenance and improvement of hydro-morphological conditions is essential to the sustainable management of RS systems, and to ensuring that they continue to be of greatest benefit for nature, economy, and society. This is also fundamental to implementation of EU directives including the WFD, which requires the assessment of river hydro-morphology, the HD (by monitoring conditions at Special Areas of Conservation), and the MSFD. Of key significance is the characterization of hydromorphological modifications of river channels, banks, riparian zones and floodplains and an assessment of their departure from 'naturalness', which may be facilitated by recent advances in classification schemes (Belletti et al. 2017) and earth observation (Bizzi et al. 2016). Having determined the extent to which hydromorphological conditions have been altered, key challenges include determining (for individual catchments), the ideal hydrological regime required to maintain, or improve, hydromorphological conditions. Assuming that fundamental questions, such as identifying what an ideal 'model' river might look like (in the Anthropocene) that satisfies both human needs and those of the 'natural' ecosystem (Apitz, 2012), the steps to achieve this goal have still to be identified. Ideally, these should comprise a series of 'win-win' interventions which address the immediate need to improve hydromorphological conditions whilst also enhancing sustainability, for example nature-based solutions to reduce flood magnitude and extent, or the use of river bank filtration systems to improve water quality (WWAP, 2018), given that rivers play a significant role in the drinking water supply through their bank filtration systems (Ray et al. 2011). However, the full economic benefits of any improvement measure may be difficult to quantify, particularly given the need to balance these against the possible economic impact of changes in hydromorphological conditions, such as those arising as a result of navigation, or regulation for hydropower.

Maintaining, and enhancing, longitudinal connectivity from source to sea is essential to maintaining the functioning of RS systems and their associated services. However, there are many examples of how engineering work, whether for flood control, hydropower, or river and estuarine navigation, has affected connectivity within the system. The deepening of navigation channels, regular maintenance through dredging, and the relocation of dredged material will affect water turbidity and amplify the tidal ranges in estuaries downstream (Winterwerp et al., 2013a, Winterwerp and Wang, 2013b). In these areas, the loss of intertidal areas has reduced resilience to further engineering works with the loss of potential sedimentation basins for suspended sediment (Winterwerp and Wang, 2013b). Moreover, continued deepening of navigation channels results in sediment displacement, which has a profound influence on nutrient uptake capacity, diminishing the resilience of the system to further impacts. In many cases, embankments prevent natural gradients from land to sea, which has also impacts on saltmarshes, for example in the Wadden Sea (de Brouwer et al., 2001).

Integrated (and inter-disciplinary) approaches to manage hydromorphological conditions in rivers are required to assess the longitudinal and lateral connectivity, given the inter-relationships between biotic and abiotic processes at different scales (Heininger et al., 2015).

For example, the disconnection between rivers and floodplains, and the loss of sedimentary basins, has environmental implications and may contribute to increased fluxes of suspended particulate matter downstream. Management interventions to maintain navigable channels along the continuum from river to estuary and the coastal sea, may increase water turbidity, with shifts in turbid zones, and the loss of channel bedforms (with a decrease in bed roughness). This may amplify the tidal range and increase tidal velocities, with implications for sedimentation dynamics. This raises fundamental questions, including how it might be possible to restore longitudinal connectivity, from catchment to the sea, along the continuum from headwater reaches through to coastal waters. Further questions include determining how morphological processes in the upper catchment influence the hydromorphology of lower river reaches and further downstream: at the river mouth and estuary. The latter poses additional problems, given uncertainties over ‘natural’ or reference conditions in transitional and coastal water, highlighting the need to extend hydromorphological references conditions from the catchment given the additional complication in these environments downstream (e.g. in hyper-turbid estuaries; effects of dredging).

CHANGES IN HYDROMORPHOLOGY: Selected Research Questions

DRIVERS & PRESSURES

- How will climate change influence seasonal water flows, what are the implications for wetland ecosystem functioning (floodplains, deltas, estuaries, lagoons)?
- What are the impacts of land use change (e.g. urbanisation, drainage of wetlands and deforestation) and flow regulation on flow regime and morphology?
- How does hydro-engineering influence RS system hydrodynamics (e.g. flow regime, suspended sediment distribution and transport in estuaries) and hence, river and coastal ecosystem structure and functioning, aquatic biodiversity and habitat availability?

STATE CHANGES & IMPACTS

- How to quantify the effects of hydrological engineering on hydromorphology (incl. tidal patterns), turbidity zones and suspended particulate matter segregation, turnover of dissolved and particulate matter, nutrient and oxygen dynamics, release of contaminants from sediments?
- Which processes trigger the transition to hyper-turbid estuaries? What is the contribution of human interventions, e.g., fairway deepening, narrowing and dredging?
- How to determine the locations of estuarine turbidity maxima (ETM) and their variability? How does fast dynamics of suspended matter in the water interact with slower dynamics of the bottom pool? What processes govern the mobile bottom pool (liquid mud) dynamics?
- What are the transport mechanisms that transfers marine suspended matter from the shelf sea into the estuary?
- What is the role of groundwater in maintaining river base flow?

HUMAN RESPONSE

- How can hydro-engineering measures be integrated into sustainable concepts (e.g., nature-based solutions) for improving hydromorphological conditions (e.g., optimize water and matter fluxes to stabilize river morphology)?
- Is the “building with nature” concept an option to harmonize ecosystem health and the provision of ecosystem services?
- How effective are natural retention measures (nature-based solutions) in the catchment in increasing water resource availability?
- How do local restoration measures influence the status of the wider RS system?
- In what way will change in human drivers (energy, transport, industry, land use) affect the catchment hydrology (surface and groundwater) and morphology (sediment use)?

2.2.2 Eutrophication & Hypoxia

Jana Friedrich & Justus van Beusekom (HZG), Mike Bowes (CEH), Thomas Hein (WCL), Marie Maßmig & Helmut Fischer (BAFG), Georgios Sylaios (DUTH), Phillipe Useglio (UL)

Sources of Eutrophication

Eutrophication; the change of the nutritional status of a water body by surplus nutrient input (Richardson and Jørgensen, 2013), resulting in excessive algal and plant growth and increased loading with organic matter (Nixon, 1995) is a major threat in many RS systems globally. RS systems receive diffuse surplus nutrients (N, P) mainly due to an excessive use of fertilizers in arable farming and extensive livestock farming in catchments (Carstensen et al., 2012), and from point source inputs from insufficient urban wastewater treatment and industry. Groundwater with elevated nitrogen concentrations due to fertilizers represents a health risk for humans and are a source for eutrophication. Insufficient treatment of industrial and urban wastewater from a growing human population represents an increasing problem for rivers in many regions, for example the significant water management issues in the Danube River Basin (ICPDR, 2015). Nitrogen inputs continue to increase globally (Battye et al., 2017) and are difficult to manage given their mainly diffuse origin (Howarth and Marino, 2006, Beusen et al., 2016). Phosphorus concentrations in many European rivers have decreased significantly in recent decades (Le Moal et al., 2019), primarily due to the implementation of the EU's Urban Wastewater Treatment Directive (EEC, 1991) resulting in improved wastewater treatment (Foy, 2007), and a ban on the use of phosphates in detergents in many industrialized countries. Considering that the global mineral P reserves may be depleted during the next century (Cordell et al., 2009), an increase in N/P ratios may be expected in coastal seas. Decreasing riverine nutrient loads in some rivers since the 1990s have led to lower nutrient concentrations and eutrophication status in well-flushed systems like the North Sea. In enclosed seas like the Baltic Sea, however, the decrease in nutrient loads is not yet fully reflected in the system (Gustafsson et al., 2012, Jutterström et al., 2014).

Responses in RS Systems

Eutrophication leads to direct and indirect responses in aquatic systems. The direct responses include increase in phytoplankton biomass (algal blooms), growth of opportunistic macro-algae and microphytobenthos, changes in C:N:P:Si nutrient ratios with subsequent shifts in phytoplankton community composition, and increase in the frequency of toxic and harmful algal (e.g. cyanobacteria) blooms (Cloern, 2001). This causes enhanced vertical flux of algal-derived organic matter to the deeper water and to the sediments as well as enhanced lateral transport in rivers from upstream to downstream, and to the sea. Decomposition of the algal biomass and zooplankton excretions results in surplus oxygen demand and often in subsequent hypoxia in a number of receiving rivers, estuaries and seas (Diaz and Rosenberg, 2008). This ultimately leads to macrobenthos and fish kills (Steckbauer et al., 2011, Hilton et al., 2006), with dramatic consequences for the functioning of coastal pelagic and benthic ecosystems (Zhang et al., 2010). These direct responses may trigger complex secondary responses, such as changes in the water transparency, distribution and abundance of vascular plants, growth and reproduction of pelagic and benthic invertebrates, physical habitats for invertebrates and fishes, and changes in redox state and the biogeochemistry of sediments (Cloern, 2001). Changes in nutrient input may thus result in major ecosystem shifts in both rivers and coastal seas, which underlines the complexity of the responses at the ecosystem level.

Sensitivity of RS Systems to Eutrophication

The natural sensitivity of rivers and coastal seas to eutrophication, i.e. the magnitude and character of response to nutrient enrichment, varies depending on the natural conditions; e.g. climate setting, catchment geology, river flow, bathymetry, basin geometry, water residence time, wind forcing, tidal forcing, optical properties, benthic-pelagic coupling and benthic and pelagic community structure (Cloern, 2001). Taking examples from DANUBIUS-RI Supersites, e.g. in the Rivers Thames (Moorhouse et al., 2018, Bowes et al., 2016) and Elbe (Hardenbicker et al., 2014), the combination of excessive nutrient concentrations and suitable flow, light and temperature conditions, and the lack of grazer control, lead to major algal blooms in the rivers and oxygen deficiency in their estuaries (e.g. Geerts et al., 2017). In contrast, intense grazer control by introduced species results in lower chlorophyll concentrations, e.g. in the Rhine (Hardenbicker et al., 2015). Nutrient and organic matter input from rivers has caused eutrophication on European coasts in the past decades (Airoldi and Beck, 2007), e.g. in the North Sea and in the Wadden Sea (Emeis et al., 2015) and the NW Black Sea (Gomoiu, 1992). In the tidal and wind-forced environment of the North Sea, the effects of eutrophicaton have been less dramatic than e.g. in systems with less exchange like the Black Sea, Baltic Sea, and Northern Adriatic Sea, which are characterised by very weak tidal forcing and strong stratification. In the latter seas nutrient input from the rivers Danube, Vistula and Odra, and Po, respectively, had caused severe eutrophication and hypoxia events from the 1970s to 2000s, leading to collapse of the pelagic and benthic ecosystems (Mee, 1992; Carstensen et al., 2014; Degobbis et al., 2000).

Multiple Pressures

For sustainable management of RS systems and effective mitigation measures, eutrophication and hypoxia must be analysed as responses to multiple pressures, originating from both climate change and human activities. Human activities compound the sensitivity of RS systems to eutrophication and hypoxia. In many regions, climate change will lead to higher water temperatures, which will intensify stratification, change the timing and increase the magnitude of algal blooms, and may shift the phytoplankton community towards e.g. cyanobacterial dominance. The mass occurrence of cyanobacteria causes serious problems for human and animal health, aquaculture and significantly increase running costs for the water companies. Climate change and variability may reduce river flows in the spring-summer period, which will increase residence times, water temperatures and point source nutrient concentrations, increasing the magnitude and frequency of algal blooms (Johnson et al., 2009). In some regions, climate change may increase the flow of freshwater and nutrients to coastal waters, and thus lead to stronger stratification, intensified coastal eutrophication and more hypoxia (Rabalais et al., 2009, Breitburg et al., 2018). Climate change may increase the susceptibility to introduced species (e.g. Hellmann et al., 2008), further reduce ecosystem resilience (Zhang et al., 2010), and act in combination with human pressures, e.g. overfishing in the Black Sea, as a trigger towards tipping points of ecosystem states (e.g. Oguz and Gilbert, 2007). The development of eutrophication is also linked to a combination of the impact of alien species, climate variability, and human activities. The Black Sea may serve again as an example with the explosive population growth of the alien ctenophore *Mnemiopsis leidyi* due to nutrient enrichment, change in planktonic foodweb and overfishing of predatory fish stocks resulting in a collapse of pelagic fish stocks (Kideys, 2002).

Human manipulation of the hydromorphological conditions in rivers and coastal seas strongly interacts with eutrophication. The recent assessment of European waters attributes 40% of pressures on surface water bodies to man-made hydromorphological changes (EEA, 2018). Taking DANUBIUS-RI Supersites as examples, large scale hydro-engineering projects such as the damming of the Rhine-Meuse Delta, port construction in the Venice Lagoon, deepening of the navigation channel of the Elbe Estuary, and chains of hydropower dams along the Danube have respectively caused deterioration of water quality (Renaud et al., 2013), increase in algal biomass (Sfriso et al., 1993), and intensification of oxygen-deficient areas in the estuaries (Kerner, 2007). In addition, wetland drainage reduces the natural ability of catchments to remove excess nutrients, exacerbating eutrophication issues (Hein et al., 2016, Hansen et al., 2018). Almost 80% of the freshwater discharged by large rivers to coastal zones in the northern hemisphere is strongly to moderately affected by fragmentation of rivers by dams, reservoir operation, decoupling and converting of floodplains, bifurcations and irrigation (Dynesius and Nilsson, 1994). Construction of dams and weirs can affect the magnitude and timing of algae blooms, by increasing residence times, and may cause seasonal anoxic hypolimnetic conditions due to stratification, an example being the Thissavros and Platanovrisi Reservoirs along the Nestos River Supersite (Sylaios and Kamidis, 2018). Reservoirs affect the nutrient ratios of the water due to sediment retention and blooms of specific phytoplankton classes. While e.g. the upstream Danube River reservoirs contribute to silica retention leading to silica deficiency favouring non-diatom blooms in the western Black Sea (Friedl et al., 2004, Humborg et al., 1997), the assimilation of nitrogen and phosphorus at the Nestos River reservoirs changes the stoichiometry of river water in favour of silica, supporting diatom blooms in the coastal zone (Sylaios and Kamidis, 2018).

Pollution by toxic organic and inorganic contaminants represents another pressure that strongly interacts with eutrophication. Heavy metals like Ag, Cu and As and herbicides are known to selectively inhibit some algal classes and therefore promote the growth of less sensitive species (cf. references in Cloern, 2001). Eutrophication may further enhance accumulation and transfer of toxic elements and PCBs to higher trophic levels (Gunnarsson and Sköld, 1999), and may change speciation and enhance toxicity of contaminants. Some authors even hypothesize whether harmful algal blooms may be supported by combined selective forces from nutrient enrichment and toxic contaminants (Cloern, 2001).

Human Response to Eutrophication

What are the social and economic costs of human impact on rivers and coastal zone, since estuaries provide more valuable ecosystem services per unit surface area than most of the ecosystems on the planet (Cloern, 2001; Costanza et al., 1997)? Understanding nutrient sources, fates, and their impact on aquatic ecosystems across the freshwater-marine transition is crucial for the effective management of RS systems. Eutrophication is one of the most important and long-lasting water quality problems in the EU. For at least two decades, several policies have been adopted to address eutrophication (e.g., WFD, MSFD, UWWD) to tackle nutrient pollution and its consequences. Thus the “Guidance document on eutrophication assessment in the context of European water policies” (EC, 2009) was developed. This document addresses a unified conceptual framework to understand eutrophication in all water categories, a conceptual read across EU directives (mainly WFD, UWWD and ND) and international policies (e.g. OSPAR and HELCOM) addressing eutrophication and an in-depth understanding of eutrophication in the context of WFD ecological status assessment. The guidance also includes an overview of current assessment methods and recommendations for harmonisation of classification criteria (EC, 2009). Although since the first generation of WFD River Basin Management Plans – published in 2006 – a lot of attention was devoted towards measures to reduce eutrophication, by 2015 eutrophication remained a key problem in Europe (EEA, 2015).

Decreasing riverine nutrient concentrations in several European rivers today, with a concomitant environmental improvement, shows that a trend reversal is possible (e.g. Carstensen et al., 2006, van Beusekom, 2017), but further reductions are necessary to deliver WFD good status. DANUBIUS-RI can inform catchment managers how to deliver these improvements most efficiently and cost-effectively and how to monitor the effects. Floodplains, wetlands and deltas, e.g. the Danube Delta (Friedrich et al., 2003) play an important role as natural filters for nutrients. Constructed wetlands have proved useful for on-site treatment and retention of nutrient and pollution for several decades (Haberl et al., 1995).

Eutrophication, hypoxia and their impacts require extensive observations and process anlysis at various study sites along the RS system as especially the freshwater – marine continuum has not yet been investigated in a holistic manner (Cloern et al., 2016) (Friedrich et al., 2014) to validate the local and large scale impacts of nutrient surplus on ecosystem functionning. The combination of field sampling campaigns, satellite observations and models will help to analyze the present status and to identify the responsible processes. This understanding may then be used to develop scenarios of how estuarine and coastal environments may respond to future environmental change and societal management options.

EUTROPHICATION & HYPOXIA: Selected Research Questions

DRIVERS & PRESSURES

- How are climate variability, warming and extreme events influencing nutrient and oxygen dynamics, sediment and suspended particulate matter dynamics?
- How are global change processes, such as increasing human population, urbanization and migration, affecting nutrient loading of surface and groundwater, and the ecosystem state downstream, in estuaries/deltas and coastal seas? ?
- What are the sources, pathways and transformations of nutrients into/in RS systems? How can sources, pathways and transformations be traced and inputs be quantified?
- What is the contribution of eutrophication legacy (stored in sediments) on present-day nutrient budgets and eutrophication?
- How do increasing human interventions on hydromorphology (e.g. navigation channels, reservoir lakes, river fragmentation, floodplain decoupling and restoration, reduction of marsh ecosystems) influence nutrient transformation and retention capacity as well as productivity and foodwebs?

STATE CHANGES & IMPACTS

- What would be indicators for threshold nutrient concentrations that need to be attained to control algal / cyanobacterial blooms and hypoxia across RS systems?
- What are the consequences of changed C/N/P/Si ratios and concentrations on ecosystem structure and functioning and the carrying capacity in the riverine, estuarine and coastal environments?
- How are eutrophication, hypoxia and climate change interacting? What are spatial scales of impact on ecosystem functioning?
- How are eutrophication and hypoxia-related effects in the catchment/headwaters impacting the ecosystem state downstream, in estuaries/deltas and coastal seas?

HUMAN RESPONSES

- What is the time lag of measures in the catchment to take effect in adjacent coastal seas?
- How efficient is the creation of nutrient retention zones (e.g. re-connection to floodplains, artificial wetlands) in RS systems for reducing the effects of eutrophication?
- Which gaps need to be closed and which links must be created in the different relevant regulations (e.g., WFD, FD, MSFD, MSPD, ND, HD, Natura 2000, common agriculture policy, water blueprint) for a coherent nutrient policy?
- How to define tolerable nutrient loads for different parts of RS systems to reach a common management goal?
- Which scenarios models of RS systems are needed to better understand the influence of policies, human behaviour and natural factors (climate) on eutrophication and its impacts?

2.2.3 Pollution

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Increasing urbanization, industrial development, intensive agriculture and an increasing population have been intensifying for many decades the release of harmful substances to the environment. As our understanding of the structure and functioning of the aquatic environment has grown, it has become clear that the capacity of rivers, lakes, and seas to assimilate chemical wastes and toxic materials is not infinite and that the exposure to these substances, even in small amounts, can be hazardous to both humans and wildlife. Once taken up, harmful substances may affect organisms through a certain mode of action, which can be related to the molecular, the sub-organismic or organismic level (Montuelle, 2017). The more complex the level, the more difficult it will be for organisms to compensate adverse effects. If compensation mechanisms fail, core vital functions such as reproduction will be disturbed, in turn leading to negative effects at the community level. Hazardous substances may enter the food web through bio-magnification or direct uptake of contaminated water or sediment. Bioaccumulation in fish and mussels, as well as the infiltration of river pollutants in drinking water resources, poses a direct threat to human health. Hence, tackling water pollution – "the introduction by man, directly or indirectly, of substances, pathogenic germs or energy into the aquatic environment resulting in such deleterious effects as harm to living resources, hazards to human health, hindrance to aquatic activities including fishing, impairment of quality for water use and reduction of amenities" (Pravdic, 1981; WWAP Report 2018)" - has been a main task of the European water protection policy since the early 1970s. Since 2000 water protection policy generally, including protection against water pollution, has been put on new conceptual footings by replacing, merging and renewing major parts of the existing European regulations (EU 2000, 2008, 2006, 2013).

Despite the considerable progress that has been made, water pollution remains relevant. Pollution from diffuse or point sources (runoff from agricultural land, other land uses, atmospheric deposition or municipal or industrial wastewater, farming discharges, accidental pollution, respectively) is still among the significant pressures on Europe's surface waters (EEA, 2018). People in many regions outside of Europe still lack access to safe sanitation (UN, 2015) with all the consequences for water quality. The range of potentially harmful substances occurring in RS systems is extensive, with only a few stemming from natural sources such as soil erosion or organic compounds produced by metabolism (WWAP Report 2018).

Pollution is one aspect of stress ecology and has to be understood and assessed in relation to, and in interaction with, other pressures such as nutrition or hydro-morphology (EEA, 2018). Recent regulation pays specific attention to the Persistent-Bioaccumulative-Toxic (PBT) concern. In addition, the susceptibility to long-range transport is considered a criterion of particular concern. The adoption of REACH (2006), which puts particular emphasis on PBT substances, along with fundamental water policy regulations (see above), demonstrates the political will in the EU for a change of paradigm in dealing with chemical compounds and products being released to the environment. However, it is most unlikely that anthropogenically influenced RS systems can be fully restored to a state that is free of contaminants or new pollutant inputs. Therefore, it is on the agenda of the society to develop conditions that allow keeping the impact of anthropic pollution below certain thresholds, and hence stabilize the resilience of the desired water quality state. Identifying such thresholds in the context of dynamically changing local and global multiple stressors is a major challenge faced by scientists, regulators and society as a whole. A regime is required that effectively integrates future-oriented economic strategies (green economy, closed material cycles), technological measures (e.g. in wastewater purification), and changes in human behaviour to mitigate, control and manage water pollution.

Rivers are vectors that transport dissolved and particulate pollutants across RS systems. The intrinsic properties of the system and basin-scale hydrodynamic processes, such as transport and dispersion, determine the environmental fate of contaminants (Li, 2014). Natural or artificial lakes can capture some of the pollutant load originating in the upstream part of a catchment. Particle-bound contaminants can temporarily or permanently be retained in zones of low flow velocity (cf. 2.3 – Sediments & their Management). It is important to understand these processes, first as a theoretical basis for exposure modelling (e.g. for coastal regions) and second to estimate the contribution of upstream and inland sources to downstream and marine contamination. Finger print analyses of monitoring data can help to identify emission sources (Plumb, 2004). Changed flow regimes of rivers, due to more frequent and more intensive extreme events as consequences of climate change, may intensify pollution pressures, for example in cases of extended periods with low rainfall and thus a decreased natural discharge of water and an increased wastewater portion or due to enhanced mobilization of historically contaminated sediments and soils during floods (cf. 2.1.2 - Extreme Events and 2.3 – Sediments & their Management). Hence, there is an urgent need for new scenarios and models to better understand water/particle dynamics of pollutants as well as their concentration gradients in environmental compartments (air, water, sediments) and their trapping in deposition, transitional and coastal zones (Montuelle et al., 2017; Machadoet al., 2016; Barletta et al., 2019, G.E.M, 2002).

Many of the pollutants were present several decades ago, but others have become significant more recently. From a legal point of view, a distinction can be made between regulated and emerging pollutants. Both historic contamination, caused e.g. by past mining activities and old industries, and recent industrial chemicals and pesticides, form substantial parts of the regulated category. Emerging pollutants (EP) are defined as compounds that are not currently covered by the existing water quality regulations, have not been sufficiently studied before and are considered to be potentially harmful for ecosystem and/or human health (Farré et al., 2008). EPs include a variety of substances and substance classes, such as pharmaceuticals, personal care products, and biocides and their degradation products, chemicals from household, technical and industrial applications (as halogenated and poly-halogenated compounds). They all may turn out to be rather persistent under environmental conditions (Norman Network: Lists of Emerging Substances; Richardson and Ternes, 2018) and may cause severe damage even at low concentration found in aquatic systems (Geissen , 2015). Moreover, in contrast to many regulated contaminants, they feature a relatively high polarity and are very mobile in the urban water cycle. Hence, they may not or only incompletely removed by conventional wastewater treatment, and may require additional, costly purification steps. Due to their elevated polarity their human metabolites and transformation products are also prone to contaminate drinking water resources (Kümmerer, 2009; Lapworth 2012).The determination of specific transformation pathways, identification of key transformation products, evaluation of their toxicity and accurate prediction of their environmental persistence (that sometime might be longer than the persistence of the parent compound) are a prerequisite for the development of strategies to reduce the negative impact of such pollutants. Genetic transfer between species (Grenni et al., 2018) s one of the major contributions to increasing antibiotic resistance. With the wide use of antibiotics as growth supplements in livestock and their impact on biota, there is a clearly negative impact of EPs on society, resulting in the need to develop adequate strategies to limit their environmental spread. Plastics, microplastics and nanomaterials (Stefanakis, 2016) have recently been recognized as new groups of pollutants that might cause harmful effects due to their uptake by aquatic organisms and release of chemicals by leaching of additives or, in the case of microplastics (Burns, 2018) by polymer degradation (Wagner et al. , 2014; Yu et al, 2018). In addition, microplastics function as passive samplers of certain contaminants, becoming a relevant matrix for the long-range transport e.g. of persistent organic pollutants. The potential environmental impact of manufactured nanomaterials based, for example, on metal oxides (e.g. SiO_2, TiO_2), carbon nano-tubes, or polymers, is a further critical concern and the ability to assess these potential impacts is a high priority both for protecting waters from potential hazards and for the progress of sustainable nanotechnology (Romero-Franco et al., 2017).

The risks linked to the simultaneous presence of several pollutants (cocktail effects; Van Genderen et al., 2015) and to medium- and long-term environmental modifications (e.g. linked to climate change) also represent a priority for pollution management in the forthcoming decades (Landis et al., 2013). Species tend to respond to different toxicants in different ways and at different stages oflife-history. The effects of a specific pollutant may also vary depending on previous exposure to other contaminants (Ashauer et al, 2017) and much remains to be researched to understand the effects of the temporal variability of pollution in real field situations. While for an important number of individual pollutants protocols exist to measure their concentration in water, sediment and biota and to understand their metabolic pathways, an appropriate environmental risk assessment (ERA) including exposure patterns, i.e. the temporal variability of concentrations and the changes in their speciation (Yates, 2013; Carter, 2006), levels of concentration, the simultaneous presence of several pollutants, the overall environmental conditions including RS system dynamics, and bioaccumulation/ biomagnification, are still lacking (Burns, 2018; Schäfer, 2015; EMA/52740/2012). Furthermore, in the case of EP a suitable ERA is also hampered by the severe lack of monitoring and (eco) toxicological data. Tackling the ERA issue, a multidisciplinary approach is needed (EPA, 2018). Harmful effects have to be tracked across various biological levels, i.e. from the molecular initiating event up to possible endpoints on the organismic level. Development of methods based on adverse outcome pathways will be a step forward (Jeong and Choi, 2017) supporting the development of mitigation strategies, methodologies and protocols. Appropriate assessment protocols have to be developed not only for the original compounds but also for their metabolites or microbial transformation products (Farré et al., 2008; Montuelle et al., 2017).

A major share of the multitude of non-priority substances present in RS systems is not part of current monitoring efforts due to a lack in regulation, awareness, suitable methodology or a combination of all. Furthermore, it is to be expected that the number of chemicals in use (and in many cases their used amounts) will further increase. Some classes of pollutants (e.g., biologically active molecules such as pharmaceuticals, antibiotics) will pose specific risks due to their prospective increasing use in an ageing population. Trace elements apart from the traditional spectrum, such as rare earth and precious metals, and their species may find their way into the aquatic environment due to continually increasing usage in new industrial applications, for new technologies and mass-market products, such as smart phones or screens. Hence, it will be likely for these reasons that surveillance monitoring will be needed in the future for various aquatic environment chemicals and microorganisms not commonly subjected to this today. Suitable chemical analytical methods have to be developed for their sensitive and reliable detection, including screening methods. An efficient way to approach an integrative monitoring, tackling all the issues related to chemical mixtures, metabolites, TPs, and unknown and cumulative effects, may be the implementation of techniques using effect-based tools/effect-directed analysis (EBT/EDA) such as bioassays and biomarkers, which allow a comprehensive diagnosis of the toxic impact[4]. In order to identify early and functional responses at organism level state of the art “omics” approaches may represent promising tools to detect e.g. expression profiles of proteins, which are suited to better understand the potential adverse effects of complex environmental contaminant cocktails, or which can be used as markers of altered physiological conditions. Such approaches may also be suited to find highly specific indicators of toxic stress, caused by the presence of e.g. emerging pollutants or for the identification and early detection of pollutants causing harmful ecological impacts. The EBT approach is able to avoid the current issue of assessment regime when dealing with proving/ confirming the absence of toxic stress induced by a significant number of EP and mixtures of chemicals. Efforts on standardisation of these EBT approaches are needed[5].

[4] www.eda-emerge.eu
[5] Ibid.

POLLUTION: Selected Research Questions

DRIVERS & PRESSURES

- How will climate change and changed extreme patterns influence the pollution pressure on RS system ecosystems and their services?
- How will global change processes such as ageing of the population influence the pollution pressure on RS system ecosystems and their services?
- How can pollution-caused stress be better understood and assessed in relation to, and in interaction with, other pressures such as nutrition or hydro-morphology?
- What is the specific pressure of emerging pollutants and new contaminant classes (e.g. plastics, nanomaterials) on water sufficiency and ecosystem health and what is the role of emerging pollutants such as antibiotics in increasing abiotic resistance?

STATE CHANGES & IMPACTS

- How can thresholds for pollutants be identified, which allow stabilizing the resilience of the desired water quality state in the context of dynamically changing local and global multiple stressors? How can scientists, regulators and society actively cooperate in this process?
- How will new scenarios and models look like helping to better understand water/particle dynamics of pollutants as well as their concentration gradients in environmental compartments) and their trapping in deposition, transitional and coastal zones?
- Which analytical methodologies are most suitable to identify chemicals and microorganisms not commonly subjected to a surveillance monitoring? Which are the most relevant non-target methods (analytics and IT-based evaluation tools) to address “unknown” (emerging) compounds? What are efficient ways to approach an integrative monitoring tackling all the issues related to chemical mixtures, emerging pollutants, metabolites, transformation products, and unknown and cumulative effects?
- What are appropriate methods to determine specific transformation pathways of EP, to identify key-transformation products, to evaluate their toxicity and to predict correctly their environmental persistence?

HUMAN RESPONSES

- How will a regime look that effectively integrates future-oriented economic strategies (green economy, closed material cycles), technological measures (e.g. in wastewater purification), and changes in human behaviour to mitigate, control and manage water pollution?
- How does a multidisciplinary approach look like that enables an environmental risk assessment (ERA) of pollutants including aspects like exposure patterns, levels of concentration, the simultaneous presence of several pollutants, the overall environmental conditions including RS system dynamics and bioaccumulation/ biomagnification?
- Which gaps need to be closed and which links must be created in the different relevant regulations for a coherent pollution policy?
- Which are the best ways to communicate scientific results in order to increase the public awareness on water contamination?

2.3 Sediments & their Management

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Sediment is an intrinsic part of RS systems and can be defined as "suspended or deposited solid, of mineral as well as organic nature, acting as a main component of a matrix, which has been, or is susceptible to being transported by water" (Brils, 2004). Sediment appears in many forms, depending on the size of the solids, ranging from very fine suspended particles (usually <63 µm) to coarse deposits of gravels and even boulders (>25 cm). It is eroded at catchments, transported, deposited and modified throughout river catchments before being delivered to coastal seas; giving rise to the RS continuum. In estuaries, sediment is transported both down- and upstream, mixing fluvial and marine sediment in response to tidal currents (Salomons & Brils, 2004). Sediment routing from source to sink through erosion, deposition and remobilization, can range from several days up to several thousand years, introducing a historical component to RS systems (Hoffmann, 2015). A better understanding of the sediment continuum – and especially of how that continuum is disrupted by human interventions as well as climate change, and the environmental (planet), societal (people) and economic (profit) impacts resulting from that – is a key scientific challenge (UNESCO, 2018).

Sediment regime can be defined as 'the change in sediment quantity through time' and thus refers to the dynamics of sediment in RS systems (Wohl et al., 2015). Sediment erosion, transport and deposition are key factors for landscape development, for the genesis and degradation of soils, water quality, and for the formation of river deltas over geological eras. River hydro-morphological characteristics influence the sediment regime and both are crucial for the diversity of habitats and biota (Langhammer, 2010; Collins et al., 2011). The sedimentary composition not only determines habitat types for fish and benthic fauna, but also for flora and microbial communities that process organic matter and recycle nutrients (Salomons & Brils, 2004). Sediment also acts as a vector as well as a sink for nutrients (e.g., burial, N-loss via denitrification and anammox (Engstrom et al., 2005)) and plays a crucial role in goods (resources) and services provided by freshwater and marine ecosystems (Van der Meulen et al., 2016). Humans utilize river sediment (i.e. alluvial sediment) as a resource for fertile farmland and construction material (Salomons & Brils, 2004; Brils et al., 2014b). Regarding coastal ecosystem services, sediment forms beaches and dunes which: a) provide the physical support on which the coastal habitats develop; b) act as a natural barrier protecting the hinterland from sea forces; and c) support recreational activities (tourism) with important economic consequences (Brils et al. 2014b; Van der Meulen et al., 2016).

2.3.1 Sediment Quality & Quantity

Challenges in Sediment Quantity

Human interventions interact with erosion and sedimentation processes; altering the natural sediment regime (Hoffmann et al., 2010). Thus, these regimes are disturbed in RS systems, worldwide (Poff et al., 1997; Nilsson & Berggren, 2000; Syvistki et al., 2005; Walling, 2009). Nearly all of the DANUBIUS-RI Supersites demonstrate disturbed sediment regimes due to human interventions, for instance those in the Danube (Giosan et al., 2012), Rhine (Frings et al., 2015), Nestos (Kamidis et al., 2017) and Ebro (Jiminez et al., 1997). Human interventions include damming, river engineering, dredging, sand and gravel extraction and soil erosion resulting from deforestation and agriculture. Peduzzi (2014) outlined in a UNEP report that sand is now being extracted at a rate far greater than its renewal. Sand must be considered as a particularly scarce resource given their importance in protecting coastal areas from rising sea levels. Syvitski et al., 2005 showed that about 26% of the global sediment transport is trapped in reservoirs. The total loss of worldwide reservoir volume is estimated at a rate of 0.5 to 1% per year due to sedimentation (Walling, 2006). Reservoir lakes behind dams are estimated to intercept more than 40% of the global sediment transport (Vörösmarty et al., 2003) and more than 50% of the large river systems are effected by dams (Nilsson et al., 2005). Locally in the RS system these alterations of the sediment regime result either in a surplus or a shortage of sediment, causing different impacts.

A surplus of sediment causes siltation of reservoirs, with negative effects on hydropower production and water storage (Brismar, 2004; Lin, 2011; Kondolf et al. 2014) and causes a siltation of waterways, with negative effects on navigation, flood conveyance and instream ecosystems (Salomons & Brils, 2004). Sediment surplus causes hyper-turbidity in estuaries, resulting in the decline of ecosystem health. The sensitivity of rivers to enhanced sediment delivery may depend on season and local hydraulics (e.g. Naden et al., 2016). In many estuarine environments, interests of different users often conflict. In the Ems estuary, for instance, navigation channel deepening to allow the passage for bigger ships, leads to changes in hydro-dynamics and this causes an increased marine sediment import and reduced seaward transport of sediments, especially in low freshwater discharge periods. Thus, sediments are traped and turbidity is increased (van Maren, 2015; Borgsmueller et al., 2016; Winterwerp et al., 2017; Becker et al., 2018).

A shortage of sediment causes erosion and thus incision of river beds and causes degradation of channel morphology (Kondolf, 1997; Bravard et al., 1999) impacting: a) river habitats, e.g. leading to a lack of suitable spawning substrate; b) floodplain groundwater; c) the stability of infrastructure (bridges and dikes); and d) navigability (Giosan et al., 2012; Maselli & Trincardi, 2013; Brils, 2017). Sediment shortage also causes coastal erosion and retreating or drowning deltas, which is further amplified by sea level rise (Graf, 2006; Klaver et al., 2007; Walling, 2008; Syvitski et al., 2009; McCarney-Castle et al., 2012). At the Ebro delta, for instance, the construction of dams along the river course during the last decades has been responsible for an intense reshaping process, with shoreline retreat rates of about 20 m/year at the apex (Jimenez et al., 1997). Furthermore, the regular hydropeaking observed during dam operations induces episodic flood events. This causes local erosion of the downstream riverbed and the sediment fractions that are transported downstream, gradually armour the riverbed (Kamidis & Sylaios, 2017).

Challenges in Sediment Quality

Human interventions (point and diffuse sources of pollution) have contaminated sediment in RS systems. Sediment accumulates contaminants and nutrients, depending on particle size reactivity (surface area), affinity to organic or lithogenic material and redox conditions (Chuan et al., 1996). Sediment is considered as the largest reservoir of trace metals and other contaminants, exchangeable between the water column and biota (Du Laing et al., 2009). Contaminants in sediment layers often provide an environmental archive of changing industrial and agricultural practices. Where water quality is improving, this 'legacy of the past' usually persists in sediments on riverbeds, floodplains, behind dams, in lakes and in estuaries, and seas of many RS systems (Salomons & Brils, 2004; Brils et al., 2014a; Bábek et al., 2008).

Above certain concentrations the contamination in sediment will locally impact ecosystem functioning (Barcelo & Petrovic, 2006; Brils et al., 2014a). However, the locally deposited contaminated sediment may be remobilized due to flooding, channel bank erosion or dredging, and then be transported further downstream (Chapman & Wang, 2001; Walling et al., 2003; Salomons & Brils, 2004; Cave et al., 2005; Bortone, 2006; Barcelo & Petrovic, 2006; Burton & Johnston, 2010; Dagnino et al., 2013). Thus, adverse environmental effects can occur not only locally but also far from the original source of contamination (Salomons & Brils, 2004; Walling et al., 2008). This is especially true when contaminated sediments are 'diluted' with pristine sediments and with higher biological activity, as is well established for the bio-methylation of metals and metalloids, e.g. mercury (Mason, 2012; Glasauer et al., 2013). Therefore an understanding of the entire RS system is needed and this should include the contaminant sources, pathways and their receptors (Brils et al., 2014a). Furthermore, contamination increases the complexity and thus costs of sediment management, in particular for the handling of dredged material (Bortone, 2006).

Sediment quantity and quality changes are closely interlinked. Changes in hydro-morphology affect sediment quality (chemistry) as well as quantity (habitat) and thus effect the achievement of EU water policy related goals and especially the 'chemical' and 'ecological' status goals of the European Water Framework Directive (WFD: EC, 2000). Furthermore, ecosystem goods and services are affected by changes in sediment quality and quantity (Van der Meulen et al., 2016; SedNet, 2017).

Research Needs

R&I focus should be set on sediment budgets, i.e. the accounting of sediment sources, transport pathways and sedimentary sinks along the full flow trajectory of the RS continuum (Reid & Dunne, 1996). Compiling catchment integrated sediment budgets is a major challenge given the large scale of RS systems, the multitude of interacting geomorphic processes and the long-temporal scales associated with the history of RS systems. Within the DANUBIUS-RI context, coherent observation systems should be developed and established, considering the large range of geomorphic processes (i.e. hillslope erosion, in-channel transport of suspended and bed load sediment, sediment deposition and remobilization within the river channel and in the adjacent floodplain). To consider lag effects in RS systems, contemporary sediment monitoring should be complemented by long-term, stratigraphical approaches to reconstruct erosion, transport and deposition at time scales of 10^2 to 10^3 years. Research efforts should be made to learn more about the origin of sediments. In the estuarine environment, research effort should focus on the mixing of fluvial and marine sediments to better understand estuarine transport processes.

To create a sediment balance for the whole or a certain part of the RS system, knowledge of bed level changes needs to be combined with information on suspended sediment transport. Further research is needed on suspended sediment measurements that are representative for a whole profile, the measurement of bed level changes and additionally considering the sediment fluxes generated by dredging and dredged material relocation (see sediment management). Methods need to be developed that combine the results of these measurements in order to be able to create a reliable sediment budget. To allow the comparison of different RS systems concerning sediment transport and hydro-morphologic processes, research should consider coherence: in the data bases, in the methods for data acquisition, and in data analysis.

SEDIMENT QUALITY & QUANTITY: Selected Research Questions

DRIVERS & PRESSURES

- What are the effects of climate change on the sediment regime in RS systems, and which parts of the system are the most sensitive?
- How to discern the impact of climate change and human drivers on the sediment regime?
- What are the significant contaminant sources and sinks (recent and legacy), where are the sinks located in the RS system sediments (tributaries, river banks, river bed, flood plains, reservoirs, in land ports, sea ports, urban areas)?

STATE CHANGES & IMPACTS

- Which sediment regime (quality and quantity) state changes have an impact ecosystem functioning and services?
- What are the ecological boundaries for minimum and maximum sediment flows for RS ecosystems to function?
- How do changes in sediment flux in RS systems affect delta and global shorelines, and coastal erosion?
- What is the impact of dredged material relocation (within the river or at sea) and sand and gravel mining on ecosystem functioning, water quality, sediment transport and morphodynamics?
- How are dams and reservoir lakes affecting sediment quantity and quality (e.g. retention of nutrients and sediment, eutrophication in reservoirs, settling tanks for pollutants)?
- How is a disturbed sediment regime negatively impacting on water sufficiency?
- What are the sediment and suspended matter associated contaminant pathways (transport, deposition, remobilization, phase transfer)?

HUMAN RESPONSES

- How can nature-based solutions help to restore the sediment flow and/or to attenuate sediment contamination?
- What are the effects of sediment management measures on sediment transport budgets, morphology, nutrient and contaminant fluxes, and what is the related effect on RS ecosystem services provision?

2.3.2 Sediment Management

Where human activities interfere with sediment quantity or quality, sediment management becomes necessary (Brierley & Fryirs, 2005; Owens, 2008; SedNet, 2014). Historically, dredging is probably the most widespread sediment management activity. Many water and port managers continuously have to dredge sediments to ensure the flow of water (e.g. for irrigation or flood control) as well as to keep waterways navigable. Europe-wide, the volume of dredged material in (sea-) ports is roughly estimated at 200 million cubic meters per year (Salomons & Brils, 2004). Dredging requires a tailored sediment management strategy, such as applied for the tidal Elbe (BfG, 2014). As sediment is intrinsically part of RS systems, relocation of dredged material in that system is the most sustainable solution (Bortone, 2006). Dredged material is also a valuable resource (SedNet, 2014). It enhances for instance the amount of sediment available for habitat formation and re-creation (Brils et al. 2014b).

Currently, much of the thinking on sediment management focuses on sediment quality and on the role of sediments in sustaining a river's hydro-morphology and by that its ecology (ECOSTAT, 2018). It is the interdependence between the management of sediment quantity and quality that has to be effectively addressed in up-to-date sediment management concepts that address the entire RS system (Owens, 2005; SedNet, 2006; Heininger & Cullmann, 2015; SedNet, 2017).

Sediment management needs to be integrated into WFD river basin management plans in order to achieve the WFD objectives (SedNet, 2006; SedNet, 2009; SedNet, 2017). Effective sediment management requires a holistic approach that takes into account (Jimenez et al. 2011; SedNet, 2014): 1) system understanding in terms of both quality and quantity; 2) the integrated management of soil, water and sediment; 3) upstream-downstream relationships; and 4) supra-regional and transboundary collaboration.

Achieving an adequate sediment management plan requires accurate knowledge of sediment erosion and transport pathways into and its movement within the RS system. It requires a survey of pathways, screening for contaminants and the establishment of a monitoring system that captures sediment quantity, dynamics and quality with adequate spatial and temporal resolution (EC, 2004; Marchand et al. 2011; SedNet, 2017). The sediment budget concept (Dietrich & Dunne, 1978) provides a valuable framework to assist in managing and controlling diffuse-source sediment pollution and associated problems. The framework helps: a) to identify the key sources, b) to demonstrate the importance of intermediate stores and c) to determine the likely impact of upstream mitigation strategies on downstream sediment and contaminant fluxes (Walling and Collins, 2008).

A sediment management plan should also consider different temporal and spatial scales and integrate the overall benefit of sediment management. A further step in the design of a management plan is a thorough risk analysis for different single objectives in the overall objective function. This means that priority areas, critical infrastructure, threshold values for sediment quality and/or scouring/sedimentation and ecological indicators need to be agreed and given a relative value in the overall objective function.

Different actors (nations, organizations, stakeholders) may have different objectives when they consider sediment issues. A framework must be devised that allows goals and priorities to be balanced in a transparent manner. Therefore, the management plan must provide concrete advice on how the different objectives can be achieved; how they will impact each other, and should include an estimate of the costs of the measures required to achieve set objectives. The latter could include: a) to guarantee certain shipping channel geometry, b) to enhance sediment transport through locks and weirs, and c) to promote sediment restoration at eroded coasts and river mouths. These objectives might be contradictory and, if pursued in isolation, a single objective might prejudice the other objective(s). Therefore, management plans must encompass tangible measures that will together address a multi-objective target. For example, the member states in the International Commission for the Protection of the Elbe River (ICPER) decided to develop a sediment management concept in preparation for the 2nd WFD management cycle (2016 to 2021). This provides for the first time in a large international river basin an integrated sediment management concept to support management planning (ICPER, 2014; Heininger et al., 2015).

An important consideration in current integrated river basin management is how sediment management is optimized by working with natural processes (working-with-nature; nature-based-solutions; or eco-engineering). Natural solutions may be used to mitigate sediment source erosion and its delivery to streams and to enhance sediment conveyance through rivers by maintaining, restoring and enhancing channel hydromorphology.

Research Needs

Focus should be set on the development of sediment management concepts for the whole RS system continuum. Research questions should address and thus enable:

- A better understanding of sediment and associated contaminant dynamics across the entire RS system;
- A better understanding of the anthropogenic influence (hydro-morphological alterations and contamination) versus natural processes, including the influence of climate change induced extreme weather events (floods and droughts);
- The definition of sound sediment management concepts that consider different demands (for example to ensure navigability, improve hydro-morphologic conditions, to ensure protection against flooding).

SEDIMENT MANAGEMENT: Selected Research Questions

DRIVERS & PRESSURES

- What are the key drivers that negatively affect the sediment regime in RS systems?
- Which human-induced changes in hydromorphology (e.g., damming, bank enforcement, fairway deepening, dredged material relocation, channel straightening, floodplain disconnection) significantly affect the sediment regime (quantity & quality) in RS systems and how does it affect the sediment dynamics and budget?

STATE CHANGES & IMPACTS

- How to provide consistent estimates of sediment budgets for RS systems, to allow for comparability?
- How are changes in sediment regime effecting (sediment related) ecosystem services provision in RS systems?
- What are the costs of misbalanced sediment conditions and bad sediment quality (dysfunctional sediment regime) to society?

HUMAN RESPONSES

- How can legacy contamination in sediments be managed?
- How can negative impacts of dams and reservoirs on the sediment regime be minimized?
- What are management approaches to sustain wetlands (deltas, marshes) effectively given sediment starvation?
- What is the potential of managing sediment through working with natural processes?
- How to effectively balance costs (who faces the costs?) and benefits (who has the benefits?) of sediment management: from local (on site) to the full RS systems scale?
- How can stakeholders be best involved in sediment management at the local, regional, national and transnational (full RS systems) scale?
- How to include sediment management in RS systems management plans?
- How to effectively balance costs (who faces the costs?) and benefits (who has the benefits?) of sediment management: from local (on site) to the full RS systems scale?
- How to establish effective sediment related Payment for Ecosystem Services (PES) schemes: from local (on site) to the full RS system scale?

2.4 Ecosystem Health

Thomas Hein, Eva Feldbacher & Gabriele Weigelhofer (WCL), Sina Bold (HZG), Elmar Fuchs (BAFG), Simona Litescu (INSB), Ken Irvine (UNESCO-IHE)

The term Ecosystem Health has been used in the scientific literature since the 1990s (Rapport 1992) and the concept has often been applied to the evaluation of ecosystems since then (Rapport et al., 1998, O'Brien et al., 2016). Ecosystem health integrates aspects of ecosystem functioning and biodiversity and provides a link to ecosystem services. A healthy ecosystem is considered stable and sustainable, maintaining its structural integrity, self-organisation over time, and resilience to stressors (Costanza and Daily, 1992), whereas highly stressed ecosystems are unable to support a variety of ecosystem functions and related ecosystem services to the same level as previously. This considers whether the ecosystem and its external inputs (such as energy or fertilizer) are sustainable in the long term as well as whether the ecosystem can withstand or recover from perturbations (resistance and resilience, respectively) and similar issues (de Groot, 2011). Ecosystems are connected by abiotic and biotic factors e.g. through the flow of water and sediments (quantity), the associated transport of organic matter, nutrients and pollutants (quality), as well as the migration and dispersal of organisms (native and non-native species). Connectivity influences ecosystem structure and functioning, ecosystem services and ecosystem health. Overall RS systems are highly modified, with far-reaching consequences on ecosystem health at European and global levels (Grizzetti et al. 2017).

Healthy RS systems provide ecosystem services fundamental for societal wellbeing. However, these systems face multiple and compounding pressures due to climate change and human drivers, such as land use change, urbanisation, energy generation, waterborne transport, agriculture and fisheries at different spatial (local, national and global) and temporal (seasons to centuries) scales. The resulting changes in the structure and the functioning of RS ecosystems (shifts in water quantity and water flows, changes of trophic conditions, modified nutrient cycles, disruption of native species populations by non-native invasive species, shifts in biodiversity of aquatic and riparian biotic communities and shifts in sediment regime (quantity and quality) lead to the decrease or loss of ecosystem functions that have, in turn, an impact on ecosystem services and ecosystem health. This poses a number of societal challenges, for example, eutrophication, hypoxia, pollution, changes in hydrology, sediment transport and morphology, loss of biodiversity, invasive species and sea level rise. Without counteraction towards sustainable development, these pressures and respective changes are likely to increase in future with implications throughout the RS continuum and with uncertain consequences for the resilience of RS systems.

2.4.1 Ecosystem Functioning & Biodiversity

Species, functional types, communities, and their interaction across ecosystems provide the basis for ecosystem functions and services (De Groot et al., 2017; Diaz et al., 2005; Green et al., 2015; Russi et al., 2013) and affect ecosystem stability towards stressors. Some species, for example, play a key role in ecosystem structure and functions, such as “keystone” species determining food webs and matter fluxes (e.g., top predators or abundant grazers; Paine, 1966) or ecosystem engineers shaping the habitat structure (Jones et al., 1994). Such functional approaches help to describe the link between biodiversity and ecosystem functions and services (Landi et al., 2018; Lawton, 1994). Nevertheless, the relationship between biodiversity and ecosystem function and its change along the RS continuum remains to be clarified, especially under changing climatic and environmental conditions.

Diverse and co-evolved ecosystems can promote efficiency in energy transfer from lower to higher trophic levels and provide a capacity to either resist change from a pressure and to recover from it (Sekercioglu, 2010; Hooper et al. 2005; Worm et al. 2006). While the investigation of trophic dynamics and ecosystem functions related to biodiversity has a long history in lakes (Lindeman, 1942; Brooks and Dodson, 1965; McQueen et al., 1989; Scheffer et al., 1993), relating structure to function in rivers and estuaries is comparatively more recent (e.g. Power, 1992; Frank et al., 2007). Research in this area has increasingly benefited from molecular and microbial techniques, as well as from *in-situ* measurements of ecosystem processes, such as nutrient transformations (Anderson & Cabana, 2007; Gomez-Velez et al., 2015; Masese et al., 2018). While these techniques provide an increasing understanding of ecological functions, the response of ecosystems to multiple human pressures remains to be investigated (Vörösmarty et al., 2010).

There is ample evidence of a global decline of biodiversity, which is most pronounced in freshwaters (WWF, 2018; Bunn, 2016; Dudgeon et al., 2006; Loh et al., 2005) due to increasing human pressures (van Asselen et al., 2013). These pressures were generalised by Dudgeon et al. (2006) as overexploitation, water pollution, flow modification, destruction or degradation of habitats, and invasion by exotic species. All of these apply to the RS systems, exemplified by documented or potential impacts on biodiversity within the Danube basin and are key issues in the Supersites in the Danube River Basin. Ecosystem community assembly is also strongly limited by dispersal, which can constrain ecosystem functioning by reducing positive selection effects (Leibold et al., 2018). This points to the fact that biodiversity and ecosystem functioning need to be investigated across different scales up to the landscape and basin scale. In fact, many RS systems are already so disturbed and fragmented that restoration is likely an impossible task due to the multiple pressures and high degree of fragmentation (Hering et al., 2010; Hilderbrand et al., 2005). Rehabilitation that aims to mimic the original system in species composition may be the more realistic goal.

For DANUBIUS-RI, two main areas need further research. The first is the link between biodiversity and the structure and function of the ecosystems along the RS continuum under changing environmental conditions and multiple pressures. The complexity of this task may require the application of established scientific approaches supported by new techniques, such as for example eDNA and spectral species analysis (species based on LIDAR and remote sensing). The second is to build a greater awareness and effective engagement strategy involving policy makers and the interested public. Citizen science could play an important role here as well to improve effective biodiversity protection policy (Cardoso et al., 2011).

It is one of the major goals of DANUBIUS-RI to translate the value of biodiversity to the ecosystem service concept. A reasonably intact community of organisms ensures delivery of essential ecosystem services that provide benefit to economic value chains beyond the immediate ecosystem boundaries (Pollock et al., 2017). Research needs and questions should therefore address the link between biodiversity and ecosystem function to investigate the connection with sustainable societal and economic welfare more closely.

ECOSYSTEM FUNCTIONING & BIODIVERSITY: Selected Research Questions

DRIVERS & PRESSURES

- How will climate change (e.g., warming, shifting seasons, changes in the hydrological cycle, invasive species) affect ecosystem structure, functioning and services?
- How do human activities interact in altering aquatic ecosystems, at which temporal and spatial scales?
- How does the combination of climate change and human activities determine the vectors and pathways for changes in ecosystem composition and function?
- How does the interaction of multiple pressures induced by climate change and/or human activities affect biodiversity and related ecosystem functions?
- What are suitable indicators assessing and quantifying multiple pressures on ecosystem health?

STATE CHANGES & IMPACTS

- What constitutes a healthy RS system in the Anthropocene?
- What are the keystone species and habitats in RS systems and what are critical interfaces?
- How can new tools, such as eDNA and spectral species, improve biodiversity assessments along the RS continuum?
- How resilient are estuarine and coastal ecosystems against accumulating pollutants from upstream, how does it affect organisms' metabolism, what are the thresholds?
- What causes regime shifts in ecosystem structure and functioning? What are early warning indicators for regime shifts?
- Which is the appropriate set of indicators for ecosystems health at different scales?
- How to assess and predict upstream-downstream impacts of man-made changes on hydro-morphology, RS continuity and matter fluxes on ecosystem functioning and biodiversity?

HUMAN RESPONSES

- How can we maintain sufficient longitudinal and lateral ecological connectivity along the RS continuum to protect ecosystem health?
- What would be required to harmonize the WFD and MSFD as a basis for a new, joint directive for environmental status assessment?

2.4.2 Ecosystem Services

RS systems, including critical interfaces such as riparian zones, floodplains, deltas and coastal areas, provide a diversity of ecosystem services, which are the benefits people obtain from ecosystems (MEA, 2005; Pinto et al., 2013). The most recent reference classification of ecosystem services is the ´Common International Classification of Ecosystem Services´ CICES in its updated version 5.1 (Haines-Young and Potschin, 2018). CICES follows the tradition of the Millennium Ecosystem Assessment (MEA, 2005), initiatives such as The Economics of Ecosystems and Biodiversity (TEEB), the Intergovernmental Platform for Biodiversity and Ecosystem Services (IPBES) and other national approaches (e.g. UK National Ecosystem Assessment). CICES 5.1 implies a 'purposeful' nature and aligns with the principles of ecosystem accounting. Three categories of ecosystem services are considered, 'provisioning', 'regulation and maintenance', and 'cultural'. The so-called supporting services are not recognized.

It is generally accepted that ecosystems provide multiple and interconnected services. The tendency to highlight provisioning services often obscures the regulating services as the hidden engine of service delivery. Furthermore, Fisher, Turner and Morling (2009) elaborated that services "must be ecological phenomena and do not have to be directly utilized", which highlights the importance of ecosystem structure and functioning, as well as direct and in-direct use as long as humans benefit from those ecosystem services (Constanza et al., 2007; Kremen, 2005). Despite uncertainties in data and the need to further develop relevant methods to assess ecosystem services, it is well accepted that loss and degradation of these systems has resulted in an immense loss of services. It is clear that the increasing recognition of the need to reverse the trend of biodiversity loss has an urgency not only to maintain global biodiversity, but the ecosystem services that depend on it (Craig et al., 2017; Darwall et al., 2018). The loss of species often implies the loss of functional diversity and risks maintenance and diversity of ecosystem services, an increasing relevant concept in the science-policy dialogue, and relevant for the implementation of the global SDGs (United Nations, 2018) and the regional EU biodiversity strategy (European Commission, 2011).

As the aquatic sphere (river, sea) and the surrounding semi-terrestrial and terrestrial spheres (e.g. floodplains, marshes, hinterland) intrinsically belong together, the characteristic ecosystems are not separate entities but rather connected hydrological units, although differing in their emergent ecological properties. These are subject to particular pressures and affected by landscape alterations, upstream-downstream linkages and river-floodplain fragmentation due to e.g. drainage, channel restructuring, dams and weirs. The ecological state relates to upstream-downstream political systems, socio-economic development, and culture, and diverse or even contradictory, policies that affect basin management as shown for the Danube and of high relevance for the three Danube Supersites (Irvine et al., 2016). At the mouth of rivers, estuaries have marine and freshwater characteristics, often with high economic value typified by ports and high population density. Ecosystem services manifest in these systems through water and sediment flow, nutrient cycling, water quality, and habitat availability. This includes upstream impoundments can dramatically affect sediment state, and its depredation a cause of coastal erosion affecting a combination of provisioning, regulating, supporting and cultural ecosystem services.

Climate change has an impact on the provision of ecosystem services (Hering et al., 2015). Furthermore, climate change induced pressures can interact with other pressures such as nutrient enrichment, leading to changes in ecosystem function and structure, and facilitate the spread of proliferation of invasive species and thus, affecting ecosystem service provision. Land conversion can initiate fundamental shifts in the structure and functioning of freshwater, transitional water and coastal ecosystems, also affecting ecosystem services (not exclusively terrestrial ecosystems). Wetlands transformation to croplands for example, while generating an increase of food production can have widespread negative impacts on wetland habitats and floodplain nurseries for fish (Falkenmark et al., 2007; Verhoeven & Setter, 2010) and the nutrient retention function and other regulating services.

While overall, the pressures and impacts on RS systems are recognized, the consequences on ecosystems services and associated economic welfare is largely under-researched. This is particularly so for understanding how alterations in regulating services affect provisioning services and what are potential trade-offs between these ecosystem services categories. The economic value of ecosystem services are widely under estimated and frequently unrecognised in decision making (Russi, 2013). Ideas and policy on the role of payment for ecosystem services are an increasing feature of protection of source water, but so far limited with respect to other services (Ruckelshaus et al., 2013; Tallis et al., 2015). This is a fruitful area for further thinking and development across all RS systems, where downstream users are vulnerable to the consequences of upstream management.

There is a urgent need to better identify realistic indicators for ecosystem health and services, that can complement existing systems in place for e.g. ecological quality assessment as done for the EU WFD (Council of the European Communities, 2000). Linking underlying environmental processes that affect ecosystem services requires further research to both identify cause-effect-relations, and the social importance of that. This includes the development of indicators of ecosystem integrity and risk. Mapping ecosystem services with the RS continuum is key to help to identify areas for priority action.

A set of measurable variables or parameters are required to guide and map management of ecosystem services of RS systems as SES (Berkes et al., 2003; Dunham et al., 2018). This needs to be complementary to the more traditional monitoring of physical, chemical and biotic indicators and can be guided by the prioritization of Dudgeon et al. (2006) categorized in the following way: overexploitation, water pollution, flow modification, destruction or degradation of habitat, and invasion by exotic species. Achieving a sustainable future for such systems requires assessing the drivers of change; the potential trade-offs between and among ecosystem services; and developing appropriate indicators to assess ecosystem health (Sekercioglu et al., 2010). Determining how ecosystem structure and functioning relate to ecosystem services and health affected by multiple pressures (Grizzetti et al., 2017) is an interdisciplinary field for natural and social sciences (Rapport et al., 1998). As RS systems cannot return to an undisturbed past, setting albeit ambitious targets of ecosystem health against appropriate benchmarks provides for realistic management objectives (Large et al., 2017).

ECOSYSTEM SERVICES: Selected Research Needs & Questions

DRIVERS & PRESSURES

- What are long-term trends of ecosystem services, what are main drivers for change?
- What are the implications of global trends, such as climate change, increasing urbanization and industrialization in RS systems, for functioning of RS SES and ecosystem services?
- How to translate multiple pressures on RS systems into consequences for ecosystem services and associated economic welfare?

STATE CHANGES & IMPACTS

- How are biodiversity and ecosystem services interrelated?
- How can biodiversity and ecological processes be parameterized to describe their key role in providing ecosystem services?
- How to quantify the effect of buffer zones (floodplains, marshes, wetlands) for nutrient cycling and retention as a regulatory ecosystem service?
- Which trade-offs between different ecosystem services categories can be found in different RS system components (ecosystem types)?
- To which extent do neobiota pose a risk for of ecosystem health and resilience? How can this risk be assessed (e.g. using taxonomy, fitness, competition)?

HUMAN RESPONSES

- What could be quantitative assessment tools for ecosystem services and their value beyond economic terms?
- What are the most relevant ecosystem services of a RS system, driving the living conditions? Which societal components in RS systems (e.g. living habits, social welfare) have to be analysed to clarify the relevant interactions between environment, ecosystem service and living conditions?
- What would be overarching cross-sectoral indices and thresholds indicating tipping points for ecosystem health to avoid over-exploitation of ecosystem services?

2.5 Living with Change in River-Sea Systems

Agustín Sánchez-Arcilla & Vicente Gracia (UPC)

This section aims at addressing the combined effects of climate change and intensive human activities in RS systems, which along with natural evolution are the driving forces of change. The text below focusses on one of the aspects of change so far; climate change in coastal regions. Towards the final version of DANUBIUS-RI's SIA, we will elaborate on the above mentioned other aspects of change.

Climate change is here to stay even if greenhouse gas emissions were to stabilize due to the thermal inertia of the water volumes on Earth (Brown et al. 2014; Jevrejeva et al.2014, Bisaro et al. 2015). Sea level rise in particular is likely to keep on increasing for several centuries. Human development will continue with significant differences in climate commitments depending on countries, their economic situation and social development. Human and climate driving forces converge on a narrow fringe of territory: the land-water interface where the level of conflicting uses will increase, particularly near large urban areas or in areas subject to multiple pressures such as combined riverine and fluvial flooding (Hinkel et al. 2015b). This situation is likely to be aggravated under future high-end scenarios (Hinkel et al. 2015a; Sánchez-Arcilla et al., 2015) assuming higher concentrations of population and intensification of land use in coastal zones, coupled with increasing global sea level and changing storm patterns that could reach values higher than the current best estimates of IPCC (Jevrejeva et al. 2016). One of the main research challenges will be to distinguish between natural and anthropogenically-induced change, which demands an inter-disciplinary approach at multiple scales (Sánchez-Arcilla et al. 2016). The RS continuum, and especially the coastal zone, represent vulnerability hot spots under climate change (Hinkel et al. 2015a; Adam et al. 2016; Tol et al. 2016) given the population density in coastal areas. Hence, deltaic/estuarine systems are ideal testbeds to analyse sustainability in the face of increasing climate change and human pressures (Ibañez et al. 2014; Moolenar et al. 2013) and identifying solutions to current and emerging societal problems.

The impact of future sea-level rise and the effectiveness of adaptation options and strategies are key elements of scientific relevance (Brown et al. 2014; Sánchez-Arcilla et al. 2016). The current barriers to implementing adaptation measures at local, regional and global scales, across a range of representative concentration pathways and shared socio-economic pathways (and exploring high-end emission scenarios not included in IPCC reports) must also be considered. High-end conditions may refer to drivers of coastal evolution/impacts such as sea-level rise (Jevrejeva et al. 2014) or to the vulnerabilities that result (e.g. assets or population affected). Specification of these high end conditions facilitate the attribution of cause/effect, and enable the results of the analysis to inform sustainability assessments. Particularly important in this respect are any tipping points where the emphasis should be on how they can: (a) be included in decision-making processes and (b) be derived from the Supersite data and tools developed by individual Nodes, linked to sustainability and resilience (García-León et al. 2016). The development of scenario models combining natural climate change and human induced changes is essential in order to develop solutions to address the main conflicts and challenges resulting from complexity in the RS continuum. Here, the monitoring and data analysis from Supersites plus the support by tools from the Modelling Node will be the basis for analysing the efficiency of potential solutions for those challenges. This will also help in ranking these interventions according to the urgency, based on risk and other criteria to respond to climate and human pressures.

LIVING WITH CHANGE IN RIVER-SEA SYSTEMS: Selected Research Needs & Questions

DRIVERS & PRESSURES

- What are the ranges of climate and human induced changes to which RS systems are able to adapt while maintaining ecosystem functioning and services?
- What are the best indicators of the socio-ecological aspects of RS services - to represent the complex drivers and associated pressures qualitatively and quantitatively?

STATE CHANGES & IMPACTS

- What are the key thresholds for the functioning of RS SES?
- How are natural and socio economic processes and changes in one part of the RSS ramifying through the whole continuum? What are the respective timescales?
- What constitutes a healthy RS system in the Anthropocene?
- How resilient are RS systems to increasing pressures, e.g. depending on their climate zone, range of human alteration, maturity of social processes?

HUMAN RESPONSES

- What are the implications of global trends, such as climate change, increasing urbanization and industrialization in RS systems, for functioning of RS SES and ecosystem services?
- Which mechanisms need to be developed to transfer the system understanding on RS systems developed in DANUBUS-RI into a new generation of environmental policy guidelines (utilizing WFD and MSFD).
- Which challenges in RS systems can be solved technically, which need a change of regulation/policy and which require changes in human perception and behaviour? How could all these measures be integrated effectively in adaptive management strategies?
- What are efficient decision-making instruments to choose the best options to manage the system to create and maintain conditions for sustainable growth and eco-innovation for jobs and economic development, for sustainable living, housing and working?

3. Implementation Strategy of Research Priorities

Sina Bold & Peter Heininger (HZG)

The implementation strategy illustrates how we aim to achieve our mission (cf. 1.1 - Vision & Mission) and how we aim to address our research priorities (cf. Chapter 2 - Research Priorities). Firstly, this requires a mission-oriented, integrated, interdisciplinary and participatory approach (cf. 1.2 - Methodological Approach). Secondly, this requires several components, such as a Hub, various Nodes and Supersites, a Data Centre and a TTO, as well as strong cooperation between them. The cooperation between components will be driven by common goals, a clear structure and rules, as well as transparency. Together they will form DANUBIUS-RI (cf. 3.1 - Role of Components & their Interactions). Thirdly, this requires common procedures (cf. 3.2 - Role of DANUBIUS Commons) as well as other services, which will be provided by DANUBIUS-RI (cf. 3.3 - Services).

Furthermore, DANUBIUS-RI's performance will be regularly monitored against a set of key performance indicators, which refer to several objectives (cf. Chapter 5 – Monitoring DANUBIUS-RI's performance). If needed, the implementation strategy will be adjusted to increase DANUBIUS-RI's performance. Additionally, our research priorities will be regularly updated, if needed, to assure maximum societal impact over time (cf. Chapter 6 – Updating of Science & Innovation Agenda).

DANUBIUS-RI will facilitate advanced research of R systems in order to achieve a step change in our understanding and management of these highly dynamic, complex and changing systems. The four research priorities (Climate Change, Water Sufficiency, Sediments & their Management, and Ecosystem Health) are interrelated and highlight the importance of integrated and IDR. DANUBIUS-RI will bring together the scientific excellence, expertise and facilities to better understand, characterise and manage RS systems (Figure 5).

DANUBIUS-RI will attract users and their projects by providing them with both an infrastructure (facilities, expertise, data) combining the best of existing leading institutions in their area of expertise (observation, analysis, modelling, and impact) and an efficient organisational framework to make the best use of them ("one-stop shop"). In addition, DANUBIUS-RI will develop scientific best practices, methods and standards to be adopted throughout the RI (DANUBIUS Commons). Thus, DANUBIUS-RI will overcome the difficulties of using several different methods across institutions, which currently hinders the aggregation, comparison and further processing of data from different institutions. DANUBIUS-RI will attract users interested in (1) achieving excellent scientific experiments and studies, (2) a consistent and reliable scientific framework provided by the DANUBIUS Commons, which enables users to lead projects at European scale without meeting methodological issues, and (3) accessing expertise in a large range of scientific disciplines relevant for RS system studies. It is expected that this will improve the quality of scientific outputs in RS system studies and the opening of new opportunities to bring integrated, interdisciplinary and participatory solutions to challenges affecting RS systems.

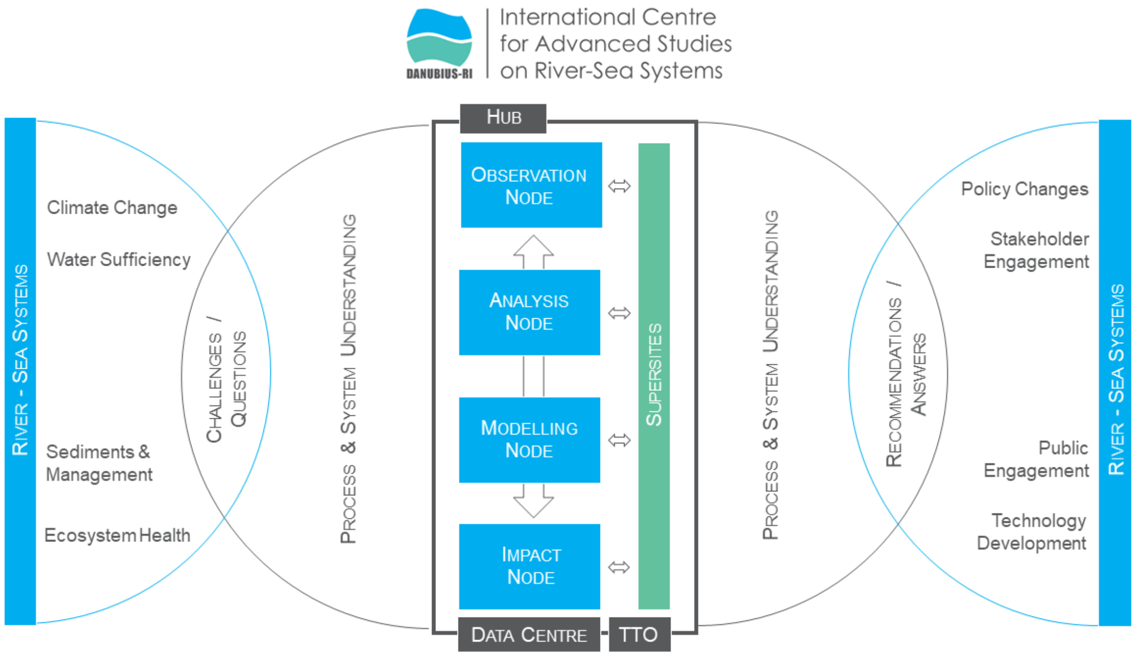

Figure 5 The implementation strategy illustrates how we aim to achieve our mission and how we aim to address our research priorities. Firstly, this requires a mission-oriented, integrated, interdisciplinary and participatory approach. Secondly, this requires several components, such as a Hub, various Nodes and Supersites, a Data Centre and a TTO, as well as strong cooperation between them. Thirdly, this requires common procedures as well as other services, which will be provided by DANUBIUS-RI to better understand, characterise and manage RS systems.

3.1 Role of Components & their Interactions

3.1.1 Hub

Manuela Sidoroff (INSB), Franck Brottier (EUROP), Adrian Stanica & Michael Schultz (GEM)

The DANUBIUS-RI Hub, located in the Danube Delta, has several roles: statutory seat of the ERIC, Headquarters of the RI, Hosting Institution for the Danube Delta Supersite, Accredited Service Provider for the Observation and Analysis Nodes, and major centre of eutrophication research. As the ERIC statutory seat and RI Headquarters (HQ), it will be the base for governance, management and administration housing the Director General and other Directors and their management and administration teams.

The primary responsibility of the HQ is to deliver effective management and coordination of the entire DANUBIUS-RI, whilst also promoting its activities and growing its outreach and development throughout Europe and internationally. Administratively, the HQ will perform the necessary central services to ensure the smooth running of the RI and its component parts (Hub, Nodes, Supersites, TTO and Data Centre), including: finance, personnel, business and communications. The HQ will coordinate and manage the overall activities of the RI, including the primary communications with the external RIs and the stakeholders. It will facilitate the communications between component parts of the RI. The management and decision structures will follow the rules of the ERIC in relation to organization and operation activities.

The Hub will contain the administrative buildings of DANUBIUS-RI, office space for DANUBIUS-RI's managers, committee members and scientists (including visitors), meeting/lecture rooms, conference halls, interactive museum and a library. As the Hosting Institution for the Danube Delta Supersite, the Hub will be the gateway to Europe's largest protected coastal wetland, facilitating the access to the Lower Danube, Danube Delta and Black Sea. The Hub will contain the Danube Delta Supersite and local ASPs, IT Centre, with data storage facilities and a direct link to the main Data Centre. It will have storage facilities for non-digital data, such as biological, sedimentological and core samples. It will host laboratories that will be open to the Danube Delta Supersite, and to other scientific requests from elsewhere. It will also host specialized areas (workshops) and testing pools for specific scientific equipment for biological, ecological, geoscientific and hydraulic research. It will provide facilities and services as an Accredited Service Provider for the Observation and Analysis Nodes.

3.1.2 Nodes

Observation Node

Andrew Tyler, Peter Hunter, Evangelos Spyrakos, Armando Marino, Adriana Constantinescu (USTIR), Victor Martinez Vicente, Steve Groom (PML)

The Observation Node will facilitate the provision of a continuum of observations, connecting catchments to coastal environments by exploiting sensors, including fully autonomous systems, deployed in-situ, on drones and satellites. It is envisaged that this will encompass the development of sensor hardware, data processing algorithms, and more sophisticated machine learning methodologies, to deliver estimates of physical, chemical, toxicological and ecological parameters. These data will contribute to understanding change in RS systems and to finding best solutions for social and economic problems worldwide. The resulting data will deliver new insights into catchment connectivity and downstream impacts, facilitating deeper understanding and cooperation across disciplinary and geopolitical boundaries. The Observation Node will provide capability for processing newly acquired satellite data in near real-time alongside on-demand processing of archived satellite data which, when coupled with available in-situ data, will enable changes in RS systems to be observed at spatial and temporal scales that would otherwise be unachievable.

The state-of-the-art for the Observation Node is a complementary set of in-situ monitoring stations, buoys and floats that provide complementary real-time data on in-water optically active biogeochemical constituents (phytoplankton chlorophyll, suspended particulate matter, coloured dissolved organic matter), key physical properties (turbidity, transparency, light attenuation, temperature), water-leaving radiances and reflectances, and atmospheric composition. Additionally, real-time data on wind speed and direction, sea surface state (wave height and frequency) and water depth, that complement the exploitation of Synthetic Aperture Radar data, will be provided for monitoring short-term changes in hydrodynamics and longer-term change in morphodynamics. This will support the calibration and validation of satellite and drone observations produced in near real-time for the Supersites. Such data will be complemented by more specialised measures of the bio-geo-optical properties (inherent optical properties) of coastal, transitionary and inland waters to support underwater radiative transfer studies and development and testing of improved algorithms for processing of earth observation (EO) data. The growth in EO capability through the rapid increase in satellite missions with complementary capabilities (thermal, optical and radar) provide the opportunity for new and synergistic approaches to the observation of environmental change in aquatic systems including, for example, the detection of microplastics.

High frequency observations will provide the evidence base needed to identify not only the nature, frequency and magnitude of extreme events including flooding, drought, phytoplankton blooms, large-scale erosion and storm events but also the changes in the recurrence, inter-annual seasonality and phenology of these events and whether this is changing systematically in relation to drivers of environmental change. Where required, this may also include operational near real-time (NRT) observations to inform timely management responses. Such NRT observations can potentially be provided through the European Copernicus Emergency Services as part of the major Copernicus Programme. Relevant sensors include geostationary satellites that can provide frequent observations, such as every 15 minutes in the case of Meteosat-SEVIRI; in the future, high-altitude platforms or constellations of nanosatellites will enable similar high-temporal frequency observations and higher spatial resolutions.

The effect of extreme events on coastal areas will be monitored using ground-based LiDAR and satellite-based Synthetic Aperture Radar (SAR) and optical data in order to identify displacements of the shoreline and wider impacts. This work will include the monitoring of coastal erosion and the degradation of coastal ecosystems (e.g. marshes, lagoons, deltas) due to anthropogenic effects (e.g. land cover change, hydromorphological alterations and pressures, pollution, etc.). A suite of change detection algorithms will be developed and validated using ground, drone and satellite data.

Data will be delivered on eutrophication and hypoxia in aquatic environments, from the river basins to the coastal zone (e.g. Tyler et al., 2016). Measuring the concentration of phytoplankton chlorophyll-a across the RS continuum using well-validated, state-of-the-art algorithms for the processing of EO data, will allow intra- and inter-annual variations in phytoplankton abundance to be observed. This is an indication of changes in nutrient status resulting from processes such as oligotrophication and eutrophication and the overall trophic state of aquatic ecosystems. These observations will be supplemented by measurements of nutrients from networks of in-situ optical sensors positioned across the water continuum. The state-of-the-art here is the determination of the abundance of cyanobacteria from phycobiliprotein pigment concentrations, detection of harmful algae blooms and phytoplankton size classes. These observations, in conjunction with data on the bulk chlorophyll-a concentration, will provide information on the trophic state of ecosystems and will facilitate improved understanding of nutrient inputs across the interface between terrestrial and aquatic systems and the downstream impacts on the biological productivity of receiving waters. This also includes improved detection and monitoring of shifts in phytoplankton species composition to less desirable toxigenic species (e.g. blooms of cyanobacteria, red tide dinoflagellates and *Pseudo-nitzschia*) that may, for example, impact on the aquaculture industry. In addition, the integration of EO-derived data on chlorophyll-a, temperature and light availability will enable changes in primary production to be observed facilitating new and improved approaches to the study of carbon sequestration in inland, transitional and coastal waters and the quantification of their role in the global carbon cycle and climate regulation. Information on primary production along with space-based observations on physical properties of coastal waters including temperature, salinity and hydrodynamic structure (e.g., eddies, fronts) will also support improved study of deoxygenation processes in coastal waters and interactions with climate forcing.

The use of EO data, coupled with parameters measured in-situ (suspended particulate matter, chlorophyll-a, turbidity) will contribute towards mapping and describing the evolution of sediment fluxes in RS systems. Satellite-derived data is proven to be an efficient tool in mapping river plumes in in coastal zones as they are the main conveyors of pollutants, plastics, and all other associated particles, to ocean basins. This has immediate application to the assessment of bathing water quality and ecosystem health in coastal areas. Plastic pollution is now recognised as an enormous threat to marine life and ecosystems. Microplastic fragments can be ingested by marine animals and fish and could be transferred via food chain to humans; the fragments can leach chemical components into surrounding seawater and release sorbed pollutants. Researchers at the University of Stirling have recently shown that, as well as crude oil, microplastic affects the sea surface microlayer (SSM). This is by the production of films and slicks that are the by-product of microbes colonising microplastic. This work will consider a combination of optical and radar data aimed at identifying: a) chemicals constituting the SSM slick; and b) wave dampening effects due to the presence of surface films. Through a collaboration with the European Space Agency, scientists at the Plymouth Marine Laboratory are able to define the specifications for optical detection of microplastics and macroplastics on shore and at sea. Experimental work at PML on hyperspectral optical data showed the potential for plastic detection using a combination of bands in the near infrared part of the spectra, from different aerial platforms (including manned and unmanned aircraft) as well as from satellite.

Methods and algorithms are also being developed to monitor and quantify coastal erosion and map coastal habitats (e.g. erosion and accretion of salt marshes and mapping of different types of vegetation), from both radar and optical sensors. The state-of-the-art is the determination of sediment quantity from EO data. Further research is required to: (i) estimate sediment quality (size fractions) from EO data; and (ii) couple EO data (satellite and in-situ) with hydrodynamic modelling (Modelling Node) to build a complete three-dimensional view of the transport and fate of sediment in this dynamic interaction zone.

The provision of near real-time EO data by the Observation Node will be crucial to understanding the status of RS systems and scale and impact of changes occurring there. The activities of the

Observation Node will be closely linked to those of the other Nodes, the Hub and the Supersites. Specifically, it will:

- Develop the capacity to acquire in-situ data within the Supersites that will support the EO calibration and validation (cal/val) activities. It is anticipated that joint research and training will be undertaken to facilitate the development and operation of these cal/val facilities;
- Ensure that data are collected in accordance with the standards and protocols defined by the DANUBIUS Commons in collaboration with the Nodes and Hub and across all Supersites;
- Contribute to the development of scientific direction through interactions between the Nodes;
- Provide a synoptic overview of the Supersites from EO images collected in near real-time. This will provide insight for the Modelling and Analysis Nodes into catchment scale drivers during flood events;
- Provide a time-series of archived satellite imagery to the Modelling Node for effective model calibration and validation;
- Distribute satellite imagery in collaboration with the Impact Node to facilitate informed decision making by RI end-users.

Analysis Node

Ole Rössler, Marie Maßmig, Katharina Schütze, Lars Düster (BAFG)

The Analysis Node has been developed under the coordination of the German Federal Institute of Hydrology. The overall role of the Node is to ensure consistency in analytical techniques requiring analytical rigour and quality control to enable an effective comparison between different users of DANUBIUS-RI. The Analysis Node provides scientific expertise and technical know-how on methods, instrumentation, and quality assurance (QA). It supports the development and implementation of laboratory procedures and *in-situ* determination of environmental parameters, relevant for describing status and processes of RS systems. The Analysis Node is concerned with data directly obtained in the RS system, apart from remotely sensed observations. It will be configured to provide a methodological point of contact for field- and laboratory measurements related to hydrology, geohydromorphology, chemistry, biology, ecotoxicology, and hygiene. The Analysis Node will provide the following services for the DANUBIUS-RI community:

1) Document DANUBIUS-RI's analytical methodologies, protocols, and appropriate QA procedures

2) Assist the Quality Assurance Panel (QAP) of DANUBIUS-RI in controlling and surveying of the DANUBIUS Commons in its field of expertise;
3) Develop DANUBIUS Commons in its field of expertise together with the other components of DANUBIUS-RI;
4) Initiate and promote analytical-methodological developments;
5) Advise on analytical-methodological questions and provide education and training
6) Conduct research and developments in its field of expertise and contribute to the research agenda of DANUBIUS-RI.

In close collaboration with the other components of DANUBIUS-RI the Analysis Node contributes substantially to the coherence of data and services of DANUBIUS-RI. The Analysis Node and the Observation Node are complementary in supporting scientists to gather and interpret data of the natural system, both using their specific means. The Analysis Node and Observation Node will cooperate in supporting the selection of sampling locations and spatio-temporal resolution of records by remotely sensed parameter distributions and site-specific conditions. In turn, field- and laboratory analyses, led by the Analysis Node, will support the high-quality calibration and verification of remote sensing data. The quality of data will – where DANUBIUS Commons exist - be ensured e.g. by inter-lab cross validation or ring tests coordinated by the Analysis Node. The multidisciplinary, multi-scale set of empirical data in combination with harmonized historical records serves as the basis for the calibration and validation of numerical models, which are provided by the Modelling Node. In turn, its model simulations cover spatial and temporal gaps of *in-situ* and *in-vitro* analyses. To comply with societal problems and research needs distilled under the guidance of the Impact Node, the Analysis Node will develop new methodological solutions for environmental challenges. The Analysis Node will, in its field of expertise, actively contribute to overall strategies for data handling and real-time provision of data to facilitate the communication and the data exchange with the other components and users of DANUBIUS-RI. For this, the Node requires comprehensive services provided by the Data Centre and the TTO. The Supersites will serve as living laboratories in which defined sampling strategies, methods, and analyses can be conducted.

The Analysis Node will make available its conceptual and methodological know-how, will provide best practice advices and standards together with training and education opportunities for all users of the RI. In specific, DANUBIUS-RI field- and laboratory measurement techniques and standards will be taught. This education program is explicitly meant as training centre for researchers, students and representatives of authorities. All users of the Analysis Node will benefit from its scientific and methodological work, the scientific expertise of the researchers and the gained practical experience with methods, devices and instruments.

The DANUBIUS Commons will enable the harmonized collection of parameters from the entire RS system. The Analysis Node will give support to the best practice advice and standards for field and laboratory measurements in hydrology, geohydromorphology, chemistry, biology, ecotoxicology and hygiene. The correct application of DANUBIUS Commons and their adaptation and development according to the needs is controlled and surveyed by the QAP supported by the Analysis Node.

In summary, the close cooperation between the Analysis Node and all other DANUBIUS-RI Nodes and Supersites will enable an interdisciplinary, international and harmonized approach to address relevant research challenges of RS systems. Thereby, facing the continuous progress in state-of-the-art methodologies may be a challenge and an advantage at the same time.

The Analysis Node will contribute to the implementation and continuous development of the SIA by:

- Providing knowledge, methods, analytical skills and practical support for implementation of (beyond)-state-of-the-art procedures for advice on comprehensive measurements across different spatial and temporal scales covering hydrology, water quality, transport of suspended matter, habitats, biology and ecotoxicological effects.
- Ensuring harmonized measurements by provision of sophisticated analytical methods, protocols and highly innovative methodologies, supported by other DANUBIUS-RI components. This regards recent and future characteristics and processes of RS systems, namely (1) quantitative aspects of the water cycle, (2) qualitative aspects of the water cycle, (3) the channel/floodplain morphology and sediment dynamics, (4) the biotic status, function and dynamics, (5) risk aspects of environmental contaminants and (6) the combined effects on ecosystems.
- Identifying and prioritizing research needs in fields of analysis and developing new methodologies, analysis procedures, sampling strategies, measurement techniques to identify and quantify new parameters not been recognized so far but crucial for an improved understanding of the system, e.g. emerging pollutants.
- Developing the quality standards of the DANUBIUS-RI parameters in its field of expertise occurring from source to sea.

The Analysis Node will contribute to DANUBIUS-RI’s overall impact:

- By its scientific, methodological and practical work.
- Through an education and training program that is meant as training centre for DANUBIUS-RI users.

Modelling Node

Georg Umgießer, Francesca de Pascalis, Debora Bellafiore (ISMAR)

Modelling, in its general sense, deals with how ‘reality’ can be represented using simplified concepts, relationships, structures, possibly focusing on particular aspects connected to environmental phenomena. Different kinds of models (conceptual, theoretical, statistical, deterministic and many more) can be developed to represent processes, feedbacks and interactions. Usually models are used jointly in order to achieve a deep understanding of systems, identifying associations and causality and to quantify potential impacts, determine the effects of human interventions and investigate possible scenarios.

In RS systems, water is the key element, flowing from the drainage basin through the soil and in the main river courses down to the sea. This links different issues and components: involving sediments and habitats as well as ecosystem functioning, human activities and human health. Therefore, understanding and correctly modelling water dynamics, across freshwater and marine environments, and the many interactions with sediment, nutrients, pollutants, ecosystems and human activities are crucial to assessing impacts, not least in climate change scenarios.

The aim of the Modelling Node is to ensure: a) representation of the physical, chemical and ecological status and processes within a RS system and providing common models and tools to achieve this aim; b) modelling expert support for researchers; and c) modelling tools for regional, local studies (e.g. at individual Supersites) and socio-economic evaluations with stakeholders.

In this way, the Modelling Node will contribute to a step change in research on RS systems by providing:

- A common place and opportunity for the research community to synthesise the range of modelling experiences and provide new modelling approaches for RS systems;
- The development of models that fulfil both the need for complexity (full process reproduction) and simplicity (usability);
- Collaboration with computing infrastructures to create synergies with other RIs;
- The possibility to combine, re-use and interchange software components between participating institutes, enhancing the present applicability of models in RS systems;
- A definition of baseline processes that a RS system model must resolve, with tailor made solutions in the studied RS systems.

The current status of environmental modelling is that models are largely developed, either for specific spatial portions of the RS systems (river models, drainage basin models, open sea models), or to address highly specialized and discipline-specific scientific questions (i.e., sediment transport module, ecological module, water quality models). Few examples can be provided where all modelled parts of a RS system interact with each other. Therefore, dealing with singular topics, the modelling community can provide a rich range of state-of-the-art specialized tools, although future research requires interdisciplinarity. The major focus of the Modelling Node will be the development of modelling tools able to reproduce the feedback and interconnections between physical, biogeochemical and ecological processes along the entire RS continuum, helping in connecting the results to the social-economic impacts, and investigating future scenarios.

In order to achieve these challenges, the following steps must be addressed:

- coupling of similar and complementary models in terms of different processes modelled (e.g. hydrodynamics – morphology – sediment transport – nutrient and pollutants fate, ecosystem functioning) to reproduce observed feedbacks and relationships;
- coupling geographical domains to model catchment (rural, urban) – river – marine systems (1D-2D-3D interfaces) and allowing multi-resolution techniques to be scaled up (and down) between global, regional and local models;
- improving data-model interaction: both to integrate into models the huge amount of data produced by new generations of sensors (e.g. assimilation into models of satellite, remote sensing, drones, and model-driven data acquisition) and to use models to help filling the gaps where data are unavailable in order to provide a key step forward in understanding the full picture on RS systems status/processes/impact;
- improving the capability of models to undertake large scale, detailed simulations (with big data, high spatial/temporal resolution), using high-performance computing (HPC) centres, which are particularly useful to assess the implications of climate change and develop interdisciplinary scenarios of environmental change;
- integrating numerical simulations, with serious gaming and decision support systems to stimulate stakeholder involvement in modelling.

Impact Node

Henriëtte Otter & Gerald Jan Ellen (DLT)

Within DANUBIUS-RI the Impact Node is being developed to encourage and facilitate the path from research to create impact and value for society. The Impact Node will develop concepts, methods and technological innovations that have the potential to increase the impact. The development of these concepts will be set up as scientific research to make sure that the concepts are scientifically validated. The same goes for the effectiveness of the application of the concepts. We will use an action based research approach, thus also bringing science and practice together.

The Impact Node will work on facilitation through application. The Impact Node will facilitate the connection of science, research and development with (the rest of) society by applying the solutions that were developed. An important challenge is to develop effective methods/technologies to enhance impact that can be used in different cultural and institutional settings and that address a diversity of stakeholders/citizens.

The Impact Node, led by Deltares, will facilitate:

i. scientific knowledge development on the interface between natural and social sciences;
ii. the development of methodologies and tools that will help decision making in highly complex dynamic RS systems;
iii. the transfer of scientific output and practical tools derived from DANUBIUS-RI to those engaged in the sustainable management and use of RS systems (to solve problems and to strengthen business in this area).

The Impact Node will facilitate **fundamental and applied research** executed along three research pillars:

Interdisciplinarity. Along this pillar, research focusses on the facilitation of natural and social scientific disciplines to work together on knowledge development and generating solutions for societal challenges related to the management and use of highly complex and dynamic RS systems. It can be characterised as facilitating the 'learning together, to increase impact together' and leaving each other's comfort zones (breaking the silos) as 'doing what we did, gets us what we got'. Such an approach is a prerequisite for achieving step changes in RS system science and innovation.

Interfacing. Along this pillar, boundary spanning related research activities will be facilitated, focussing on boundaries between science disciplines to facilitate 'learning together' and on boundaries between science and the rest of the world (policy, decision-making, management, business, education, public). This type of research will a.o. result in validated and standardised impact assessment parameters (DANUBIUS Commons) that can be included in the scope of activities of the other Nodes and may thus become regular impact parameters to be monitored or analyzed at Supersites.

Innovations. Along this pillar, research activities are targeted at achieving innovations to provide operational perspective, practical solutions, methods and tools for policy makers, managers and entrepreneurs.

Naturally, the Impact Node will also play an important role in addressing the research areas that have been identified in the SIA, i.e. climate change and extreme events, water safety, sediments and their management, and ecosystem health. Here also, the focus of the Impact Node is to address the impact of research activities that are carried out within the identified research areas.

The Impact Node will **provide services** to facilitate the achievement of Impact. Services provided include:

- Excellent IDR
    - This includes research on topics that are related to the development, measuring and monitoring of societal impact including interdisciplinarity, interfacing and innovations. This is also related to the subjects mentioned on monitoring in chapter 5 on the monitoring of impact of research projects and RIs more specifically.
- Impact assessments and design
    - This includes the assessment of the potential societal impact (before) and evaluations of impact generated (after). This will be done by means of different research methods, such as focus groups, surveys and
    - Supporting the design of stakeholder participation processes and interdisciplinary learning processes to optimise their impact. For this specific part, we want to develop a decision theatre that could be used to gather information and to be able to present/discuss this with stakeholders. Furthermore, the concept of citizen science – especially in close relation to decision-making and knowledge management – will be an important focal point.
    - Transfer of questions from society (policy, industry, citizens) into scientific research questions and transfer of scientific findings of DANUBIUS-RI into practical, operational perspective.
- Impact guidelines
    - This includes guidelines and handbooks for achieving societal impact. Here we foresee an important role for learning/experiencing and propose to apply serious gaming or Massive Open Online Courses (MOOCs) as methods.
- Impact training/capacity building
    - This includes training of all types of professional in how to achieve societal impact in their work. This will be in line with the approach mentioned above concerning the impact guidelines

3.1.3 Supersites

Jana Friedrich, Sina Bold & Peter Heininger (HZG)

Role of Supersites

DANUBIUS-RI Supersites cover representative and defined areas of land-water interface to study the functioning of RS systems, to assess impacts and risks from various human activities, to diagnose cause-effect relationships, and to develop and test potential measures to address common challenges in RS systems across the DANUBIUS-RI research priorities described in Chapter 2. As such, Supersites represent IDR platforms of the distributed RI. Supersites will be test beds of the DANUBIUS-RI scientifically excellent ideas; areas where the developed concepts will be refined and verified. The Supersites will provide natural laboratories for observation, analysis, modelling, R&I at locations of high scientific importance and opportunity, covering the RS continuum from river source to transitional waters and coastal seas. Ranging from the low to heavily modified, the Supersites are, and will be, selected to provide contrasting systems across environmental, social and economic gradients that have been impacted, to varying degrees either directly or indirectly, by industrialisation, urbanisation, population expansion, land use change and farming. In this way, they will help to identify, model and define system states and conditions for naturally and anthropogenic triggered transitions in the physical, biogeochemical and biological states. They will provide excellent opportunities to undertake social and economic investigations in contrasting settings. Supersites do not represent a local network of institutions, nor a research site only for DANUBIUS-RI components, and are not the only locations where DANUBIUS-RI will support research.

Supersite Tasks

Supersites provide ‘gateways’, i.e. they facilitate access for research in specific parts of RS systems: ‘from the mountains to the sea’. This includes helping to acquire any necessary permits/ authorization for visiting the sampling sites, taking samples and doing analyses, experiments and modelling. The Supersites provide opportunities to store physical samples locally and/or to prepare such samples and send them to a central storage facility at the Hub or to a specialized laboratory, e.g. of the Analysis Node. Access will be granted to international researchers, students from inside and outside DANUBIUS-ERIC member countries, and to professionals; to carry out research needs-driven studies, to test, validate and apply newly developed methods and tools in collaboration with the Nodes, in a real-world setting, to teach best-practise, to do research oriented to problem-solving, and to transfer knowledge and experience. Another task of Supersites is the integration and interpretation of existing and often fragmented data of its region. The Supersites will also generate data and knowledge about process- and system understanding to derive recommendations for solving common challenges in RS systems. Supersites will not duplicate existing monitoring efforts by e.g. river or sea commissions. On the contrary, DANUBIUS-RI aims at working complementarily and collaboratively, by building on existing infrastructure and monitoring efforts, where offered, and making use of existing data (e.g. from monitoring), and make them available via the DANIBIUS data portal. The involvement of end users and other stakeholders will be crucial for the success of the Supersites. Access to Supersites and their services are regulated by the ERIC Statutes and Internal Rules. The "Access Policy Reference Document" (D4.4) provides a complete description of the DANUBIUS-RI access policy.

Supersite Governance
Each Supersite will be led by a single Hosting Institution with a Supersite Manager, who is responsible for the implementation, maintenance and user support at local level in accessing the Supersite. The Hosting Institution, which will have research activities at the Supersite, will be responsible for coordinating activities: providing field, laboratory and computing facilities, facilitating field access, and capturing data. Each Supersite will form a local consortium consisting of Hosting Institution, DANUBIUS-RI staff and the local community of collaborators and users. A local consortium will be established by training staff to understand the principles of the RI and the DANUBIUS Commons, by connecting to the local community of users to enhance cooperation, and by connection with the rest of the RI. Each Supersite is on equal terms, rights and responsibilities with the other Supersites.

When a new Supersite is created, other Supersite teams will help by sharing their experience, best practice, and advising on how to overcome practical and technical problems. Other Supersites will also assist the connection of a new Supersite to the other Supersites and the other components of the RI. The Supersites will complement each other’s expertise; i.e., not every Supersite Hosting Institution has to have expertise in every science discipline relevant for DANUBIUS-RI. The work in the Supersites will take advantage of the expertise provided by the Nodes and the Hub. The Supersites will benefit from common methodologies and comparable data across the RI thanks to the DANUBIUS Commons, which are crucial pre-requisites for successful operation of the RI. A detailed description of the Supersites and their interaction with the Hub, Data Centre and Nodes is given in 3.1.6 – Interactions between Components, and in D5.10 “Final Report on the Role and Operation of Supersites”[6].

Additional Supersites may be included in DANUBIUS-RI in the future according to the following criteria:

- demonstration of scientific importance and relevance to DANUBIUS-RI;

[6] http://danubius-pp.eu/www/wp-content/uploads/2018/06/5.10.-Final-report-on-the-role-and-operation-of-Supersites.-Rules-for-selection-and-development-of-Supersite-Hosting-Institutions-and-associated-facilities.pdf

- proven or potential scientific and technological capabilities of Hosting Institution (including development of local consortium and availability of suitable staff);
- long term financial sustainability for the Supersite to maintain itself as part of DANUBIUS-RI, as demonstrated by a statement of political support / financial commitment from government or funding body, which will ensure the running costs of the facilities over the years.

Characteristics of Supersites

Each Supersite represents a RS system, or part of a RS system, where unique scientifically relevant aspects can be studied. Each covers a spatially determined area, but not with pre-defined size; scientific criteria define the extent. Supersites may cover an entire (small) RS system, like Nestos, or in a large RS system there may be several Supersites, like in the Danube river basin, where currently three are located (Figure 6).

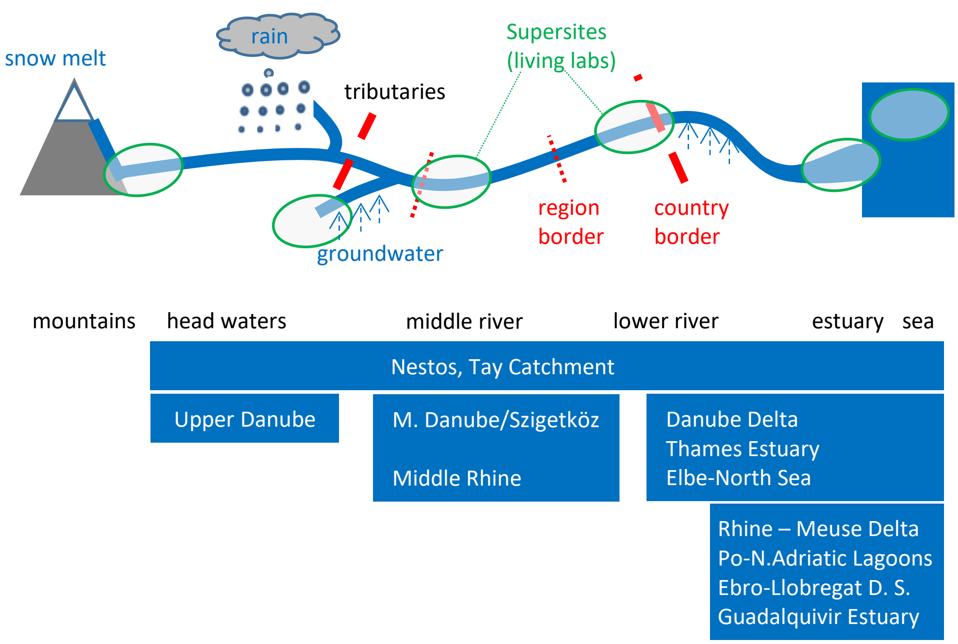

Figure 6 Positions of the current DANUBIUS-RI Supersites within the RS continuum.

The Supersites are chosen to provide contrasting examples of RS systems with respect to climatic and geographical setting, tidal influence, and across gradients of human impact, ranging from low to heavily altered by humans. Currently, DANUBIUS-RI hosts 12 Supersites, which cover some of the major river catchments discharging into European Seas (
Figure *7*). An overview of the Supersites (current drivers and pressures, resulting state changes and their impact on ecosystems and human well-being) and responses taken or required to either mitigate the pressures or manage the drivers is given in Annex II.

Figure 7 RS systems and their catchments (hatched) under investigation in DANUBIUS-RI.

Danube - Black Sea System:

- Upper Danube (Wasserer Cluster Lunz, Austria)
- Middle Danube – Szigetköz (István-Széchenyi-University, Hungary)
- Danube Delta (GeoEcoMar, Romania)

River – Mediterranean Sea Systems:

- Po Delta & North Adriatic Lagoons (ISMAR, Italy)
- Nestos (Hellenic Centre for Marine Research, Greece)
- Ebro-Llobregat Deltaic System (Universitat Politècnica de Catalunya, Spain)

Guadalquivir - Atlantic Ocean System:

- Guadalquivir Estuary (Port Authority of Seville, Spain)

River – North Sea Systems:

- Elbe-North Sea (Helmholtz-Zentrum Geesthacht, Institute of Coastal Research, Germany)
- Middle Rhine (Federal waterways Engineering and Research Institute, Germany)

- Rhine-Meuse Delta (host to be decided, Netherlands)
- Thames Estuary (Centre for Ecology and Hydrology, United Kingdom)
- Tay Catchment (University of Stirling, United Kingdom)

Rivers that have Supersites and discharge into the North Sea are the Elbe, the Rhine, the Thames and the Tay. All are situated in the temperate oceanic climate zone. Their river mouths and coastal areas are influenced by meso- to macrotidal forcing. While the areas of the Elbe-North Sea Supersite, the Rhine-Meuse Delta Supersite and the Thames Estuary Supersite are considered as heavily modified by human activities, the Tay Catchment Supersite is considered low to medium modified.

In the Elbe-North Sea Supersite, the biggest pressures are hydromorphological adjustments for shipping like fairway deepening and dredging over centuries, dyke construction for flood defence, and eutrophication due to organic matter and nutrient input from upstream. The Rhine-Meuse Delta is heavily impacted by hydromorphological adjustments like canalisation, extensive drainage systems, polders, the embankment of rivers, and coastal protection. The system is regarded as "Anthropocene Delta SES" (Renaud et al., 2014), (Renaud et al., 2013). The Thames Estuary faces pressures resulting from increasing urbanization, agriculture and climate change, resulting in service water shortage despite short flood events, surface and groundwater pollution with nitrogen, cyanobacteria blooms and wastewater treatment problems. In the Tay Catchment Supersite pressures are arising from extreme events, land use changes and industry, resulting in flooding and point and non-point source pollution. It is an important site for land-ocean transfer of organic matter and the sea a place of carbon sequestration, as the river originates in the Scottish Highlands.

Rivers that have Supersites and discharge into the Southern European Seas (Black Sea, Adriatic Sea and Mediterranean Sea) are the Danube, the Po, the Nestos, the Ebro and the Llobregat. They are situated in temperate continental to warm continental and Mediterranean climate zones, the receiving seas are characterised by microtidal forcing. The Supersite in the upper Danube is in a lowly to medium modified area, while the Szigetköz Supersite in the middle Danube represents a heavily modified area. The Danube Delta itself represents a lowly modified system, compared to other European Deltas, while the receiving sea, the north-western Black Sea shelf had been heavily impacted by the Danube in the 1970 to 1990s, leading to hypoxia and ecosystem collapse. The Nestos River, the lower Po and associated lagoons, and Ebro-Llobregat represent in different ways heavily modified systems:

The Supersite area of the upper Danube is affected by pressures from climate change, hydropower generation and changing land use, which are leading flood events, damming and river fragmentation and diffuse nutrient inputs. The Szigetköz Supersite is situated in the centre of an inland delta harbouring one of Europe's largest subsurface aquifers. Hydropower generation has led to 80% water diversion from the original riverbeds into an artificial channel, and floodplain disconnection. The Danube Delta , being relatively young (ca 2000 years) grew to its current form due to deforestation in central Europe (Maselli and Trincardi, 2013) and is the second largest Delta in Europe. According to (Renaud et al., 2014) the Danube Delta is on a positive trajectory from a Holocene Delta SES to a Holocene modified Delta SES, where the delta provides valuable ecosystem services for humans due to human intervention while sustaining rich biodiversity and valuable ecosystems. However, upstream damming for hydropower generation (Iron Gates I & II reservoirs) and resulting river fragmentation have led to a negative sediment balance, causing delta erosion, subsidence and changing nutrient ratios in the north-western Black Sea. This shallow and stratified shelf is very sensitive to climate change, compounding seasonal bottom-water hypoxia (Friedrich et al., 2014).

The Nestos is a relative small river, and heavily modified by a sequence of reservoir lakes, which are suffering from anoxia, while the remaining river suffers from rigid flow regulation and hydropeaking. The negative effects in the coastal zone are changes in nutrient ratios and food chain, insufficient flooding of coastal bays and coastal (delta) erosion. The Po Delta and North Adriatic Lagoons Supersite is located in an area used for intensive agriculture, industry, hydropower generation, but harbours a unique urban historical location in the Venice lagoon. Pressures and impacts are arising from frequent denudations due to sea-born floods, land subsidence, reclamation of salt marshes, erosion, insufficient wastewater treatment, nutrient input and pollution, and decline in service water quality and ultra-large cruise vessels entering the lagoon. The Ebro-Llobregat Deltaic System is heavily modified by hydromorphological adjustments due to agriculture, urbanisation and tourism, and affected by extreme event like storm surges and floods. 70% of the delta area has been converted into agricultural land and 97% of the Ebro basin is flow regulated.

The Guadalquivir Estuary is linked to the Atlantic Ocean. The Guadalquivir is situated in warm Mediterranean climate. The estuary is affected by mesotidal forcing. The area of the Supersite is medium to heavily modified by humans. The Guadalquivir has been used for shipping for centuries like the lower Elbe River, resulting in pressures, including from the port of Seville, leading to a hyperturbid estuary. Agriculture is leading to desiccation of marshland while horticulture is introducing nutrients leading to eutrophication. To save parts of the estuary, Ramsar Sites were established in the estuary to protect the river mouth.

3.1.4 Data Centre

Octavian Rusu & Paul Gasner (ROEDU), Mihaela Paun (INSB)

The Data Centre is the connection of DANUBIUS-RI with the major e-infrastructure initiatives in Europe and globally and will be the digital connection with other major RIs. It is responsible for data availability and processing. The data portal will be the gateway to DANUBIUS-RI, covering digital data from: remote sensing; automatic stations in real time and periodic downloading; cruises; computer models; and the results of other physical, sedimentological, chemical, and biological and ecotoxicological analyses. The database will also give access to the metadata base concerning the non-digital data existing in various RI components. The Data Centre of DANUBIUS-RI will be the central point of the ICT infrastructure providing single point of access for the users to all services. The Data Centre has to provide a set of services to the research and academic community: collect all gathered data from Supersites and Nodes involved or associated to the RI, store the primary data and aggregate the data by different criteria from local and distributed storages, provide the necessary computing power and storage space for modelling the data or digital simulations, store and classify the results of modelling with the associated metadata, provide search functionalities to access the data.

Data management plan and policy for DANUBIUS-RI will follow the FAIR (findable, accessible, interoperable and re-usable) principles and will focus on long-time preservation, high availability and security of stored information. One of the main concerns of the Data Centre has to be operational continuity, so it is necessary to build a reliable digital infrastructure for IT operations. Another important concern is security; the Data Centre has to implement the necessary environment to minimize the probability of security breaches and data loss.

From the DANUBIUS-RI user community perspective, the Data Centre services will be accessible through the Data Portal, the access being granted using credentials provided by an authentication system like EduGAIN. According to the user's credentials and the policy of the DANUBIUS-RI e-Infrastructure, the access is granted to specific areas of the Data Centre like data repositories, storage space and/or computing/HPC facilities. The Data Portal should be built on top of a middleware software to accomplish two functions: integrating all the data and metadata from local and distributed storages, and providing dedicated services to automate the process of collect and check data from the data providers (Nodes, Supersites). Once the data pass the check, they will be uploaded in the main storage system in the Data Centre being accessible for the users. The data transport for data providers will be secured by GÉANT and NRENs communication infrastructures using secured connections between Data Centre and all users. To use the Hub as an offline backup site (highly recommended facility) for the Data Centre a layer 2 link between these components should be installed.

3.1.5 Technology Transfer Office

Jeremy Gault (UCC)

The Technology Transfer Office (TTO) will underpin the implementation of the SIA by ensuring that the contracts between DANUBIUS-RI and external partners fully represent the best interests of DANUBIUS-RI. As such its primary, though not only, role will be to leverage the Intellectual Property Rights (IPR) and the infrastructural resources to successfully engage a range of end-users and stakeholders. It aims to identify and increase the number of potential developments and innovations and ensure that they are effectively exploited for the advantage of individual innovators, their partners and the RI as a whole and thus maximise the RI's overall impact.

A distributed model has been proposed for the TTO across jurisdictions and ability to satisfy the IP/IPR requirements, policies and legislation of the member countries. This will maintain a TTO Office in Ireland, to act as coordinator and secretariat, with representatives for technology transfer in each of the member countries who will liaise with national government, industry and research institutions and report back to a Co-ordination Committee

This Committee would draw on Expert IPR services as required, would report to the Business Development Director and be responsible for ensuring that:

1. all potential opportunities created by DANUBIUS-RI through the SIA are identified and fully realised;
2. national requirements in terms of government policy, industry needs and research priorities are considered by the RI and used to inform subsequent iterations of the SIA.

Given the above, it is envisaged the TTO would work closely with the national technology transfer representatives to:

- support researchers in identifying potential business ideas and market and license any commercially viable technologies;
- manage DANUBIUS-RI's IP including evaluation of commercial potential of any inventions;
- inform DANUBIUS-RI researchers on the invention disclosure, the technology transfer process and the protection of inventions through the filing of patent applications;
- assist with the drawing up of confidentiality agreements;
- provide support for start-up or spin-out companies.

The distributed model will satisfy national expectations with respect to Technology Transfer and IPR. They are still, however, significant challenges to be resolved as DANUBIUS-RI moves towards its operational phase, including the following:

- provision of relevant agreements through the ERIC Statutes of the duties that can be delegated to the TTO and the role of the national technology transfer representatives;
- agreement on a common language in the DANUBIUS-RI ontology for key terms such as IPR;
- identification of the relevant stakeholders and end-users and agreement on how these should be contacted;
- agreement on the final role and scope of responsibilities of the TTO and the mechanism of interaction with the Hub, Nodes and Supersites.

There remains the ongoing and overarching need to balance applied and fundamental research in order to deliver the SIA whilst meeting the requirements of the stakeholders and end-users engaged.

3.1.6 Interactions between Components

Peter Heininger, Jana Friedrich & Sina Bold (HZG)

In essence, DANUBIUS-RI is an assembly of people pursuing the common aim of 'Making RS systems work'. The people who are working together for this shared aim either are domiciled in DANUBIUS-RI's components or are integrated through them. Hence, the cooperation between the components decides finally between success and failure of DANUBIUS-RI. Consequently, the interaction of the components to function as a whole is based on three crucial prerequisites: (1) Strive for common goals, (2) Create and maintain clear structures and governance and (3) Ensure at every stage and in all respects full transparency. To fulfil them, institutional and financial as well as methodological and scientific conditions and the ways to meet them have to be defined. These conditions are laid down in the statutes of the ERIC, and in and in a number of deliverables of the PP project underpinning DANUBIUS-RI's functioning. Furthermore, they are subject of matter of the methodological approach of DANUBIUS-RI to science and innovation (cf. 1.2 – Methodological Approach) and of this SIA as a whole.

Common Goals

Striving for common goals is based on: (i) integrative thinking, i.e. the understanding of RS systems as an entity of abiotic and biotic, social and economic processes, functioning and change across a variety of temporal and local scales (SES); (ii) mission-oriented approach, i.e. facilitating concrete R&I projects, not in isolation, but interlinked within a long-term framework in order to address global challenges; (iii) interdisciplinarity and participation, i.e. the integration of information, data, techniques, tools, concepts, and/or theories from different academic and social actor's perspectives facilitating their close interaction for the benefit of shared aims.

Clear Structures, Governance & Transparency

Creating and maintaining clear structures and governance, and ensuring full transparency at every stage of interaction within DANUBIUS-RI and in the cooperation with partners outside is guaranteed by: (i) the ERIC of DANUBIUS-RI and the statutes regulating issues such as architecture, management, coordination, decision structures, and financial responsibilities; (ii) the Principles that form the framework for the common values of DANUBIUS-RI covering scientific, social and technical issues, such as research integrity, mobility of knowledge, commitment to social mission, interoperability, self-learning from best practices and diversity, transparency to users and stakeholders, common access, commitment to education and training, evaluation and quality control, the commitment for protecting human health and the environment; (iii) the DANUBIUS Commons, based on the Principles, forming the whole of harmonized regulations, methods, procedures and standards for all kinds of scientific and non-scientific activities, to guarantee the integrity, relevance, consistency and elevated quality of DANUBIUS-RI's scientific output (cf. 3.2 – Role of DANUBIUS Commons); (iv) the clear description of the specific roles and functioning of the components within DANUBIUS-RI as a unitary whole, as given in 3.1.1-3.1.5; (v) the transparent programming, monitoring and updating of DANUBIUS-RI's SIA and of the DANUBIUS Commons.

Interactions of Components

The scientific and operational interactions between the components are defined by their specific roles within DANUBIUS-RI as a unitary whole. Case-by-case they are driven by a concrete research topic, when each component will be challenged to put its specific capabilities at the service of *solving a commonly defined problem*. The Hub is responsible for the effective management and coordination (including being the access point) as well as the communication between the components, with other RIs and major stakeholders. Each component as well as DANUBIUS-RI as a whole benefit permanently from the excellent standards, the integrity, functionality, high availability and efficiency of the services provided by the Data Centre. The Supersites are those living laboratories where activities, competences and commitments of all Nodes will primarily be put into action. The capability and functioning of the Nodes, which (1) are key facilitators, spanning observation and analysis across biological, physical, chemical and social sciences, and modelling and (societal) impact, (2) leading relevant standardization of methods and procedures within the DANUBIUS Commons and (3) providing training and capacity building, may depend on the replication of facilities and methodologies within Supersites, where conditions permit and where measurements or observations are required. They will take advantage from the data collected from the Supersites, and at other sites of opportunity, and will benefit from the scientific expertise of the researchers there and the gained practical experience with methods, devices and instruments across the wide spectrum of research sites. The Analysis Node and the Observation Node are complementary in capturing a research topic in terms of physical-chemical and biological data and information. Expertise and methodologies provided by the Impact Node are used to take into account the diversity of scientific and life-world perceptions of problems (e.g. existing in the Supersites), to actively involve stakeholders in the research problem definition and to capture the research topic in its social and economic dimensions. The Modelling Node will rely on the data and information from the Observation, Analysis and Impact Nodes as well as from Supersites and other research sites in delivering high performance numerical and scenario modelling solutions. The Impact Node aims to integrate the advanced knowledge on RS systems with governance and policy-making to improve management and to transfer, with support of the TTO, the DANUBIUS-RI knowledge, products, services and spinoffs to the business sector (Figure 8).

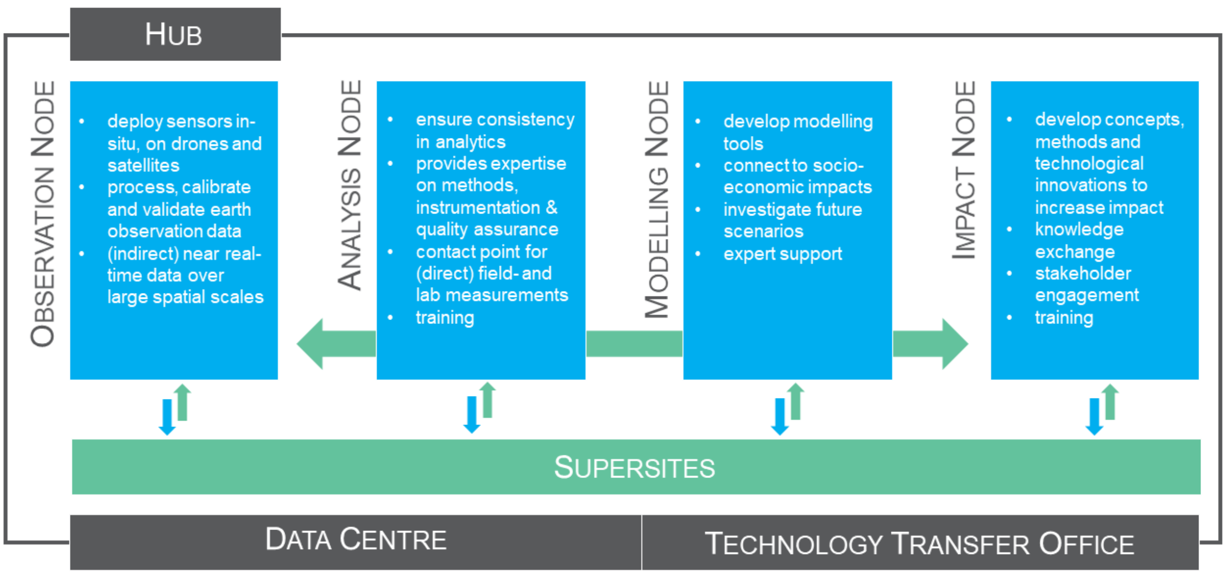

Figure 8 The scientific and operational interactions between the components are defined by their specific roles within DANUBIUS-RI as a unitary whole (green arrows: data, blue arrows: expertise & methods).

3.2 Role of DANUBIUS Commons

Marie Maßmig, Ole Rössler, Katharina Schütze, Lars Düster (BAFG)

Inter-disciplinary R&I that spans freshwater and marine environments across RS systems requires the development and adoption of a common awareness, language, scientific standards, and methodologies. To-date, the lack of harmonised principles and common standards has been a significant impediment to research in these environments and hence a key element of DANUBIUS-RI will be the DANUBIUS Commons: a toolbox to link different disciplinary approaches, standards, languages and methodologies. The DANUBIUS Commons will underpin all the activities of the RI and will help to advance interdisciplinary knowledge and understanding. They will provide the framework to ensure that the outputs of DANUBIUS-RI are compatible, comparable, and exchangeable throughout the RI, and with the user community. In doing so, the DANUBIUS Commons will facilitate IDR and understanding of how RS systems are changing, and enable the development and application of new management and intervention strategies to ensure the sustainable functioning of RS systems that ultimately promote prosperity and security. The DANUBIUS Commons are a set of harmonized regulations, methods, protocols and standards for the activities of the RI. They will guarantee the integrity, consistency and quality of service provision that will enable the RI to achieve the vision as presented in the SIA and work to address the key scientific priorities (Figure 9). The DANUBIUS Commons will provide added value to users of the RI as they are based on internationally accepted standards and will be continually reviewed and revised while established control mechanisms (e.g. ring tests) will ensure comparability between the different facilities of DANUBIUS-RI.

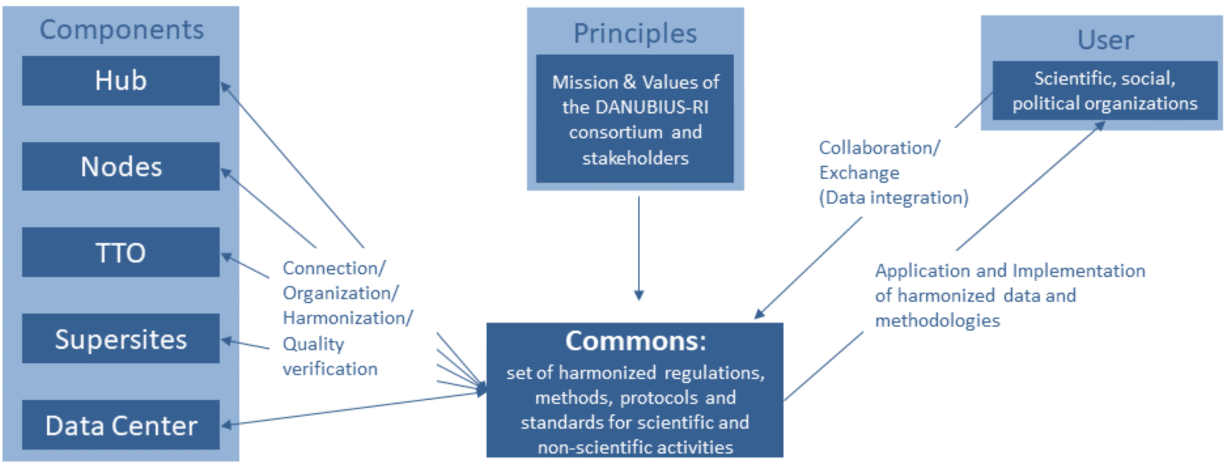

Figure 9 The relationship between the DANUBIUS Commons, the facilities of DANUBIUS-RI, the user community and the overarching Principles of the RI.

Harmonisation of approaches to R&I on RS systems is essential for mutual understanding, and to enable IDR. The DANUBIUS Commons will integrate ideas and approaches from different disciplines, stakeholders and users of DANUBIUS-RI, thus providing a mechanism for enhanced participation and collaboration, and promoting the RI to external users. The development of common approaches to R&I on RS systems in this way addresses a recognised gap in the current RI landscape, and offers significant added value to users of the RI. For example, the ability to compare data from points extending from the catchment headwaters to the coastal sea will only be possible by adopting comparable sampling schemes across river and seas for fresh, brackish and salt water. At the same time, analytical methods need to be adjusted to cope with the increasing salinity. Thus, consistent methods must be adopted and developed in order to be able to measure certain parameters in waters with different salinity.

Implementation of the DANUBIUS Commons will be facilitated by the adoption of appropriate methodological and technological selection criteria for individual Commons (e.g. with respect to accuracy, range, sensitivity, specificity, robustness, capacity, longevity and cost efficiency). This will ensure data quality at the spatial and temporal resolution required by users, with the associated metadata, defined by the Commons, to ensure comparability (of data, knowledge, etc.) throughout DANUBIUS-RI and when communicating with external organizations. The DANUBIUS Commons will also help in developing and implementing standards that are currently “beyond state-of-the-art” in areas where there is an identified research need or gap.

The wider argument for developing the DANUBIUS Commons can be illustrated by the challenges in long-term data sets for methyl mercury species and the given analytical artefacts from certain time periods. Some of the methods used to detect different mercury species in sediments are biased by the creation of analytical artefacts although they may have represented the ‘state-of-the-art’ in the past (e.g., Hellmann et al. 2018). A lasting consistent approach is required on how to process data of this nature, where there are possible questions over the comparability of different methods for statistical and modelling purposes.

It is also important that the datasets maintained by DANUBIUS-RI are developed using harmonised methods to ensure that data accuracy and precision are sufficient for a range of end-user purposes. For example, there may be different definitions of “anoxia” or “oxygen concentrations below the detection limit” depending upon the methodology used to measure dissolved oxygen concentrations. This is problematic when determining, or comparing, oxygen thresholds for anaerobic respiratory pathways such as denitrification. Further problems arise, if any discrepancy in the oxygen sensitivity of a biological process, is not taken into account when these data are used in model development, as it could potentially in severe significant disparities in nitrogen budgets or predictions of carbon turnover. This emphasises the importance of developing the DANUBIUS Commons to ensure consistency of approach, language, and methodology in undertaking environmental research through DANUBIUS-RI.

The motivation for developing the DANUBIUS Commons is to provide practical information to enable IDR on RS systems, to address the current scientific priorities of the RI and encourage collaboration with external “users”, including academic researchers, industry, and society. This will only be possible if the highest possible standards can be ensured throughout DANUBIUS-RI, to encourage wider collaborations between the different user communities, and enable excellent research on RS systems.

3.3 DANUBIUS-RI's Services

Franck Brottier (EUROP)

The DANUBIUS-RI service line-up spans a large range of disciplines, which are all needed to address the major questions and challenges. However, DANUBIUS-RI also reaches beyond the academic and scientific realm to attract companies and charities, with whom DANUBIUS-RI wishes to engage in collaboration, notably for the development of solutions to the RS system issues analysed as part of this SIA. Another major target group for DANUBIUS-RI is composed of local, national and transnational authorities in the field of environment, which are both potential funders and potential beneficiaries of the work and expertise at DANUBIUS-RI. Some services listed below have been developed with consideration for their specific needs. Overall, potential users can be classified in five target groups: Research institution staff, Business & Professionals, Students, Authorities, and Public at large.

Currently, seven categories of services to external users have been developed spanning across disciplines and sites: Digital & Non-Digital Data; Methods, Tools & Expert Support; Study & Measurements; Diagnostic & Impact; Solution Developments; Tests, Audit, Validation & Certification, as well as Training Services. Most services at DANUBIUS-RI are delivered by more than one partner institution, and therefore combine the expertise present in the different research institutions that are taking part in the provision of the service.

The category “**Digital & Non-Digital Data**” encompasses those services that consist in offering in-situ or remote access to scientific resources, data and samples developed or collected by DANUBIUS-RI. Most of those services are e-services, but a few of them require a physical access, such as the mineralogy library or sample and core repositories. This service category also includes the DANUBIUS Commons Encyclopaedia, i.e. the organised set of common norms, methods, standards adopted throughout the RI. All data generated by DANUBIUS-RI and users will be made available to registered users through the DANUBIUS-RI website, portal or client.

Digital data will be made available as an e-service, with data stored at the Data Centre, and with possible duplication at local (i.e. Node, Supersite) level. Samples, seeds and cores will be made available either in-situ or remotely, depending on the user preferences, at the Hub, and in Supersites and Nodes participating in the service.

The category “**Methods, Tools & Expert Support**” includes services that consist in providing access to scientific devices and facilities, specific methodologies developed by DANUBIUS-RI partners, with or without scientific and technical support from DANUBIUS-RI experts to users. Those tools and methods may be related to information treatment (i.e. Data processing tools, Visualisation tools, Numerical modelling codes, Mesocosms, Climate chamber, Hydraulic physical modelling (through HYDRALAB), Geodynamic physical modelling (in collaboration with EPOS), or state-of-the-art, DANUBIUS Commons-compatible scientific methodologies (i.e. RS system condition diagnostic methods, Standard impact guidelines, Development and practical implementation of European directive norms and regulations).

The “**Expert Support**” range of services is conceived as assistance to users in the use of above-mentioned tools and methods, but also digital and non-digital data. This sub-range includes Support in the use and Interpretation of data, Support in DANUBIUS Commons-compliant sensor deployment and calibration, Support in numerical modelling, Support in modelling standardisation and guidelines, Support in impact assessment and design, or Assistance to public authorities in (1) defining and weighing evaluation criteria in public tenders and/or (2) evaluating and ranking offers. Eventually, some services in this category relates to custom-based experimental designs, such as Definition of ad hoc analytical methodologies, Support for designing measurement field surveys, Support in the selection of measurement methods in water quality, water quantity, ecology and sediment budgets. Any given service may address several target groups, such as research institution staff, businesses and professionals, students and authorities.

The category “**Study & Measurements**” encompasses services that consist in carrying out analyses and measurements with external users or on behalf of them. Most services in this category can be rendered in-situ or remotely. Those services range from Sample collection and provision (according to DANUBIUS Commons, to chemical analyses (identification and concentration of nutrients, pollutants), eco-, geno- and xenotoxicological analyses, biological analysis (bio/molecular marker identification, microbial and plant proteomics and metabolomics), field surveys (presence and number of endemic species, alien species), geological analyses (magnetism, isotopes, geochemistry, seismo-acoustic profiling, bathymetry, etc.). The wide range of possible analyses and measurements at DANUBIUS-RI, as well as the different scientific disciplines involved, is testimony to the versatility and interdisciplinarity of DANUBIUS-RI.

The category “**Diagnostic & Impact**” includes services that entail, beyond measurements, the interpretation by specialists of data obtained. This interpretation can be done through the comparison of data with previous or expected results (diagnostic) or with forecasts (from models). Eventually, the translation of evolutions observed into effects on the well-being of populations is done by specialists of impact. This whole category of services is based on the expertise at DANUBIUS-RI in terms of modelling, ecological assessment practice and impact assessment. Services related to modelling include Nutrient dispersion modelisation and scenarii at RS system scale, Pollutant dispersion modelisation and scenarii at RS system scale, Population dynamics for alien species, Population dynamics for endemic species, Ecosystem modelling and Fundamental plant and microorganism bioprocess models. Services more focused on the measurement of impact (ex-ante or ex-post) include Social and economic impact of nutrients, pollutants, alien species on ecosystem functionalities, and impact of transient defence measures. Some services require both modelling and impact assessment, such as RS system condition diagnostic, or the Ecosystem service assessment family of services (sediment retention, Green protection measures, Sediment management, Role of nature in flood retention, Role of ecosystems in water quality improvement, Role of ecosystems in carbon retention, Role of ecosystems in of spawning areas).

The category "**Solution Developments**" consists of services addressing users looking for a scientific partner with wide-ranging expertise to develop solutions to the various problems affecting RS systems. Unlike other service categories, this is defined in terms of development themes rather than data, tools, methods, methodologies and models, as the provision of this sort of service is focused on the purpose of the service, rather than on the means employed. Services in this category include the design and development of new sensors (advanced sensor hardware, components and software, Advanced machine learning technology deployment for observation and measurements), field and laboratory equipment (Development of field survey equipment, Development of laboratory equipment), anti-pollution devices (bioremeditaion technologies, Development & application of classical physico-chemical methods, Development of tailored (customized) solution based on green-technologies using intelligent new materials (nanoparticles)), valorisation of RS system organisms (such as Aagae fish, plants), new analytical devices and software (Co-development of "beyond state-of-the-art" measurement techniques for water quantity, water quality, sediment transport and biology in fresh and salt water, Analysis software development), new impact mitigation techniques and methods (Development of conservation and rehabilitation methods, Development of solutions to mitigate the effects of anthropic activities on food chains, Development of solutions to limit endemic species invasion), or development of DANUBIUS-RI-relevant industrial sector techniques (aquaculture diagnostics). Some services are of direct interest for authorities such as Pollutant and vessel spill observation and modelling, scenario cases and forecasting, Development of transient defense measures, Sustainable dredging management plan development (for shipping), and Sustainable dredging management plan development (for ecosystem service maintenance).

The category "**Tests, Audit, Validation & Certification**" completes the typical scientific methodology (observation and analysis, experimentation and/or modelling, diagnostic and/or forecasts) by the comparison of theoretic results with the reality. This category also includes the quality assurance and control of laboratories external to DANUBIUS-RI, e.g. in the context of DANUBIUS Commons accreditation or ASP certification. This service category includes

Quality assurance (Laboratories), Equipment testing and/or validation, DANUBIUS Commons accreditation (laboratories), Laboratory benchmarking, Aquaculture knowledge transfer, In-situ validation for models, In-situ validation for methodologies, Calibration and validation for remote sensing, Validation of transient defence measures, Validation of field survey equipment.

The category “**Training Services**” is not restricted to students and includes all the potential trainings and courses that DANUBIUS-RI can offer to e.g. staff, companies and authorities. This service range is highly dependent on the capacity of DANUBIUS-RI to liaise and establish collaborations with universities and companies. In this respect, the list below should be construed as a standard list, which does not preclude the creation of *ad hoc* courses and programs, depending on the actual needs of higher education institutions, other RIs, authorities and/or companies. There are three directions in which the training services have been developed. The first one relates to the four areas of expertise represented in Nodes: Observation, Analysis, Modelling and Impact. The second one relates to best practices, methods, standards in the scientific disciplines identified and/or developed by DANUBIUS-RI and integrated into the DANUBIUS Commons, the set of standards to be adopted by all components of DANUBIUS-RI, and beyond, to all institutions that wish to participate with DANUBIUS-RI as Accredited Service Provider (ASPs).

4. DANUBIUS-RI IN RESEARCH & RESEARCH INFRASTRUCTURE LANDSCAPE

Franck Brottier (EUROP)

The DANUBIUS-RI project should be understood in the wider context of the unprecedented effort, initiated in 2000, from the European Union and Member States to develop "the most competitive and dynamic knowledge-based economy in the world capable of sustainable economic growth with more and better jobs and greater social cohesion[7]". The modernised "Europe 2020" strategy builds on this initial effort to achieve several targets reflecting the ambition of generating a "smart, sustainable and inclusive growth as a way to overcome the structural weaknesses in Europe's economy, improve its competitiveness and productivity and underpin a sustainable social market economy[8]".

Research, innovation and knowledge play a key role in the Europe 2020 strategy. Acknowledging technical progress as a decisive factor of growth in advanced economies, the European Union launched the European Research Area policy[9] as part of the Lisbon Strategy in 2000, to foster multinational collaborations in research and bring European research to a degree of efficiency comparable to what exists in countries like the USA and Japan. This objective had to be achieved by overcoming the fragmentation of resources (facilities, data, expertise, equipment) that earmarks European research, notably the poor mobility of researchers in Europe, the scattering of financial resources in national facilities that lack a critical size and suffer from chronic, national underinvestment, and the rarity of cross-border collaborations. The success of international, treaty-based research organisations, such as the CERN, was there to gauge the efficiency deficit of national research institutions.

In this context, the European Union and its Member States launched ESFRI in 2005, "to support a coherent and strategy-led approach to policy-making on research infrastructures in Europe, and to facilitate multilateral initiatives leading to the better use and development of research infrastructures, at EU and international level". At regular intervals, ESFRI selects promising pan-European RI projects designed to overcome fragmentation and foster scientific excellence at a pan-European scale. Selected projects are meant to become reference organisations in their scientific domains, providing scientific communities with state-of-the-art and beyond state-of-the-art facilities, expertise at the knowledge frontier, outstanding data to carry out ambitious research. Another objective is to avoid the classic European separation between research, education and innovation: the role of pan-European, modern RIs is to constitute knowledge hubs that eventually foster the "knowledge-based economy" and "smart, sustainable and inclusive growth" sought after by the Lisbon Agenda and Europe 2020 strategy.

[7] www.europarl.europa.eu/summits/lis1_en.html
[8] https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2010:2020:FIN:EN:PDF
[9] https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=LEGISSUM:i23010&from=EN

Abiding by the ESFRI philosophy, DANUBIUS-RI was selected in 2016 as the pan-European RI of reference for RS system studies. DANUBIUS-RI is meant to provide services to users – as a general rule – on the basis of scientific excellence only. Consequently, DANUBIUS-RI services will be accessible to a wide range of users, with five major target groups identified (researchers, businesses and professionals, students, authorities and public at large) in Europe and beyond. It will take part in other programmes and seek cooperation with other organisations.

The expected contribution of DANUBIUS-RI to the Europe 2020 strategy achievement explains the support from the European Commission to DANUBIUS-RI. The PP of DANUBIUS-RI benefits from the support of the Commission through the Horizon 2020 programme, while the implementation and operation of DANUBIUS-RI is expected to benefit from the use of European Structural and Investment Funds (ESIF).

4.1 DANUBIUS-RI in European and Global Research Landscape

Adrian Stanica, Michael Schultz, Maria Ionescu (GEM), Franck Brottier (EUROP)

European Commission funded Programmes

DANUBIUS-RI offers major opportunities to support implementation of, and benefit from, the work programmes of several of the European Commission's Directorate-Generals (DG). Since DANUBIUS-RI intends to support excellent research with a major social and economic impact, its facilities and services are open to the communities of users for a wide range of activities, from fundamental science to finding practical solutions by the use of science. Participation in these programmes will bring new collaborations, ideas and opportunities for DANUBIUS-RI.

DG Research and Innovation

Programmes funded by DG R&I, from the current Horizon 2020 and Horizon Europe to future framework programmes, are of the highest relevance to the users of DANUBIUS-RI. The RI supports activities developed in all the specific sub programmes, as it provides a major role in research (potential to implement ERC grants, Research and Innovation Actions, Support Activities, Integrated Actions) and education (all Marie Curie specific instruments). DANUBIUS-RI has its opportunities with the specific Infrastructures instruments – where it must strengthen its well established position in the landscape of European RIs.

Other DGs (DG Environment, DG MARE, DG MOVE, External Services, etc.)

Since the scientific agenda of DANUBIUS-RI is problem–solving oriented, it provides excellent quality services to use research for specific topics which need solutions at the European scale. DANUBIUS-RI, through its services, is able to support the practical implementation of various framework directives. The research priorities of DANUBIUS-RI – water sufficiency, sediment management, ecosystem conservation and rehabilitation and the cumulative impact of human activities and global climate change on RS systems – are to be found in specific calls in many priorities and actions of several DGs. DG Environment and DG MARE offer some of the biggest opportunities for cooperation, but DANUBIUS-RI can collaborate also with other DGs – such as DG MOVE (for example, sediment management is crucial to decrease the risk of accidents in RS navigation networks). DANUBIUS-RI has a significant potential for science diplomacy, giving collaboration opportunities with the External Services of the EC, ranging from collaboration in the Eastern Partnership, two of the countries being members of the H2020 DANUBIUS-PP consortium, to the possibility to open services to communities from all continents, as problems in RS systems are global.

European Environment Agency

DANUBIUS-RI has a major potential in supporting the development and successful practical implementation of scientifically sound environmental policies. It can also help by becoming actively involved in the selection and testing of new environmental quality standards.

COPERNICUS Programme

The COPERNICUS[10] Programme is of great importance to DANUBIUS-RI, in particular through the Observation Node. The DANUBIUS-RI focus on entire RS systems, using remote sensing observation coupled with in-situ measurements, requires the practical involvement of all the technical opportunities offered by COPERNICUS. DANUBIUS-RI will support the practical implementation of dedicated calls, ranging from research to practical implementation and transfer of know-how to SMEs.

Cooperation between National Funding Agencies

DANUBIUS-RI, as an ESFRI Project, has the political and financial support of several national funding agencies and governments. When DANUBIUS-ERIC is operational, it will have construction and operational costs covered by the supporting funding agencies. Calls dedicated to the DANUBIUS-RI SIA agenda can be organized either by individual funding agencies, or through bilateral and multilateral cooperation. Funding agencies will have a particular role in the construction of facilities in countries hosting components of the RI. Recognising that funding arrangements vary in different countries, the early establishment of the Preparatory Phase Board of Governmental Representatives (BGR) is already preparing the ground.

Joint Programming Initiatives - Water JPI and JPI Oceans

Joint Programming Initiatives (JPIs) bring together research funding agencies in Europe that aim to fulfil common objectives by launching competitions open to research communities in the various member countries. DANUBIUS-RI has a major potential in supporting the

[10] http://copernicus.eu

implementation of both Water and Oceans JPIs[11], as the scientific agendas have many points in common. DANUBIUS-RI can provide its services to communities of researchers from the various JPI member countries.

As is mentioned in the ESFRI Roadmap 2018: "The Water JPI[12] Strategic Research and Innovation Agenda and the WssTP[13] Strategic Innovation and Research Agenda provide frameworks for collaborative research and innovation efforts. The Water JPI intends to increasingly play a role in facilitating the use of relevant RIs, whereas for example WssTP advocates the use of "real life living labs" where innovative solutions can be tested hence facilitating the scaling up of solutions[14]".

United Nations and other International Bodies

DANUBIUS-RI, will be able to support international cooperation in its specific field of activity in two major directions:

a. Facility for research, innovation and education open to communities dealing with RS systems on all continents. DANUBIUS-RI has been specifically aiming to fulfil this goal and can open access to its services not only to the global scientific community but also more widely to other communities such as education, business, government and general public. The most effective way to implement this goal is to develop strong cooperation with United Nations bodies such as UNESCO, IUCN, UNDP, UNEP and IWA. The fact that DANUBIUS-RI supports the practical implementation of several SDGs represents a starting point for agreements.
b. Building block/nucleus towards the creation of a global RI dedicated to RS systems in accordance with the current efforts to develop global research facilities (ESFRI 2018 Roadmap[15]). DANUBIUS-RI can take the lead in creating a global RI covering major RS systems on other continents.

[11] www.waterjpi.eu; www.jpi-oceans.eu
[12] www.waterjpi.eu
[13] www.wsstp.eu
[14] Ibid.
[15] www.roadmap2018.esfri.eu

4.2 DANUBIUS-RI in the European and Global RI Landscape

Adrian Stanica, Michael Schultz, Maria Ionescu (GEM), Franck Brottier (EUROP)

ESFRI, an independent body composed of EU Member States and associated countries, supports a coherent and strategy-led approach to policy making on RIs in Europe, facilitates multilateral initiatives leading to their better use and development, publishes and updates a European Roadmap for RIs, stimulates and assesses implementation of these RIs. The ESFRI Roadmap 2018 includes 37 landmark projects (projects implemented or well on their way to be implemented), seven of which are from the environment section (ESFRI Roadmap, 2018). There are 18 additional projects, including DANUBIUS-RI, currently in preparation, with four in environmental sciences. DANUBIUS-RI is given 10 years for preparation and construction: it should be operational by 2026 at the latest. DANUBIUS-RI fills a gap in freshwater/coastal hydrosphere study between other ESFRI RIs dedicated to atmospheric studies (EISCAT-3D, www.eiscat.se/eiscat3d; ACTRIS, www.actris.eu; IAGOS, www.iagos.org; ICOS www.icos-ri.eu), marine hydrosphere (EMSO, www.emso.eu; Euro-ARGO, www.euro-argo.eu; LifeWatch, www.lifewatch.eu), biological sciences (EMBRC, www.embrc.eu; AnaEE, www.anaee.com; eLTER, www.lter-europe.net; DiSSCo, www.dissco.eu) and earth sciences (EPOS, www.epos-ip.org).

ESFRI recognises the place occupied by DANUBIUS-RI in the European RI landscape:
"For the comprehensive analysis of the changes in the aquatic ecosystems an integrated basin approach is necessary to understand the impact of different drivers and to find measures for sustainable water resources management. The ESFRI Project DANUBIUS-RI, with its structure consisting of the four Nodes (Observation/Measurements – Analysis – Modelling – Impact), is aiming to bridge the before mentioned gaps, at a basin-wide, river-to-sea approach" (ESFRI Roadmap, 2018).

ESFRI associates DANUBIUS-RI with:
"**Advanced studies on river-sea systems for health and food:** Surface waters analysis in global biogeochemical cycles, food and energy production, food security, aquaculture, environmental medicine,
Sustainability scenario development for human societies in river-sea systems: Integration of data from interdisciplinary Earth and Life sciences with social, economic ad behaviour information on communities living in river-sea systems, aiming to support sustainable management plans at entire basin scale
Open data resources and management for interdisciplinary research on river-sea systems: Development of DANUBIUS Commons – common set of standards, rules, methodologies supporting interdisciplinary research in freshwater, transitional and coastal marine environments"

If the reference to health and food is surprising, the presentation of DANUBIUS-RI insists on its interdisciplinarity as well as on the holistic approach of RS systems and the issues that affect them. Because DANUBIUS-RI has established itself as the pan-European RI for the study of RS, and because both its research themes and disciplines are extensive, there are several interfaces through which DANUBIUS-RI will cooperate with other RIs, organisations or projects. These interfaces may include specific research locations, data, standards, services and facilities, focussed through the DANUBIUS-RI Nodes (Observation, Analysis, Modelling, Impact).

DANUBIUS-RI Interaction with ESFRI Projects and Landmarks

Even before acceptance on the ESFRI Roadmap, DANUBIUS-RI, when shaping its scientific case study, was establishing connections with existing RIs on the ESFRI Roadmap, with specific networks of RIs, and with global and regional initiatives. Agreements with new projects on the ESFRI Roadmap 2018 will be developed later during the lifetime of their Preparatory Phases.

DANUBIUS-RI's observations and analyses, at Supersites and elsewhere, will provide an upstream continuation of the **EMSO-ERIC** approach from coastal waters to the upper reaches of the hydrographic basins of joint interest. EMSO-ERIC has given its full support during the development of DANUBIUS-RI as the two RIs will provide compatible data and specific services to the scientific communities they support. In addition, DANUBIUS-RI will facilitate a better and tighter cooperation and development of mutual languages and work plans between the marine and freshwater communities.

Common plans have been developed with **EPOS-ERIC**, as DANUBIUS-RI brings supplementary expertise on highly sensitive parts of the Solid Earth (www.solid-earth.net), such as rivers, deltas, estuaries, coastal seas, generally marked and controlled by active tectonic and other (e.g. subsidence) geological processes. A series of "strong points" (sites that provide data and expertise to both RIs) are under development at the Supersites.

DANUBIUS-RI, through two of its Supersites (Danube Delta and Nestos), aims to contribute to **ICOS-ERIC**, by providing dedicated data on greenhouse gas emissions in wetlands. The Danube Delta – Europe's largest coastal wetland – is to become a "strong point" where the greenhouse gas emissions will be put in a more complex natural context.

LifeWatch-ERIC, as an e-infrastructure supporting ecosystem research, is another ESFRI Landmark with which there is strong potential for collaboration observation and data, using DANUBIUS-RI's information and dedicated services on aquatic ecosystems.

Potential of cooperation exists with **eLTER**, a new project on the ESFRI 2018 Roadmap. Some of the DANUBIUS-RI Supersites coincide with eLTER sites even though they have different characteristics. DANUBIUS-RI Supersites look at processes at larger scale, and focus on RSS, whilst eLTER covers mainly terrestrial environments. A harmonization of parameters measured and methodologies used by each of the two major projects has been agreed, as a practical step towards a smooth and beneficial cooperation on both sides, in a manner that avoids duplication.

DiSSCo is another new ESFRI project and is dedicated to biota and geological collections providing expertise and "strong points" of cooperation on the non-digital data provided by DANUBIUS-RI.

DANUBIUS-RI Cooperation with European Networks of RIs

Probably the most relevant network of RIs is HYDRALAB (www.hydralab.eu). This network of major physical modelling facilities in Europe aims to address many of the same scientific questions as DANUBIUS-RI. It has a well established position in the European landscape of environmental RIs, due to its specific services. A joint DANUBIUS-RI – HYDRALAB group has agreed on the need for strategic cooperation, recognising the complementarity of the two initiatives. The critical point of interest is that HYDRALAB needs high quality and detailed observation and analysis of in situ data (DANUBIUS-RI Observation and Analysis Nodes) to integrate and adapt the physical modelling experiments it runs. The data from HYDRALAB will provide a major input for the complex numerical models to be developed by the Modelling Node of DANUBIUS-RI.

An agreement is also possible with the JERICO (coastal observatories; www.jerico-ri.eu) and AQUACOSM networks (www.aquacosm.eu), currently active under the H2020 INFRA DEV funding schemes, due to the existing points of mutual interest. JERICO can provide additional information and data to DANUBIUS-RI, as it includes coastal observatories farther away from river mouths, whilst DANUBIUS-RI has a major role in providing services specific to transitional zones / river mouths / deltaic and lagoon coasts.

Cooperation of DANUBIUS-RI with Regional Initiatives

DREAM stands for Danube River – Research and Management and is one the two distributed RI projects, which were declared as Flagship Projects in the Priority Action 7 (Knowledge Based Society) in the EU Strategy for the Danube Region. DREAM is a distributed RI, led by Austria with a focus on physical modelling services to improve river engineering and navigation along the Danube River. A partnership agreement between DANUBIUS-RI and DREAM was already written as one of the final deliverables[16] of FP7 DANCERS and it shows how cooperation is possible with major benefits for both parties.

[16] http://www.dancers-fp7.eu/project-outcomes/

MOSES (Modular Observation Solutions for Earth Systems) is being created by nine research centres of the Helmholtz Association in Germany over the next five years as a flexible, mobile measuring system for EO. The infrastructure is designed to decipher the interactions of short-term events and long-term trends in Earth and environmental systems. MOSES primarily targets four events: heat waves, hydrologic extremes, ocean eddies and the thawing of permafrost. The observation concept follows an "event chain" approach, initiated by recording the extent and intensity of the investigated events and capturing the processes they trigger along and across the surrounding Earth compartments. MOSES is being coordinated at the Helmholtz Centre for Environmental Research in Leipzig. HZG is one of the partners. COSYNA stands for Coastal Observing System for Northern and Arctic Seas. COSYNA's mission to operate an integrated observing and modelling system suitable for investigating the environmental state and variability of coastal areas, with a focus on the North Sea and Arctic coastal waters. COSYNA aims to provide data and knowledge tools to help evaluate the role of coastal systems for local and regional scientific questions and to provide authorities, industry, and the public with tools to plan and manage routine tasks, respond to emergency situations and to evaluate trends. COSYNA specifically develops scientific products and instruments, and provides its infrastructure to the scientific community. COSYNA is financed and coordinated by the HZG (Germany). As there is complementarity in the goals and considerably mutual interest between DANUBIUS-RI, MOSES and COSYNA, HZG aims at developing the Elbe-North Sea Supersite as infrastructure that integrates the components of COSYNA, MOSES and DANUBIUS-RI at HZG in a complementary way. The flexible measuring containers of the HZG MOSES component, the ferry boxes, underwater nodes and benthic lander of COSYNA will be used jointly, and supplemented by additional ferry boxes where required to arrive at an systems understanding of the Elbe estuary-German Bight system.

Position of DANUBIUS-RI in the landscape of Global Research Infrastructures

A series of initiatives to create RIs aiming to support excellent interdisciplinary science at the scale of river basins (including the coastal seas) exist in the USA, where the Gulf Institute is dedicated to the interdisciplinary science of the Mississippi River-Delta–Gulf of Mexico system. There is mutual interest in cooperation. There have been discussions and expressions of interest with from the ASEAN region: the Mekong River Commission has opened discussions about cooperation and possible use of the services of DANUBIUS-RI. Other expressions of interest have been received from the Eastern part of the Black Sea, the Caspian Region (Azerbaijan), North Africa, China and India. Intentions of collaboration exist, but it is difficult to take further steps until a series of technical issues are discussed and agreed by the EU with its counterparts.

5. Monitoring DANUBIUS-RI's Performance

Andrew Tyler & Adriana Maria Constantinescu (USTIR)

DANUBIUS-RI will deliver scientific excellence as an RI in RS systems and to create impact through the development of meaningful and sustainable societal benefits including prosperity and security. This will be implemented through all its components - Hub, Nodes, Supersites, Data Centre and TTO, through a series of products and services. The products and services include: (i) the RI platform itself for R&I; (ii) exemplary Supersites to elucidate the drivers and impacts of environmental change and optimisation on interventions and solutions; (iii) the provision and storage of digital and non-digital data, which includes the systematic and standardised (DANUBIUS Commons) collection and analysis of samples and measurements (in-situ and remotely); and (iv) the development of tools, technologies and expert support.

Key Performance Indicators (KPIs) provide an indispensable tool to ensure that DANUBIUS-RI is delivering on its mission and enable evidence-based decision making (remedial actions/investments) for management, whilst also providing the evidence base to develop future management priorities, strategies and business plans. The OECD Global Science Forum (OECD, 2018) has developed a reference framework that presents a list of standard indicators to assess the societal impact of RIs, based on the existing practices of multiple RIs to assess their activities and impacts. This framework is being used as a starting point to further adjust and specify KPIs to better reflect the strategic objectives of the RI. In DANUBIUS-RI, KPIs aid in transparent communication both internally and externally, illustrating the performance of the RI within the international research landscape and helping to deliver the sustainability of the individual component parts that contribute to the overall distributed RI.

DANUBIUS-RI has a number of objectives including to be a world leading scientific RI. The KPIs to deliver main indicators are likely to be: (i) the total number of papers using knowledge or data provided by DANUBIUS-RI in a given period; the number of publications using DANUBIUS-RI services and outputs in top quartile (Q1) journals; (ii) the number of citations of these papers attract; (iii) the number of scientific users both within and outside the EU within a given period and the change in this number with time. DANUBIUS-RI also aims to promote best practices in the study and use of RS systems, through DANUBIUS Commons and long-term, continuous and good quality environmental data. The successful implementation of the DANUBIUS Commons is likely to be a KPI along with the number and type of users of the DANUBIUS Commons and data outwith the RI as a measure of recognition of the importance of the RI globally. Interdisciplinarity is also central to DANUBIUS-RI and this will also be assessed with KPIs, including: (i) the interdisciplinarity of the research outputs (articles, reports); and (ii) the connection of DANUBIUS-RI with other RIs in connecting fields. Data as a key output will also be subject to a KPI and the principle of FAIR (Findable, Accessible, Available, Interoperable and Reusable) data will be used.

The overall good functioning of the RI will be important in achieving its objectives and the expected outcome. This will be monitored through: (i) the number of Partner Countries signing the ERIC; and (ii) the geographical distribution of service points or node. The health of the RI will also be measured through its financial sustainability, the KPIs for which may include: (i) the upgrade/reuse of national pre-existing investments that acquire an European/international relevance; and (ii) the value and number of RI related investments.

A core objective is to deliver societal impact, making the best of the knowledge and technological progress in the field. DANUBIUS-RI aims to be an enabling facility to support scientific and technological development, patenting and co-developing patents with other RIs, researchers, and industry. KPIs for this may include: (i) the number of co-patents developed; (ii) the number of joint technology development projects with industry; and (iii) the number and amount of funding for collaborative research projects. DANUBIUS-RI, through its various components situated in several European countries, will also want to be a focal point in the development of regional strategies and collaboration. Its contributions will be evaluated by looking at the economic and financial impact on (i) the local and the regional scales; (ii) the number and amount of investments and expenditures in economic sectors relevant to the regional/national Smart Specialisation Strategies, number of full time equivalent jobs within the RI, companies created by people associate with the RI; (iii) the number of jobs created by the presence of the RI; (iv) the number of graduates associated with the RI; and (v) the number of actors in the region using the facilities or collaborating with the RI. Another important impact to achieve in societal impact is promoting education outreach and knowledge diffusion. The KPIs for this can include: (i) the openness to public and web access will be assessed; (ii) the number and nature of events in which DANUBIUS-RI will participate; and (iii) the track record of careers that graduate students from DANUBIUS-RI will develop. DANUBIUS-RI also wants to provide scientific support to public policies, through expert advice, resources and direct contributions and the KPIs for this might include: (i) the number of meetings with public policy makers; and (ii) the number of citations of DANUBIUS-RI related published research within policy documents.

6. Updating the Science & Innovation Agenda

Chris Bradley (UoB), Adrian Stanica (GEM)

This draft SIA for DANUBIUS-RI, presented in this document, is required for the detailed planning necessary to implement the RI. The SIA offers a synthesis of recent research on RS systems, structured around key scientific priorities to demonstrate the gap in the RI landscape that will be addressed by DANUBIUS-RI. It is recognised, however, that the problems, challenges, and societal priorities associated with RS systems are continuously evolving and changing. Hence it is important that there are mechanisms in place to: 1. ensure that the services provided by the RI continue to satisfy the key user communities; and 2. formalise the process whereby the SIA will be updated at regular intervals in response to changing circumstances (such as developments in research capabilities; changes in user demand; emerging societal challenges; opportunities to enhance R&I).

When DANUBIUS-ERIC is fully operational, ownership of the SIA will rest with the governing bodies (i.e. the General Assembly and Director General), while the Scientific and Technical Committees (SC and TC) will be responsible for updating the document. This will complement other functions of these committees, notably to monitor the scientific quality of DANUBIUS-RI and oversee the development of the infrastructure. Updates to the SIA may be requested by the committees, subject to the agreement of the member countries providing the facilities.

The process of revising and updating the SIA will be an iterative process that will be coordinated by a task force led by the Scientific Director and acting under the aegis of the Science and Technical Committees. This will form part of a wider, collaborative, and forward-looking exercise that will comprise:

- an annual review of:
    - the performance of the RI against KPIs;
    - recent developments in the disciplines serviced by DANUBIUS-RI;
    - engagement with National, European and International initiatives to ensure provision of services and facilities align with funding opportunities.

- a quinquennial (5-yearly) mapping exercise to
    - identify and confirm key societal challenges in RS systems;
    - openly consult users of the RI to identify latest scientific findings and technological developments;
    - propose revisions to priority thematic areas and draft a new SIA for approval by the Science and Technical Committees and the Board of Government Representatives.

Following publication of the SIA in November 2019, the SIA will become the Scientific Case of the DANUBIUS-ERIC Statutes. From the moment that the ERIC Statutes are accepted and published by the Official Journal of the EU (envisaged around 2022), the procedures to update the SIA, detailed above, will commence.

Hence, the mapping exercise (of societal challenges and research needs) will re-commence in 2023, one year after the approval of the ERIC, as will the annual evaluation of the performance of the RI. The subsequent SIA will draw upon these annual evaluations, and will be discussed, written and approved in the 5 years after the first SIA is confirmed. Thus, SIA 2.0 will supersede the current SIA by 2027.

The process will be repeated every 5 years, while the document can be revised at any point in the event that there is a major breakthrough in related scientific activities (at the request of the Science and Technical Committees. The scientific and technical bodies that will undertake this exercise in DANUBIUS-ERIC will work with, and benefit from, the support of the user community, stakeholders, funding agencies, and national representatives at all stages of the process.

ANNEX I - DPSIR FRAMEWORK APPLIED TO EUROPEAN RIVER-SEA SYSTEMS

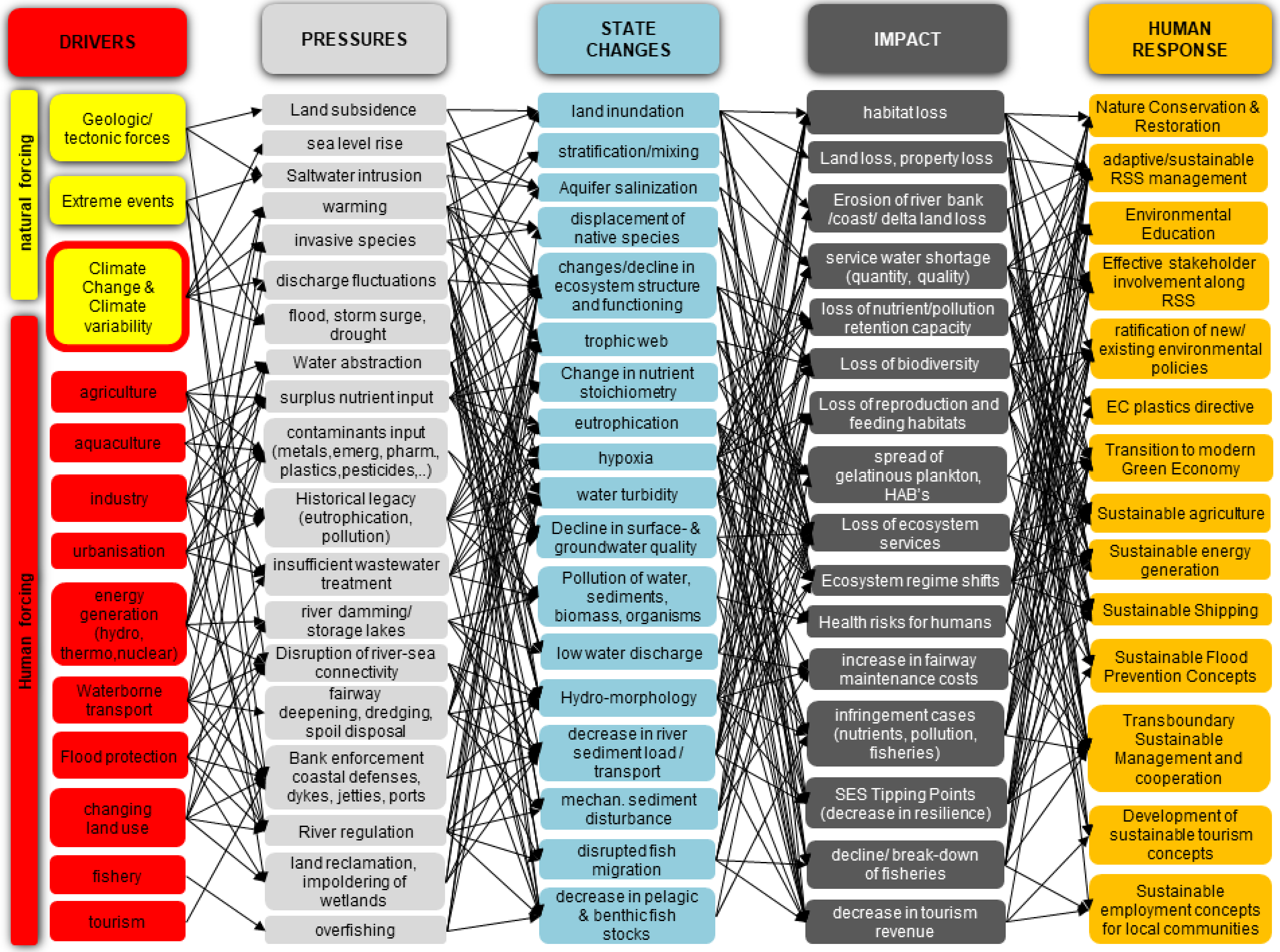

Figure 10 DPSIR conceptual framework applied to European RS systems. This conceptual framework illustrates the causal chain from driving forces (human and natural), resulting pressures that lead to state changes in the environment, which in turn impact on environment and on human well-being. Human responses may either reduce the negative effects of pressures or try to avoid negative pressures by adaptive management of the drivers. Feedback loops are not displayed in this sketch. It further illustrates the multiple and interacting pressures and the resulting complexity of environmental and societal interdependencies in RS systems.

ANNEX II - OVERVIEW OF SUPERSITES CHARACTERISTICS

Table 1 Overview of Supersites characteristics; position in the RS system, climate system, tidal influence, and summary of social-ecological problems structured according to DPSIR.

SUPERSITE	DRIVERS	PRESSURES	STATE CHANGES & IMPACT	HUMAN RESPONSE	HUMAN IMPACT	RESEARCH FOCUS
Upper Danube (Lake Lunz) - headwaters - temperate continental	- climate change - extreme events - changing land use - hydropower - agriculture/ forestry	- floods - damming/ fragmentation - bank stabilization - fairway dredging - diffuse nutrient & pollutant input	- change in sediment regime - riverbed incision siltation, erosion floodplain loss habitat - fragmentation & loss - loss in nutrient retention capacity - loss of supporting & regulating service	- river & floodplain habitat restoration - fish migration aids - sustainable flood prevention concepts - sustainable hydropower	medium	- influence of climate change on aquatic ecosystems, on catchment's ecological functions and ecosystem service provision - connectivity issues within riverine landscapes on ecological processes and biodiversity patterns - influence of climate change and land use change on stream ecosystem functioning (nutrient & C cycling, hydrodynamics) and biodiversity - influence of multiple stressors on aquatic ecosystems and communities - determinants of resilience & resistance of benthic communities to multiple stressors, change in stressor dominance, to restoration efforts
Middle Danube (Szigetköz) - middle waters (inland delta, subsurface aquifer) - temperate continental	- hydropower plant (HPP) in SK - shipping	- damming/ fragmentation-artificial canal to HPP (80% of flow) - water scarcity in main Danube arm (20% of flow)	- floodplain loss - riverbed clogging - reduced baseflow - habitat fragmentation & loss - drop in sub-surface groundwater (GW) - biodiversity loss - loss of supporting & regulating service	transboundary sustainable management missing	heavy	- effects of decreasing river discharge on groundwater - spatiotemporal dynamics of infiltration/ tapping of the groundwater - genesis & evolution of inland Delta, under human influence and in changing climate - water and sediment dynamics in Szigetköz, focus on riverbed clogging - conceptual model/framework on the processes of surface water-GW system of an inner delta, affected by anthropogenic activity

SUPERSITE	DRIVERS	PRESSURES	STATE CHANGES & IMPACT	HUMAN RESPONSE	HUMAN IMPACT	RESEARCH FOCUS
Danube Delta (Black Sea) - lower river, transitional to coastal - microtidal - temperate to warm continental	- climate change - agriculture in catchment - shipping - hydropower upstream of delta - nature conservation in delta - fishery in Black Sea	- alien species - river damming - rigid environmental protection - lack of channel maintenance - negative sediment balance - eutrophication & hypoxia in Black Sea	- delta erosion - legacy of eutrophication, pollution - clogging of channels and delta water flow - risk of eutrophication & hypoxia on shelf depopulation of delta - loss of provisioning service	- compromise between environmental protection and local communities development needed - transboundary sustainable management is missing	low (Delta) medium (Black Sea)	- genesis & evolution of the Danube Delta, under human influence & changing climate - understand biogeochemical processes in transitional waters; at the Danube – Black Sea interface - water and sediment dynamics in the Danube River - Delta – Black Sea continuum - eutrophication/hypoxia in the Danube Delta/western Black Sea area - plans for sustainable use of biological resources (stocks of marine, freshwater and migratory organisms) - eco-engineering (“green”) solutions for sustainable management of the Danube Delta – Biosphere Reserve - how to balance protection of the Danube Delta and sustainable development of local communities?
Nestos - headwaters to coastal - microtidal - temperate continental to warm Mediterranean	- hydropower - agriculture in delta - industry on coast	- damming/ fragmentation - hydropeaking - low flow - water abstraction- - water scarcity - pollution input	- hypoxia/anoxia in reservoirs, redox changes - habitat fragmentation & loss - floodplain loss - change in physico-chemical regime - change in nutrient ratios in coastal zone and change in food chain - insufficient flushing of Bay,	- ecological flow regulation of needed	heavy	- coastal erosion mitigation, sediment dynamics assessment and sustainable sediment management along the river/delta/coastal zone system - development of a unified methodology for ecological flow determination following the holistic habitat techniques and other modern approaches - alteration in river flow dynamics and consequent physico-chemical changes and impacts to river flora and fauna

SUPERSITE	DRIVERS	PRESSURES	STATE CHANGES & IMPACT	HUMAN RESPONSE	HUMAN IMPACT	RESEARCH FOCUS
			pollution in coastal water - coastal erosion - loss of supporting, regulating & provisioning service			
Po Delta & North Adriatic Lagoons - transitional to coastal - microtidal - temperate to warm oceanic	- agriculture - industry - shipping - urbanisation - tourism - hydropower	- diffuse nutrient & pollution input - insufficient WWT - flooding - water abstraction - land reclamation (saltmarsh - river fragmentation	- denudations - water pollution - decline in water quality - bank erosion - biodiversity & ecosystem function loss - decrease in fish population - loss in nutrient retention potential - loss of supporting, regulating, provisioning & cultural service		heavy	- role of transitional environment between the river and the sea, quantify feedbacks of sediment & pollutant trapping & release - role of deltaic lagoon ecosystems & fishery (nursery function, sustainable management of fishing) to assess resilience and capability to cope with (climate) change - interaction of land uses to identify major drivers for pollution (from water & sediments), water quality (waste waters, microplastics, emerging pollutants, nutrients loads), water and groundwater exploitation and their effects on biota under climate change - preservation of natural habitat in transitional environments and maintenance of their diversity (seagrass meadows, salt marshes, inter-tidal flats habitats, freshwater habitats)
Elbe-North Sea - lower river to transitional & coastal - mesotidal - temperate oceanic	- shipping - agriculture - climate change - urbanisation - industry	- fairway deepening - port of Hamburg - sediment disturbance - organic matter & nutrient input from upstream - floods, low flow	- alteration of hydrodynamics - low oxygen Hamburg port area and downstream - high turbidity zones - bank erosion		heavy	- impact of climate change, extreme events, dredging & deepening of ship fairway, disposal of spoils in river and sea on: on morpho- & hydrodynamics, tidal patterns, sediment dynamics, dynamics of dissolved & suspended particles, turbidity zones & SPM and organic matter segregation, turnover processes, Nutrient & O2 dynamics, pollution, release of toxic substances & pathways

SUPERSITE	DRIVERS	PRESSURES	STATE CHANGES & IMPACT	HUMAN RESPONSE	HUMAN IMPACT	RESEARCH FOCUS
		- pollution input - disposal of dredged material	- biodiversity &ecosystem function loss - loss in N retention potential - loss of supporting, regulating & provisioning service			- pollutant baseline patterns (within the catchment), variability over time - pathways and bioaccumulation of pollutants and microplastics - implications of urbanisation in RSS for release of pollutants in water and air - eutrophication: plankton dynamics nutrient cycling, oxygen dynamics benthic-pelagic coupling, interaction with global change, foodweb changes, bio-geochemical interaction? - connectivity between land-based measures and river – sea response?
Middle Rhine - middle waters - temperate oceanic	- shipping - Urbanisation - industry - agriculture - flood protection	- river rectification - fairway adjustments - river fragmentation - input of pollutants - invasive fauna	- incision of riverbed, bedload deficit - change in hydrodynamics - increase in erosion - loss of floodplains - continuity, biodiversity &ecosystem function loss - decrease in fish population - loss in drinking water quality - loss of supporting, regulating & provisioning service	- harmonisation of water uses needed - green shipping - sustainable flood protection needed - river restoration measures - handle competing demands	heavy	- How to adapt inland waterways to eco-sustainable shipping? - Key causes of poor morphological conditions – how to improve the status - Impacts of extreme events on morphology - Interaction of processes in river channel, floodplains and groyne fields; sedimentation and consolidation in reservoirs - climate change impacts on water-related sectors, incl. transnational flood protection - How far can the expected negative outcomes be limited by adaptation measures? - Which biological, chemical and physical processes are relevant for the long-term transport, storage, accumulation, degradation of contaminants in the water (dissolved and particulate) and sediment? - assessment of monitoring strategies to deliver efficient and state of the art detection and tracking?

SUPERSITE	DRIVERS	PRESSURES	STATE CHANGES & IMPACT	HUMAN RESPONSE	HUMAN IMPACT	RESEARCH FOCUS
						- approaches to reduce anthropogenic impact to reach environmental goals - How far can ecological objectives be realistically pursued in intensively regulated rivers without negatively affecting socio-economic activities and water resources management goals?
Rhine-Meuse Delta - transitional to coastal - mesotidal - temperate oceanic	- climate change - urbanisation - shipping - industry - agriculture	-channelisation, drainage of delta - river embankment - coastal protection - nutrient, pollution input - fragmentation - artificial hydrological regime	- sediment deficit - delta subsidence - salt water intrusion - closure of 2 estuaries - deterioration in water quality - biodiversity & ecosystem function loss - loss in nutrient retention potential - loss of supporting, regulating, provisioning & cultural service	- application of concept of tipping points	heavy	- hydrology: low & high flow of water, associated water quality issues (chemistry and ecology), response to climate change - sediment quantity: sediment distribution/balance, its evolution, bed- and coastal erosion, hydromorphology, - navigation related issues, response to climate change etc. - salt Intrusion
Thames Estuary - middle, transitional to coastal - macrotidal - temperate oceanic	- climate change - extreme events - increase in population& urbanisation - agriculture - shipping?	- droughts - increase in water demand - insufficient WWT - insufficient water supply - flooding - input of pollution	- eutrophication - pollution - periodic large algal blooms (cyano) - inundation of farmland, houses, sewers, land & property loss - service water scarcity	- infrastructure projects: inter-basin transfers, estuarine desalinization plants, new reservoirs, reduce sewage loading to estuary	heavy	- cost-effective means to achieve WFD GES in the Thames water bodies - full understanding of the multiple-stressor controls of algal blooms in the Thames, the river network, estuary into the North Sea - How will the improved water quality of the estuary due to the Thames Tideway Tunnel scheme, WW reuse, desalination schemes, impact on ecology, chemistry and hydrology of the estuary?

SUPERSITE	DRIVERS	PRESSURES	STATE CHANGES & IMPACT	HUMAN RESPONSE	HUMAN IMPACT	RESEARCH FOCUS
		- input of nutrients	- WFD standards not met - groundwater pollution with N - ecological impact of cyanobacteria blooms - loss of supporting, regulating & provisioning service			- assessments of UK's efforts to supply drinking water to London effective (growing population and water usage, reduced water due to climate change - How do schemes such as inter-basin transfers / reservoir construction etc. compare with similar projects across other Supersites - "best practise" management by taking a Europe-wide view?
Tay Catchment/ Loch Leven - headwaters to coastal - macrotidal - temperate oceanic	- land use changes - extreme events - industry - agriculture - hydropower	- flooding - flow regulation - diffuse & point source pollutants & nutrients - morphological alteration - water abstraction	- decline in river, lakes &GW quality - decline in service water quality - land-ocean transfer of organic matter - changes in C biogeochemical cycling and sequestration	- drinking water Protection areas Special Areas of Conservation - special protection Areas Sites of Special Scientific Interest - nitrate vulnerable zone surface & GW NERC LOCATE Land Ocean Carbon Transfer	low to medium	- evolution of catchment in relation to land use and anthropogenic changes - sedimentation dynamics from the substantial drainage in catchment & impacts within the transitional and coastal environments - availability of C for global biogeochemical cycling - phytoplankton phenology and eutrophication dynamics - managing extreme events: implications for land management and mitigation measures - assess impact of industrial development in Estuary, develop appropriate mitigation strategies to support social-eco development
Ebro-Llobregat Deltaic System - transitional to coastal - microtidal warm Mediterranean	- agriculture - hydropower? - urbanisation - extreme events - tourism	- weirs and dams - coastal defences - delta drainage - floods - storm surges - 70% delta into agriculture	- sediment deficit (total reduction of solid discharge), change in coastal sediment transport regime - high erosion rates & coastal erosion - 97% of Ebro basin regulated	- Natural Park Ebro delta(1983), Ramsar Wetlands List 1993 - sustainable environmental engineering needed	heavy	- quantify coastal erosion/subsidence at different scales - operational prediction of flooding and water quality, combination of short to long term scales in predictions for impact mitigation - How to extend the use of high resolution suites of coupled models, (hydrodynamics morphodynamics – water quality, etc)? - How to incorporate new generated knowledge (observations & modelling) into

SUPERSITE	DRIVERS	PRESSURES	STATE CHANGES & IMPACT	HUMAN RESPONSE	HUMAN IMPACT	RESEARCH FOCUS
			- natural flow reduced to 1% - habitat loss - delta subsidence - increase in coastal vulnerability	- develop sustainable culture of land & water use		sustainable engineering, decision making, to overcome social-economic barriers?
Guadalquivir Estuary - transitional to coastal - warm Mediterranean - mesotidal	- agriculture - shipping - tourism - fishery, aquaculture - climate change	- Port of Seville - desiccation of marshland horticulture - fairway dredging - alien species	- hyperturbid environment - desiccated marshland - habitat loss - loss in native species - change in incoming tidal range - eutrophication	- Donana National Park (Ramsar site) - river mouth - fishing reserve (2004) - estuary special conservation zone	medium to heavy?	- impact of changing tides, hyperturbidity, flow regulation, changing salinity lateral range on benthic & pelagic ecosystem - impact of hydro-dynamical regime on hyperturbidity - influence of alien species on native species; early warning protocols - impact of water regime regulation on physicochemical and biological conditions - identification of ecological relationships in the estuary, its relation with the ecology of fisheries - climate change monitoring through sentinels - how to manage overlapping and competing uses of the estuary

ANNEX III – ABBREVIATION LIST

ACTRIS	European Research Infrastructure for the Observation of Aerosol, Clouds, and Trace Gases
AnaEE	Analysis and Experimentation on Ecosystems
ASEAN	Association of Southeast Asian Nations
ASP	Accredited Service Provider
BAFG	Federal Institute of Hydrology, Germany
BAW	Federal Waterways Engineering and Research Institute, Germany
BGR	Board of Governmental Representatives
C	Carbon
CEH	Centre for Ecology and Hydrology, United Kingdom
CICES	Common International Classification of Ecosystem Services
COSYNA	Coastal Observing System for Northern and Arctic Seas
DANCERS	Danube Macroregion: Capacity Building and Excellence in River Systems
DG	Directorate General
DiSSCo	European Research Infrastructure Distributed System of Scientific Collections
DLT	Deltares, Netherlands
DPSIR	Drivers, Pressures, State (Changes), Impacts and (Human) Responses
DREAM	Danube River Research and Management
DUTH	Democritus University of Thrace, Greece
EBT	Effect-Based Tools
EDA	Effect-Directed Analysis
eDNA	Environmental DNA
EEA	European Environment Agency
EEC	European Economic Community
EISCAT	European Incoherent Scatter Scientific Association
eLTER	European Long-Term Ecosystem Research Infrastructure
EMBRC	European Marine Biological Resource Centre
EMSO	European Multidisciplinary Seafloor and Water-Column Observatory
EO	Earth Observation
EP	Emerging Pollutants
EPOS	European Plate Observing System
ERA	Environmental Risk Assessment
ERC	European Research Council
ERIC	European Research Infrastructure Consortium
ESFRI	European Strategy Forum on Research Infrastructures
ESIF	European Structural & Investment Funds
EU	European Union
Euro-ARGO	European Research Infrastructure for Argo Floats
EUROP	Europportunities, Estonia
FAIR	Findable, Accessible, Interoperable and Reusable
FD	Flood Directive
GCOS	Global Climate Observing System

GEM	National Research and Development Institute for Marine Geology and Geoecology, Romania
GES	Good Environmental Status
H2020	Horizon 2020
HD	Habitat Directive
HELCOM	Helsinki Commission
HPC	High-Performance Computing
HQ	Headquarters
HZG	Helmholtz-Zentrum Geesthacht, Germany
IAGOS	In-service Aircraft for a Global Observing System
ICOS	Integrated Carbon Observation System
ICPDR	International Commission for the Protection of the Danube River
ICPER	International Commission for the Protection of the Elbe River
IDR	Interdisciplinary Research
INSB	National Institute Research and Development for Biological Sciences, Romania
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
IPR	Intellectual Property Right
ISMAR-CNR	Institute of Marine Sciences, National Research Council, Italy
IUCN	International Union for Conservation of Nature
IWA	International Water Association
JERICO	Joint European Research Infrastructure of Coastal Observatories
JPI	Joint Programming Initiative
KPI	Key Performance Indicator
LIDAR	Light Detection and Ranging
MEA	Millennium Ecosystem Assessment
MOOC	Massive Open Online Course
MOSES	Modular Observation Solutions for Earth Systems
MSFD	Marine Strategy Framework Directive
MSPD	Maritime Spatial Planning Directive
N	Nitrogen
ND	Nitrates Directive
NREN	National Research and Education Network
NRT	Near-Real Time
OECD	Organisation for Economic Co-operation and Development
OSPAR	Oslo and Paris Convention
P	Phosphor
PBT	Persistent, Bioaccumulative, Toxic
PML	Plymouth Marine Laboratory, United Kingdom
PP	Preparatory Phase
QA	Quality Assurance
QAP	Quality Assurance Panel
R&I	Research & Innovation
RI	Research Infrastructure

ROEDU	Romanian National Research and Education Network
RS	River-Sea
S2S	Source-to-Sea
SAR	Synthetic Aperture Radar
SC & TC	Scientific and Technical Committees
SDG	Sustainable Development Goal
SedNet	European Sediment Network
SES	Social-Ecological Systems
Si	Silicon
SIA	Science & Innovation Agenda
SIWI	Stockholm International Water Institute, Sweden
SSM	Sea Surface Microlayer
SZE	Széchenyi István University, Hungary
TEEB	The Economics of Ecosystems and Biodiversity
UCC	University College Cork, Ireland
UL	University of Lorraine, France
UN	United Nations
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
UNESCO-IHE	Delft Institute for Water Education, Netherlands
UNFCC	United Nations Framework Convention on Climate Change
UoB	University of Birmingham, United Kingdom
UPC	Polytechnic University of Catalonia, Spain
USTIR	University of Stirling, United Kingdom
UWWTD	Urban Waste Water Treatment Directive
WCL	WasserCluster Lunz, Austria
WFD	Water Framework Directive
WMO	World Meteorological Organization
WSSTP	Water Supply and Sanitation Technology Platform
WWAP	World Water Assessment Programme
WWF	World Wide Fund For Nature
WWT	Waste Water Treatment

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Preparatory Phase for the pan-European Research Infrastructure DANUBIUS–RI "The International Centre for advanced studies on river-sea systems"

European Commission

This project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No 739562