DANUBIUS-RI

International Centre
for Advanced Studies
on River-Sea Systems

DANUBIUS-RI Science and Innovation Agenda

November 2019

Preamble

This Science and Innovation Agenda presents challenges and research needs, as identified by DANUBIUS-RI, for achieving healthy River-Sea Systems. It highlights our research priorities for the first five years of DANUBIUS-RI's operation and outlines the scientific rationale that underpins the technical and organisational design of the research infrastructure. These challenges and research needs will shape the development of the infrastructure to ensure it provides the inter-disciplinary expertise, tools and capacities required. The Science and Innovation Agenda describes how DANUBIUS-RI will transfer its mission into science and services for the benefit of healthy River-Sea Systems. The Science and Innovation Agenda also summarises the reasons for policy makers and funding agencies to support DANUBIUS-RI and it shall attract users from research, environmental, industrial and policy making organisations as well as inform the wider public.

DANUBIUS-RI, the International Centre for Advanced Studies on River-Sea Systems, is a distributed environmental research infrastructure on the Roadmap of the European Strategy Forum on Research Infrastructures (ESFRI). Our aim is to provide interdisciplinary expertise and integrated research infrastructure: remote and in-situ observation systems (including ships), experimental facilities, laboratories, modelling tools and resources for knowledge exchange along freshwater-seawater continua throughout Europe, from river source to sea. In this way, DANUBIUS-RI offers a new paradigm in aquatic science: the River-Sea continuum approach. Given that our lives depend on water this research infrastructure meets a critical need.

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Science and Innovation Agenda of DANUBIUS-RI

Executive Summary

This Science and Innovation Agenda summarises the scientific and technical framework for the development of DANUBIUS-RI. The International Centre for advanced Studies on River-Sea Systems is a distributed environmental research infrastructure dedicated to River-Sea Systems on the Roadmap of the European Strategy Forum on Research Infrastructures (ESFRI). The agenda highlights the research priorities for the first five years of the infrastructure's operation.

DANUBIUS-RI's Vision is to achieve healthy River-Sea Systems and advance their sustainable use, in order to live within the planet's ecological limits by 2050. **DANUBIUS-RI's Mission** is to facilitate excellent science on the continuum from river source to sea; to offer state-of-the art research infrastructure; and to provide the integrated knowledge required to sustainably manage and protect River-Sea Systems. **DANUBIUS-RI's goal** is to overcome the current fragmentation of science, knowledge, data and management in rivers and seas by integrating spatial, temporal, disciplinary and sectorial thinking. We will provide science-based solutions to environmental and societal risks arising from global and climate change. We will offer a source to sea perspective to resolve problems arising from human impacts on River-Sea Systems.

Our Motivation and Challenge: Healthy River-Sea Systems

Rivers, estuaries, deltas and coastal seas connect more than three quarters of the Earth's land surface with the ocean. The natural connection between land and ocean is essential for humankind in providing key ecosystem services including food, water and transport. However, these connections are increasingly impacted by global change, affecting entire River-Sea Systems worldwide. Urgent action is needed to harmonise future human use and the protection of River-Sea Systems to counter the effects of climate change and unsustainable use, such as landscape fragmentation, river regulation and damming, water and sediment abstraction, eutrophication and pollution, the loss of biodiversity and the spread of invasive species.

DANUBIUS-RI has identified challenges and gaps in knowledge that must be addressed if we are to achieve healthy River-Sea Systems. These include ensuring sufficient flows of water and sediment, maintaining structural integrity and continuity, facilitating processes of natural self-organisation over time and promoting resilience to extreme events. We will facilitate a source-to-sea perspective to understand the evolution and functioning of River-Sea Systems considering: the effects of Climate Change and Extreme Events; Water and Sediment Quantity and Quality; Hydromorphology; Biodiversity; Ecosystem Functioning and Services; and multiple impacts on River- Sea Systems, taking into account the need to respond to complexity.

Our Strategic Research Priorities

DANUBIUS-RI has distilled its **research priorities for the first five years** to guide the starting activities as it proceeds to operation. These research priorities are socially relevant; they are in line with forthcoming **mission areas of Horizon Europe**, applied to River-Sea Systems, and will be regularly updated:

Mission Area 1: Achieving healthy inland, transitional and coastal waters.

Priority (1) Water Quantity: Understand and quantify water stores and flows across River-Sea continua to enable sustainable water resource management and mitigate against extreme events.

Priority (2) Sediment Balance: Understand and quantify sediment dynamics in a source to sink system, and manage sediments sustainably across River-Sea continua**.**

Priority (3) Nutrients and Pollutants: Understand and quantify singular and combined effects of nutrients and pollutants in water and sediments to establish critical thresholds as a means to support the achievement of good status at the scale of the River-Sea System.

Priority (4) Biodiversity: Understand the relationship between biodiversity and connectivity across River-Sea Systems and its response to multiple stressors.

Priority (5) Ecosystem Services: Understand and quantify how changing River-Sea Systems will affect future provision of ecosystem services and how these can be sustained.

Mission Area 2: Adapting to Climate Change: Enhancing Resilience of River-Sea Systems.

Priority (6) Climate Change: Support collection of data and the development of innovative methods and tools to assess the effects of climate change and to improve adaptation measures within and across River-Sea Systems.

Priority (7) Extreme Events: Understand and quantify the occurrence and severity of extreme events such as floods and droughts, impacting River-Sea Systems and find cost-effective nature-based solutions to support disaster mitigation and management.

Our Modus Operandi

The DANUBIUS-RI Components comprise the **Hub, Data Centre, Nodes, Supersites, e-Learning Office and Technology Transfer Office,** distributed across Europe. DANUBIUS-ERIC, as the legal entity, provides the effective governance framework.

DANUBIUS-RI will provide **users from science, environmental agencies, river basin and regional seas commissions and business** access to a range of River-Sea Systems, facilities, data and expertise, and enable interdisciplinary research, innovation opportunities, knowledge exchange, education and training.

Cooperation is key for DANUBIUS-RI. We will cooperate closely with other research infrastructures, including ICOS-ERIC, EMSO-ERIC, EURO-ARGO ERIC, LifeWatch ERIC and eLTER; with research infrastructure networks such as HYDRALAB and JERICO; with River Basin and Regional Seas Commissions; with data programmes and initiatives such as the European Copernicus programme, EUMETSAT and SeaDataNet; and with research programmes and initiatives such as JPI Water and JPI Oceans.

Our Vision for Success in 2030

By 2030, DANUBIUS-RI is a fully -funded operational environmental research infrastructure, which attracts top scientists worldwide. State-of-the-art services and data facilitate collaboration between stakeholders in research, industry, policy and third sector organisations. This contributes to new understandings, effective interventions and policy instruments that ensure the sustainable functioning of River-Sea Systems and ecosystem service provision. The first generation of young scientists trained by DANUBIUS-RI are internationally recognised specialists in their field. The River-Sea System approach is established as the new paradigm for sustainable management of River-Sea Systems.

1.

Our Vision & Mission

1. Our Vision & Mission

DANUBIUS-RI's Vision is to achieve healthy River-Sea Systems and to advance their sustainable use, in order to live within the planet's ecological limits by 2050.

DANUBIUS-RI's Mission is to facilitate and contribute excellent science on the continuum from river source to sea; to offer state-of-the art research infrastructure; and to provide the integrated knowledge required to sustainably manage and protect River-Sea Systems.

DANUBIUS-RI's Goal is to overcome the fragmentation of science, knowledge, data and management approaches in river and seas by integrating spatial, temporal, disciplinary and sectoral thinking.

DANUBIUS-RI will provide science-based solutions to societal risks arising from global and climate change as well as coincident extreme events. Likewise, it will offer a source to sea perspective to resolve the problems of adverse human impacts on water and sediment quality and quantity, hydromorphology, and biodiversity and ecosystem functioning.

DANUBIUS-RI will be a distributed research infrastructure offering:

- State-of-the-art and fit-for-purpose facilities of river to coastal sea observation systems;
- Development and implementation of interoperable and harmonised methods, tools and models, to achieve comparability across the freshwater-seawater continua;
- A data portal to integrate existing data and knowledge across sectors and disciplines, supplemented by new data and syntheses;
- Smart observation and analytical technologies developed jointly with small and medium-sized enterprises;
- Test beds for nature-based management and restoration solutions;
- Education and training programmes for scientists;
- Engagement with public authorities and policy makers through assessment, evaluation and measures to improve the environmental status of River-Sea Systems;
- Outreach to, and education for, the interested wider public.

DANUBIUS-RI's Strategic Objectives

- **Advance integrated understanding** on the functioning of the River-Sea Systems covering a wide spectrum of climatic, environmental, and societal contexts. This encompasses the interaction of humans and the environment, the drivers of change, the resulting pressures and impacts, and the responses by nature and society.

- **Advance transboundary, interdisciplinary and world-leading research** on the River-Sea continuum. This links field observations (Earth Observation, in-situ measurements) with analysis (laboratory analysis, experiments) and modelling (coupled socio-ecological models, scenario modelling), and ultimately engaging with stakeholders e.g. to support blue growth.

- **Deliver the knowledge base and the practical solutions** to enable sustainable management of River-Sea Systems, and to reconcile conflicting interests and pressures in a well-informed, adaptive and participatory manner.

- **Provide comparable long-term data across sectors and disciplines**, and promote knowledge exchange and education.

- **Support the implementation of the United Nations' Sustainable Development Goals**, by contributing to initiatives such as the Global Environment Monitoring System for Freshwater and the United Nations' Decade of Ocean Science for Sustainable Development.

- **Support assessments of European Union's environmental legislation** and provide the scientific evidence base for environmental policymaking at the European level by bridging the current gaps between land, freshwater and marine environmental policies.

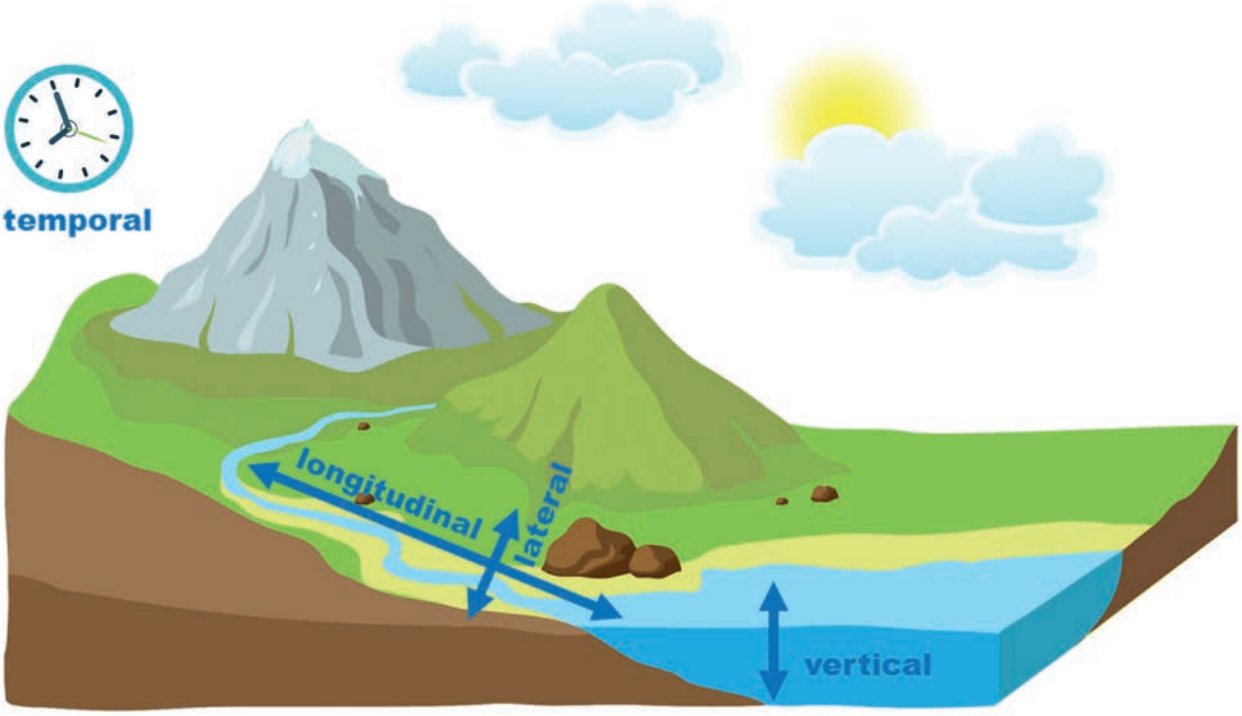
2.

Our Approach

2. Our Approach

Human activities are exerting increasing impacts on the environment on all scales, in many ways outcompeting or enhancing natural processes. Because they have become significant geological forces the term "Anthropocene" is used for the current geological epoch[1,2]. In the Anthropocene, River-Sea Systems are shaped by humans while, at the same time, humans depend on the ecosystems and the services they provide. Due to this strong coupling, **DANUBIUS-RI regards River-Sea Systems as social-ecological systems**[3] and strives to contribute substantially to overcome the dichotomy of nature and society.

River-Sea Systems encompass whole river basins and adjacent coastal seas. Their extent is delineated on land principally by the catchment. The marine boundary is more variable and is determined by the extent of riverine influence in the sea. DANUBIUS-RI takes into account the connectivity between landscapes and riverscapes and seascapes[4]. **DANUBIUS-RI strives for integrated understanding** of the River-Sea continuum in space and time, of biotic and abiotic factors, of water and material fluxes and cycling, and of system processes, functioning and change. DANUBIUS-RI's focus on environmental protection, nature conservation and River-Sea System management encompasses also social sciences.



DANUBIUS-RI considers the four-dimensional context of River-Sea Systems, which comprises (1) longitudinal connectivity between freshwater, transitional, e.g. estuaries and deltas, and marine ecosystems; (2) lateral connectivity between semi-aquatic and semi-terrestrial ecosystems like floodplains and wetlands; (3) vertical connectivity between hyporrheic, benthic and pelagic ecosystems, and (4) temporal connectivity over diverse temporal scales[14].

DANUBIUS-RI considers change and resilience as key to understanding the evolution, functioning and sustainable management of River-Sea Systems. Resilience is the ability of a system to cope with disturbance, to adapt to change, and transform into a new state following regime shift[5]. DANUBIUS-RI considers resilience as the role of water and sediment in safeguarding and sustaining a particular desired state of a social-ecological system, ranging from sustaining the state of ecosystems and biomes to the ability of the natural cycles to maintain ecosystem services that are fundamental to societal wellbeing[6]. Consequently, in DANUBIUS-RI's concept of River-Sea Systems there is no place for the "ignorance of the feedbacks and interactions between humans and ecosystems and the definition of conservation objectives in terms of reverting to a prior, pristine nature"[7].

DANUBIUS-RI applies an ecosystem services-based approach to understand the complex relationships between nature and humans to support decision-making, with the aim of reversing the declining status of ecosystems and ensuring sustainable resource management[8]. Ecosystem services are understood as the benefits that people obtain from ecosystems[9]. These encompass both goods such as drinking water, services such as self-purification capacity, and abiotic flows such as soils and substrate.

Considering River-Sea Systems as social-ecological systems requires interdisciplinary research. Interdisciplinary research has been defined 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

Water of good quality and in fair amounts is crucial for the achievement of the Sustainable Development Goals (SDGs) of the United Nations[16].

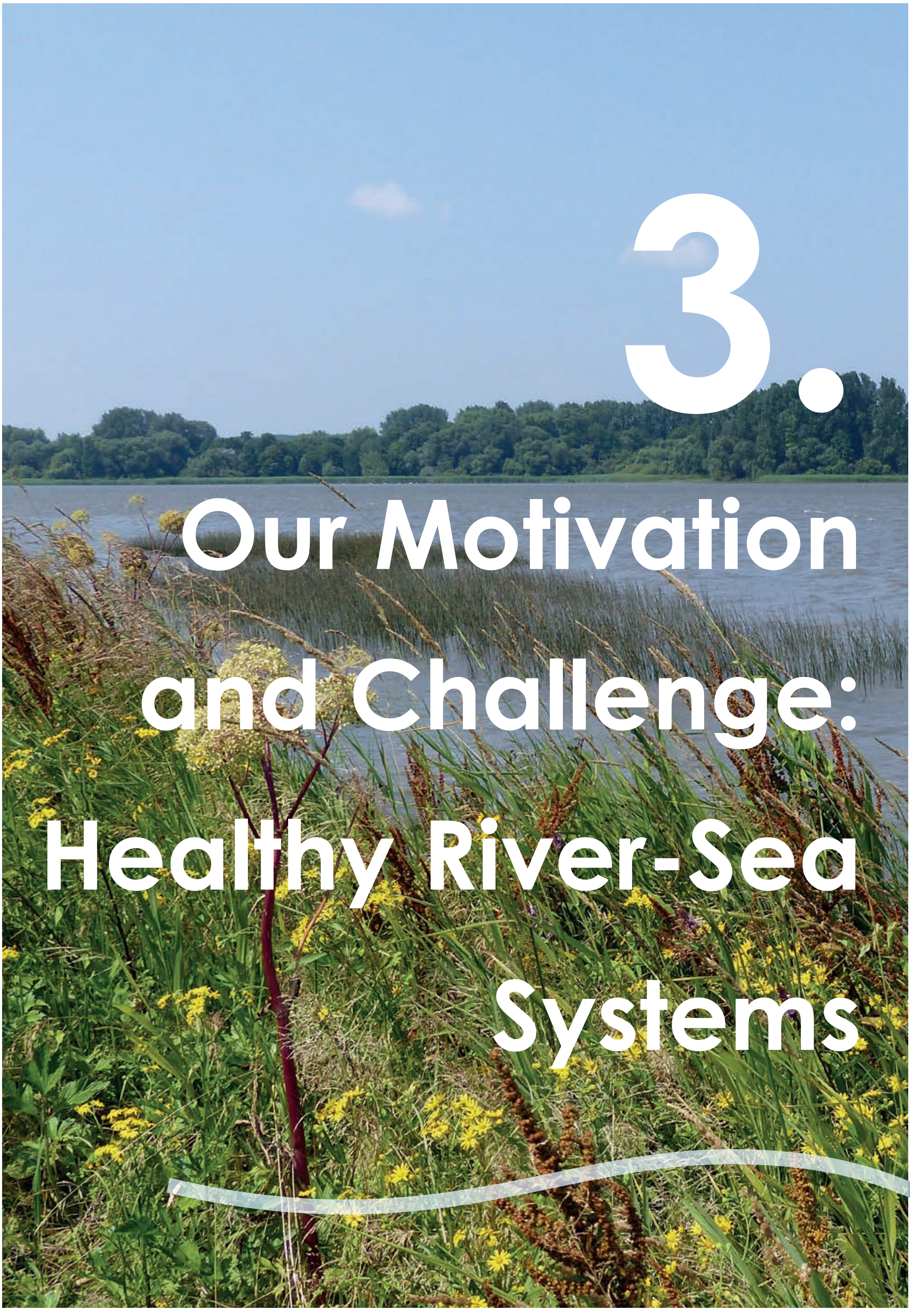
bodies of specialised knowledge to advance fundamental understanding or to solve problems whose solutions are beyond the scope of a single discipline or area of research practice"[10]. DANUBIUS-RI will satisfy both; to advance fundamental understanding and to solve problems. A **problem-based approach** is used to identify, structure and assess the links between both human and natural forces and the resulting pressures and effects they exert on River-Sea Systems. Challenges and research needs in River-Sea Systems have been identified using the Driver – Pressure – State Change – Impact – Response conceptual framework (DPSIR)[11,12] with reference to DANUBIUS-RI's Supersites.

Throughout human history, **technological progress and engineering have driven the development of civilization.** Inevitably, the Fourth Industrial Revolution will transform the world again in many ways. History shows that the eventual benefits and risks of a new technology can differ widely from expert opinion at the outset[13], and hence, in the face of the global environmental crisis today, engineering solutions of the past may require substitution or transformation. DANUBIUS-RI deals with technologies in three respects. First, it will provide knowledge about the benefits and risks of emerging technologies for River-Sea Systems to enable informed decisions and a governance that is stable, predictable and transparent enough to build confidence among economy, scientists and society at large. Second, it will strive for nature-based solutions which help to overcome the negative consequences of past measures, e.g. in river engineering. Third, in close cooperation with business, DANUBIUS-RI will seek technological solutions that have the potential to advance River-Sea System research and management.

Water is at the core of sustainable development[15], since social development and economic prosperity depend on sustainable management of water resources and ecosystems. Water of good quality and in sufficient quantity is crucial for the achievement of most Sustainable Develop-ment Goals (SDGs) of the United Nations[16]. Good water governance is key to achieving the world community's long-term visions and goals, and calls for **participatory methods** in knowledge development and decision-making. Thus, a strong voice for users will be mandatory in defining the research priorities of DANUBIUS-RI and in the level of engagement between science, policy making and the private sector. In this way, DANUBIUS-RI will stimulate also the science-policy dialogue, for example by providing science-based solutions for the implementation, continued development and integration of the different European water and environment policies.

3.

Our Motivation and Challenge: Healthy River-Sea Systems



3. Our Motivation and Challenge: Healthy River-Sea Systems

Rivers connect more than three quarters of the Earth's land surface with the ocean. This natural connection between land and ocean by rivers, estuaries and deltas, as well as coastal seas, is essential for humankind in providing key ecosystem services (including food, water and transport). Most of the world's population lives close to rivers, lakes, estuaries and deltas, as well as along coasts where many of the world's megacities are located[18,19,20]. Hence, human activities in rivers, transitional and coastal waters are pervasive, and few areas remain untouched. In addition, changes arising from human activities are evident at rates that exceed the pace of most natural changes[1].

River basins and adjacent coastal seas are continuously changing on different spatial (local to global) and temporal (seasons to centuries) scales due to a combination of natural forces and human drivers summarised in global change. The resulting multiple pressures and stressors affect all parts of the River-Sea System, as rivers and seas are intrinsically linked through transfers of water, sediment, biota, nutrients and contaminants. Hence, River-Sea System health, the quantity and quality of water and sediment as well as biodiversity and functioning of ecosystems are subject to permanent anthropogenic stress, as are the vital goods and services obtained from these systems. However, crucial for achieving healthy River-Sea Systems will be the political and economic will to support a paradigm shift towards sustainable management with a River-Sea continuum's perspective.

The following fundamental questions are guiding DANUBIUS-RI:

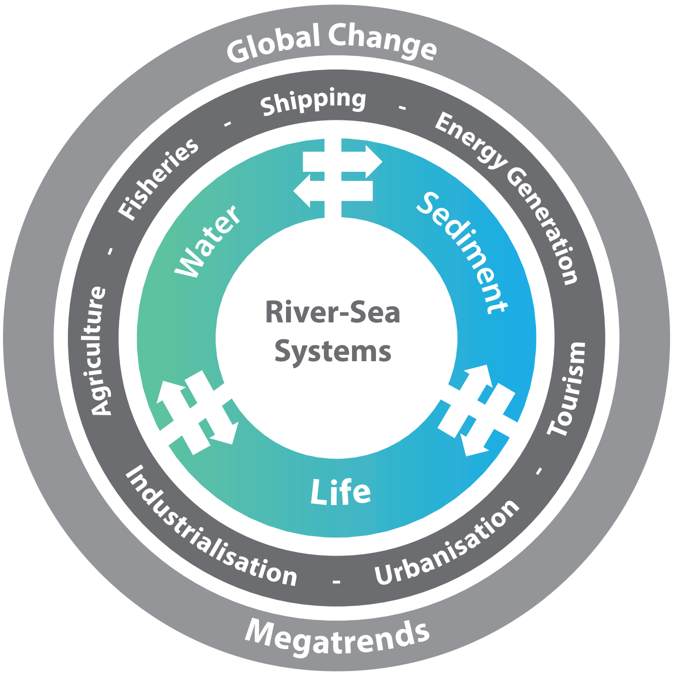
- What constitutes a healthy River-Sea System in the Anthropocene?
- How are River-Sea Systems changing due to multiple and interacting pressures?
- How do processes and changes in parts of the River-Sea System propagate within the River-Sea continuum, both up and downstream?
- How are these changes affecting ecosystem health, its functioning and services?
- How can we sustainably balance use and protection of River-Sea Systems?
- How can we define and implement a management regime that can sustain the ecosystem services of a River-Sea Systems?[21]

over **85%** of Earth's land surface is connected to the ocean by rivers[17]

around **60%** of the world's international river basins do not have a cooperative management framework *(UN WWDR 2012)*

50% of the world's population lives within 3 km of surface freshwater bodies[19]

27% of the world's population inhabit an area within 100 km from the coast[20]



Global change and the megatrends[22] are a consequence of human pressures resulting from basic human needs for food, shelter, energy, transport and recreation. Global change impacts the resources water, sediment and life provided by River-Sea Systems. These impacts affect the ecosystem services that humans derive from River-Sea Systems.

Global Change and Megatrends

Global change encompasses planetary scale changes, which may alter the Earth's capacity to sustain life, for example by impacting the climate system, carbon and nitrogen cycles, food webs, and biodiversity. While global change is not solely caused by human activities, humans have vastly accelerated the pace of change. Humans are driving global change in many ways; for example increasing population, unbounded economic growth along with unsustainable resource use and energy generation, unsustainable mobility, and military conflicts leading to migration. This is leading to large-scale, high-impact and often interdependent social, economic, political, environmental and technological changes[22], referred to as global megatrends.

Global megatrends which are important for Europe's future environment are: (1) demography, (2) urbanisation, (3) disease burdens and health risks, (4) accelerating technological change, (5) continued economic growth, (6) increasing multipolarity, (7) intensified competition for resources, (8) growing pressure on ecosystems, (9) intensification of climate change, (10) increasing pollution and (11) diversifying approaches to governance[22]. All megatrends are expected to further increase the demand for water, food, and energy and hence, the pressures on River-Sea Systems. Resulting impacts and common challenges in River-Sea Systems include the effects of climate change, eutrophication and pollution, effects of major morphological alterations like disrupted river-sea connectivity, landscape fragmentation, major changes of flows, and the spread of invasive species.

Consequently, if Europe is to achieve its 2050 vision of 'living well within environmental limits'[23], a fundamentally transformation towards a circular economy is needed. Thus, the interdependencies of megatrends emphasise the need for a new paradigm in River-Sea System research and management. Land and water, and rivers and seas, need to be considered as a continuum. At present, water

and land are too often managed separately, as are rivers, transitional waters and coasts. There need to be solutions that involve multiple scenarios with associated adaptability and enhanced system resilience to enable a response to the rapid changes.

In summary, global change and megatrends affect River-Sea Systems in multiple ways; at scales ranging from local to global. As water is inherently interconnected with all processes of the River-Sea social-ecological system, water occupies three central roles in the global system[24]: as a control variable, water is the ''source'' of resilience and key to sustaining life on earth; as a state variable, water is subject to external changes, for example land-use change and pollution; and as a driving variable, water is affecting resilience through changes in spatial and temporal distribution of water flows and stocks, for example due to hydrological impacts of climate change[6].

DANUBIUS-RI identified challenges and research areas

to be addressed for achieving healthy River-Sea Systems:

- **Global Change and Megatrends**
  - Climate Change and Extreme Events
- **Water and Sediment**
  - Hydromorphology and Quantity: From Source to Sea
  - Quality: Nutrients and Pollutants
- **Biodiversity and Ecosystems**
  - Ecosystem Functioning
  - Ecosystem Services
- **Responding to Complexity**

The following sections outline the challenges resulting from global change and the research needs for achieving healthy River-Sea Systems. This provides the long-term framework that guides the implementation and operation of DANUBIUS-RI.

Climate Change and Extreme Events

Climate change is recognised as one of the global megatrends and is contributing to an intensification of the hydrological cycle through increasing temperatures, melting polar ice and glaciers, rising sea level, changing precipitation and river flow regimes[25,18], with significant implications for River-Sea Systems. Climate change is projected to cause changes in the frequency, timing and magnitude of floods and droughts, with variable consequences for northern and southern Europe: given differences in climate, snowmelt timing, soil moisture maxima and river basin characteristics[26,27,21]. Changes in terrestrial conditions, due to land-use changes such as deforestation and urbanisation, affect the global and regional climate by accentuating the intensity, frequency and duration of extreme events[28].

Increasing temperatures affect water oxygenation and water body stratification[18], increasing the vulnerability to hypoxia. The expansion and increased frequencies of harmful algal blooms are attributed partly to the effects of ocean warming and oxygen loss, and partly to eutrophication and pollution, with negative impacts on ecosystem services[18]. Shifting of seasons has manifold effects: it may alter life cycles of aquatic organisms, the timing of algal blooms or lead to the displacement and migration of native species and an increase in invasive species.

Sea level rise and changes in coastal storm surges will impact coastal ecosystems and key coastal infrastructure**.** Coastal ecosystems are affected by ocean warming, acidification, loss of oxygen, salinity intrusion and sea level rise, in combination with adverse effects from human activities on ocean and land. Impacts are already observed on habitat area and biodiversity, as well as ecosystem functioning and services[18]. Vegetated coastal ecosystems protect the coastline from storms and erosion and help buffer the impacts of sea level rise. Nearly 50% of coastal wetlands worldwide have been lost over the last 100 years, as a result of the combined effects of localised human pressures, sea level rise, warming and extreme climate events[18]. This presents unprecedented risks to society[25]. The speed of these changes hinders our ability to adapt; and mitigation of climate change and adaptation to climate change impacts will be crucial in maintaining River-Sea Systems for future generations.

The impacts of climate change and extreme events propagate through River-Sea Systems. River floods will affect the coastal zone, and as coastal flooding extends up-river it will affect major cities, for example Hamburg and London. Rising sea level (0.43 m and 0.84 m rise projected for 2100 relative to today, in a low emission-high mitigation future and high emission-no mitigation future, respectively[18]) influences tidal amplitudes; waves and storm surges are rapidly increasing the severity of coastal flooding[29,18]. Sudden increase in surface runoff may lead to intense erosion events, inputting significant volumes of sediment to rivers and coastal waters suddenly with implications for fluvial and coastal geomorphology and navigation. These events may also lead to changes in elemental cycles by providing new sources of matter to aquatic ecosystems (e.g. black carbon stocks), remobilizing pollutants from sediments, and changing elemental cycles[30,31]. More frequent and intensive extremes may also intensify pollution pressures, either during droughts with increased concentrations of nutrients or pollutants or during floods due to enhanced mobilization of historically contaminated sediments and soils. These can lead to new combinations of multiple pressures affecting River-Sea Systems.

Societal impacts of floods include direct effects (damage to buildings, crops, infrastructure, loss of life and property) and indirect effects (reduction in productivity, increased investment risks, indebtedness and human health impacts). Water quality can be severely affected when floods impact physical infrastructures, and coastal areas are often polluted during storm surges when, for example, sewerage systems are compromised. The drivers of future global flood risk are both climate change and economic growth, with global absolute flood damage increasing by up to a factor of 20 by the end of this century without action being taken[18].

Droughts can also interrupt the longitudinal connectivity of river networks, potentially leading to desiccation, intermittent flows and the drying of riverbeds. In addition to climate change, changing land-use and increasing use of water for domestic, agricultural and industrial purposes[32,33] contribute to an intensification of droughts[34] with impacts on shipping, power generation, industrial production, irrigation, and groundwater recharge[35]. Lower groundwater levels may affect drinking-water supply with an increased risk of saltwater intrusion into coastal aquifers. The far-reaching consequences for River-Sea Systems include changes in biodiversity, ecosystem function and ecosystem services[36,37].

Research Needs

Addressing the impacts of climate change in River-Sea Systems relies on understanding the interaction, feedback and responses between the climate system, the water and biogeochemical cycles, organisms and human activities and the adoption of a systems perspective to develop adaptation, mitigation and associated management strategies. It is essential to know how to quantify the effects of climate change on the water quantity and quality of rivers and seas. Sustainable and nature-based solutions to mitigate the impacts of droughts and floods are required, considering for example the negative role of many dams and reservoirs for sediment cycles and species migration.

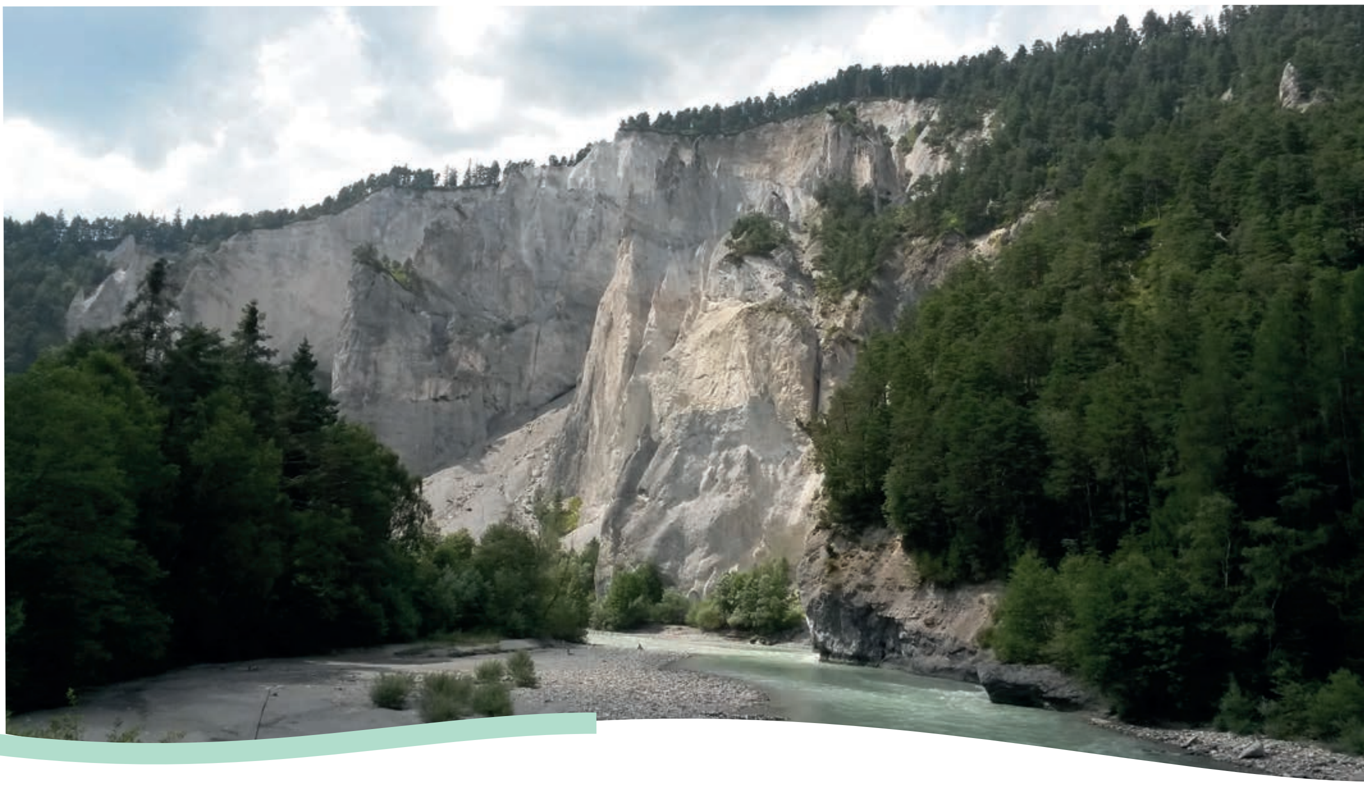
Systematic studies on variability and methodological implications are lacking, despite the need to record the spatial and temporal variability of the hydrological cycle and associated parameters in the response to climate change. This represents a considerable challenge for monitoring River-Sea Systems. The knowledge deficit includes data from national monitoring networks as well as from scientific projects and international initiatives under auspices of the World Meteorological Organization (WMO) or the Global Climate Observing System (GCOS).

There is inherent uncertainty associated with predicting the scale and timing of impacts from climate change and extreme events. How can we account for uncertainty in magnitude and occurrence probability of extreme events when designing mitigation measures? How are extreme events changing hydromorphological conditions, and hence ecosystem functioning of River-Sea Systems? What determines the resilience of River-Sea Systems against extreme events and how can their resilience to climate change and extreme events be increased? How efficient are nature-based solutions for a variety of issues (multifunctionality)? Understanding extreme events and the combination of factors that can lead to an extreme event, may help to reduce their impact.

The development of non-stationary probabilistic models is required, given the complexity of River-Sea Systems. The widely used assumption of stationarity for the management of flood risk turns out to be too simplistic. Any management approaches must consider changing climate and hydrological regimes.

Attribution of current coastal impacts on people to sea level rise remains difficult in most cases since impacts are exacerbated by human drivers, such as land subsidence (e.g., groundwater extraction), pollution, habitat degradation, reef and sand mining[18]. Studies on climate change impact and attribution are currently largely based on model simulations. Despite considerable efforts involved in developing these scenarios, considerable uncertainties often remain. Therefore, these modelling approaches need to be complemented by observations and experiments. This will help in attributing changes in the climate signal at global, regional and local scales, including changes in water quality, in sediment dynamics and nutrient fluxes. This knowledge is essential to enhance resilience to environmental change, and assist high-level panels, e.g. the global stock-take conducted by the United Nations Framework Convention on Climate Change.

The impact of future sea-level rise and the effectiveness of adaptation options and strategies are of high scientific relevance[38,39]. There is a need for consideration of strategies to overcome current barriers to implementing adaptation measures at local, regional and global scales, across a range of shared socio-economic pathways. Particularly important is the identification of tipping points. The emphasis should be on how they can: (a) be included in decision-making processes and (b) linked to sustainability and resilience[39].



Water & Sediment

Water and sediment are fundamental components of River-Sea Systems and crucial natural resources for human wellbeing. Morphological dynamics shape the fluvial landscape, the diversity of habitats and coastline morphology. Humans have made major changes to the ways in which water and sediment move through catchments, from rivers to seas. Intensive patterns of land use, regulation for hydropower, navigation and flood protection, water abstraction for irrigation, industry and urbanisation, as well as pollution by inorganic and organic contaminants and surplus nutrients causing eutrophication and hypoxia have changed fundamentally the water and sediment regime and quality of River-Sea Systems worldwide[40,41,42,43,21]. Nearly all of the DANUBIUS-RI Supersites demonstrate disturbed water and sediment regimes, including the Danube[44], Rhine[45], Nestos[46], Elbe[47] and Ebro[48] Rivers. Furthermore, climate change is causing significant changes in sediment and water regimes.

The future challenge is to ensure the continued availability of water and sediment of sufficient quality within the River-Sea System to sustain key ecosystem services, reconcile potentially competing uses in the context of fast changing environments. Water and sediment conditions in rivers, transitional and coastal waters cannot be understood in isolation from catchment processes. Hence, in many respects, the whole soil-water-groundwater-sediment system must be addressed. The following sections highlight key challenges and related research needs associated to the quantity and quality of water and sediment and the hydromorphological conditions in River-Sea Systems.

Morphology and Quantity: From Source to Sea

Dams. More than 50% of the large river systems worldwide are altered by dams[49]. More than 40% of the global sediment transport is intercepted by reservoirs[50], while about 26% of the global sediment transport is being trapped in reservoirs[40]. The total annual loss rate of worldwide reservoir volume due to sedimentation is 0.5 to 1%[51]. On one hand, reservoirs and dams serve for energy generation, irrigation, provision of drinking water, improvement of shipping conditions and flood control. On the other hand, they are altering both the water and sediment regime and surface and groundwater conditions downstream[21]. Examples from DANUBIUS-RI Supersites are the three Nestos dams, the Iron Gates I&II on the Danube, and the Ebro dams. Flow regulations for navigation, flood control and hydropower alter channel morphology and the hydrology of floodplain wetlands, contribute to reductions in floodplain productivity, and change the dynamics of deltaic systems[49].

Management interventions like dredging and deepening to enable and maintain shipping and navigation from the river through the estuary to the coastal sea change flow velocities and sediment transport patterns, may amplify the tidal range and may increase tidal velocities in tidal systems leading to bank erosion and higher turbidities. Climate change will also alter the volume and timing of water flows and flood events, impacting water availability, sediment flux, ecological functioning[21], and hence ecosystem services provision. For effective and adapted mitigation measures, it will be necessary to differentiate the effects of human alterations from climate change effects. For example, recent work suggests that globally river regulation has a greater effect on river flow on snow-fed rivers than changing climate[52].

To date, rivers, estuaries, deltas and coastal seas have been managed largely in isolation, despite hydrologists and geo-morphologists have been emphasizing for over a century that the river basin is the fundamental unit of study and management[53,54]. The consequences of solving water issues in isolation are either too little or too much water and sediment in the wrong place and at the wrong time, with consequences such as increased floods, drying of riverbeds, decrease in groundwater levels and saltwater intrusions, and habitat destruction. For example, human water consumption upstream may severely intensify the magnitude and frequency of drought through substantially reducing local and downstream flow, especially during low-flow conditions[21].

The reductions in fluvial sediment supply along with excessive sand and gravel extraction in some areas support coastal erosion in the land-sea transition zone and the drowning of deltas, on which is superposed the additional risk of sea level rise. For example, the construction of dams along the Ebro River during recent decades has been responsible for intense reshaping of the Ebro Delta, with shoreline retreat rates of about 20 m/year at the apex[48]. Sand extraction in many rivers takes place today at a rate far greater than its renewal[55]. Sand must be considered as a particularly scarce resource given its importance in protecting coastal areas from rising sea levels.

Changes in coastal morphology. Coastal protection through hard measures, such as dykes, seawalls, and surge barriers, is widespread in many coastal cities and deltas, which leads to changes in coastal morphology. Ecosystem-based and hybrid approaches combining ecosystems and built infrastructure are becoming more popular worldwide. Coastal advance, which refers to the creation of new land by building seawards (e.g., land reclamation), has a long history in most areas where there are dense coastal populations and a shortage of land[18].

Hydromorphology describes the hydrological (water flow) and geomorphological (landform) processes and attributes of rivers, lakes, estuaries and coastal waters. Good hydromorphological conditions are essential for the health of aquatic ecosystems as they provide physical habitat for biota such as fish, invertebrates, aquatic macrophytes and microbial communities that process organic matter and recycle nutrients. Any change in hydromorphological conditions, however caused, will affect habitat availability, ecosystem functioning, and thus ultimately ecosystem services provision. Morphological alterations and unbalanced water and sediment conditions have been directly linked to the reduced abundance and diversity of freshwater fish populations [49].

Today, deficits in hydromorphology account for 40% of the pressures on Europe's water bodies and are in many rivers the main obstacle towards the desired good ecological status[56]. Dams fragment aquatic habitats, impeding species movement across River-Sea Systems, as observed in the Nestos River – Kavala Bay system of Greece [57] and the Danube River – North Western Black Sea [58,59]. The increasing disconnection of rivers from their floodplains and their catchment as well as sediment trapping behind dams and unsustainable land use practices have had multiple consequences. In some reaches riverbed incision rates of centimetres per year occur[60], with severe consequences for bridge and dyke stability, navigability and for river and floodplain habitats, given a lack of suitable spawning substrate, and decreasing floodplain groundwater levels[44,61]. Clogging of the streambed with fine sediment[62] leading to river-floodplain decoupling is another unwelcome consequence.

In response to changing climate and intensive river regulation, the environmental flow concept developed over the past 20 years[63,64], may help to provide the water and sediment needed to sustain river, estuarine and ultimately coastal ecosystems. According to this concept, a 'natural flow' baseline is envisaged for rivers that are natural or semi-natural, with the primary objective to maintain biodiversity and ecological integrity. In contrast, in heavily managed systems where a return to a natural regime is unrealistic, the aim is designing flow regimes to achieve specific ecological and ecosystem service outcomes. Sustainable water and sediment flow regimes may also be useful for dam operation to restore and sustain downstream ecosystems and their services[65].

Maintaining, and enhancing, longitudinal, lateral and vertical connectivity from source to sea is essential for maintaining the functioning of River-Sea Systems. There are considerable uncertainties and difficulties, however, in determining the ideal hydrological or environmental flow regime to maintain or improve hydromorphological conditions. Ideally, 'win-win' interventions should be identified to enhance sustainability, such as nature-based solutions to reduce flood magnitude and extent, or using river bank filtration systems to improve water quality[15]. Interdisciplinary approaches to manage hydromorphological conditions are also required to assess longitudinal and lateral connectivity[66] and determine how the connectivity may be restored, from catchment to sea, along the continuum from headwater reaches through to coastal waters.

Research Needs

For efficient measures to mitigate the impacts of climatic and man-made hydrological and morphological changes, it is essential to improve the current data bases on fluxes of water and sediment through River-Sea Systems and enable quantitative mapping of human influence. Without high quality and consistent data from long-term observations we will be unable to assess and quantify the economic impacts (e.g. navigation, hydropower), the social impacts (e.g. flooding), and environmental impacts (e.g. ecosystem functioning). Applying and improving the concept of environmental flow regimes requires adequate data and improved understanding of the impacts of global change on the River-Sea continuum.

Comparable and entire River-Sea System sediment budgets are required as the core of River-Sea System-based sediment management concepts. Such concepts also provide the basis for reducing both the economic costs of navigation channel maintenance and the environmental impacts of channel dredging. This requires detailed insights into sediment dynamics; and knowledge of, for example, changes in bed-level combined with information on bedload (sand, gravel) and suspended sediment transport, sources and sinks of sediments from source to sea. A better understanding of the processes that trigger regime shifts in system behaviour, such as caused by changes in sediment dynamics, and the transition to hyper-turbid estuaries, will be crucial.

Measures to improve hydromorphology and/or water and sediment quantities in highly complex River-Sea Systems inevitably demand a source to sea system understanding. Improving hydromorphology and thus, the ecological conditions, requires evaluating undesired side effects, like sudden changes in sediment quantity or unfavorable grain size distribution of sediment downstream. This particularly applies for the decommissioning of dams[67,68]. Integrative approaches that consider all the related pressures on the ecosystem call for long-lived consistent monitoring and early planning. Closing 'missing links' between measures (causes) and intended and unintended effects as far as possible by environmental impact assessments is the key to a successful management of River-Sea Systems.

For most European River-Sea systems the return to pristine conditions is not desirable but the desired ecosystem state is ultimately a matter of societal choice. Hence, we need to know how hydro-engineering measures can be integrated into concepts to enhance hydromorphological conditions, which safeguard ecosystem functioning and ecosystem services provision. The application of the environmental flow regimes concept for sustainable operation of hydroelectric power plants and dams requires assessing the minimum and maximum water and sediment flows to enable River-Sea ecosystems to function properly. In order to achieve complete understanding, research is required into the influence of local hydro-engineering measures (flood and coastal protection, dredging or dam operation) on the wider River-Sea System and on how local restoration measures influence its status. Is the "building with nature" concept an option to harmonise the provision of required ecosystem services and health? What are the costs of nature-based solutions compared to classical hydro-engineering measures?

Transboundary River-Sea Systems management and governance frameworks that balance environmental, societal, economic, institutional and political interests are needed to resolve conflicts between key stakeholder needs on, for example, agriculture, drinking water supply, shipping, and hydropower generation. This requires answers on how to balance the costs (who meets the costs) and benefits (who has the benefits) of water and sediment management from local to full systems scale. Innovative approaches at River-Sea System scale must be developed and implemented to transcend geographical and sectorial boundaries. These approaches will provide opportunities to test and apply new solutions, such as 'nature-based solutions', which have the potential to reduce or restore the impacts of anthropogenic processes on rivers, deltas, estuaries and coastal systems.

Quality: Nutrients and Pollutants

Pollution and nutrients are still among the main significant pressures on Europe's surface waters[56], despite the considerable progress that has been made in recent decades through European water protection policy and technological progress. Current threats to water and sediment quality and biota arise from surplus nutrients (nitrogen and phosphorous), anthropogenic pollutants that have been present for decades (heavy metals, organochlorine and polycyclic aromatic compounds), emerging pollutants, pathogenic microorganisms and complex matrices (plastics, microplastics, nanoparticles). While the pollution sources are often located in distinct parts of the catchment, the effects are largely visible in the whole River-Sea System. Hence, the resulting problems can only be resolved efficiently by taking a source to sea perspective encompassing regional and transboundary solutions.

Nutrients. The sources and sinks of nutrients are reasonably well known. However, improving the nutrient status of water and sediment is largely a matter of political and economic will: complying with directives like the Nitrates Directive and decreasing fertiliser application. A large percentage of surplus nutrients in surface and groundwater originates from excessive use of fertilizers in arable farming and manure from industrial livestock farming[69].

Nitrogen & Phosphorus. Nitrogen inputs continue to increase globally[70] and are difficult to manage given their mainly diffuse origin[71,72]. Groundwater with elevated nitrate concentrations may pose a serious human health risk. Phosphorus concentrations in many European rivers have decreased[73] due to improved wastewater treatment and a detergent ban, but diffuse inputs from soils and sediments continue especially during low oxygen conditions.

Eutrophication. Natural responses to surplus nutrients are massive phytoplankton blooms, increased water turbidity, algal growth, changes in C:N:P:Si nutrient ratios, which result in changed phytoplankton community composition, and toxic and harmful cynaobacteria blooms[74]. Decomposition of surplus biomass increases oxygen demand, often contributing to hypoxia in rivers and estuaries (e.g. Thames, Elbe and Schelde)[75,76] and seas (e.g. Northern Adriatic and Baltic)[77,78]. Subsequent impacts are macrobenthos and fish kills[79,80]. This was seen in the north-western Black Sea a few decades ago[81], with dramatic consequences for coastal pelagic and benthic ecosystems[82]. The legacies of eutrophication are elevated release of nutrients from the sediments for many years, fuelling pelagic productivity and eutrophication, creating a time lag for decrease in nutrient concentrations that may be longer than legislative periods[83].

Harmful substances from point sources (municipal, industrial and livestock farm wastewater), diffuse sources (runoff from agricultural land and urban areas) and atmospheric deposition may enter the aquatic food web through bio-magnification or direct uptake of contaminated water or sediment. Bioaccumulation in fish and mussels, and infiltration of river pollutants in drinking water resources, pose a direct threat to human health. Once taken up by organisms, harmful substances may have adverse effects from the molecular and sub-organismic to organismic level[84]. If compensation mechanisms fail, core vital functions such as reproduction will be disturbed, with negative effects extending up to the community level.

Regulation. In Europe, substances used in industrial applications must be registered under the chemical regulation REACH (Registration, Evaluation, Authorization and Restriction of Chemicals). However, current regulation on pollutants pays specific attention to recent industrial chemicals and pesticides and historic contamination. Many have been accumulated in fine sediments on riverbeds, floodplains, behind dams, in harbour basins, lakes, estuaries and seas[85,86,87]. Sediment is considered as the largest reservoir of trace metals and other contaminants, exchangeable between the water column and biota[88]. Contamination increases the costs of sediment management, in particular for handling dredged material[89]. DANUBIUS-RI will contribute to closing knowledge gaps across the different regulatory areas for a coherent, proactive pollution policy.

Emerging pollutants[90], **plastic litter, including microplastics**[91,92,93] **and nanomaterials**[94] are hardly covered by current water quality regulations and have been insufficiently studied to evaluate environmental health risk. Plastic litter, including microplastics, has been recognised as one of the most important global environmental problems as it occurs at practically all levels of freshwater and marine ecosystems and has also been detected in fish and shellfish at alarming levels and frequency[16]. Typical emerging pollutants are pharmaceuticals, personal care products, biocides and chemicals from household, technical and industrial applications. They all may be rather persistent under environmental conditions[95,96] and may cause severe damage even at low concentration levels in aquatic systems[97]. Due to their relatively high polarity and mobility in the urban water cycle, emerging pollutants, their human metabolites and transformation products are likely to contaminate water resources and may not be sufficiently removed by conventional wastewater treatment. Additional, costly purification steps may be required.

Pharmaceuticals, antibiotics, pathogens. Some classes of emerging pollutants such as pharmaceuticals (e.g. in German estuaries and the German Bight[98]) and antibiotics will pose specific risks given their increasing use in aging populations, while others such as rare earth and precious metals may find their way into the aquatic environment due to increasing use in new industrial applications and technologies and mass-market products. Water-borne pathogen contamination in ambient water bodies and related diseases is a major water quality concern throughout the world, while climate change induced perturbations in weather patterns can potentially impact pathogen levels in water resources[99].

There is an urgent need to transform economic and consumption patterns to ensure that humans operate safely and sustainably within the planetary boundaries. The current biogeochemical flows of, for example, nitrogen and phosphorus are already beyond the planetary boundaries of safe operation, creating high risk of earth system destabilisation[100]. This implies a number of research needs addressing River-Sea Systems.

Research Needs

Indicators for eutrophication effects on ecosystem function. The definition of tolerable nutrient loads for different parts of River-Sea Systems to reach a common sustainable management goal requires a set of threshold indicators for eutrophication effects on ecosystem function and services, to provide compelling evidence to policy makers that urgent action is needed. This would build on the "Guidance document on eutrophication assessment in the context of European water policies"[101]. Which gaps need to be closed and which links must be created between different regulations within the water sector (WFD and MSFD) and across sectors (water, waste, agriculture) for a coherent nutrient policy?

Scenario models are required that highlight the influence of human activities, natural factors, climate change and policies on eutrophication and its impacts. DANUBIUS-RI can inform River-Sea System management on how to deliver improvements in water and sediment quality most efficiently, cost-effectively and how to monitor the effects. Research is needed on the influence of a warming world on the vulnerability of River-Sea Systems to eutrophication and hypoxia.

The planetary boundaries for chemical pollution including new substance groups are still unclear[100] in contrast to nutrient flows. We do not know the environmental fate and consequences of harmful substances entering River-Sea Systems such as emerging pollutants. What are their specific transformation pathways and key transformation products? What changes in chemical and biological activity occur during transition from freshwater to marine waters? What is the long-term adverse impact of microplastics on the aquatic system and what are potential risks for human health through the consumption of fish and marine products? This knowledge is urgently needed to define thresholds below which a system can permanently sustain its current diversity and functions, thus safeguarding key ecosystem services.

Many new classes of pollutants are not currently monitored due to a lack of regulation, awareness, methodology or a combination of these. DANUBIUS-RI will enable (a) developing analytical and effect-based methods and tools for their sensitive and reliable detection and (b) an integrative monitoring tackling all the issues related to chemical mixtures, emerging pollutants, metabolites, transformation products, and unknown and cumulative effects.

Pollution as one aspect of stress ecology must be assessed in relation to, and in interaction with other pressures. The environmental fate of nutrients and contaminants is determined by basin-scale hydrodynamic processes (morphology, transport, dispersion and sedimentation) and the complex interactions between dissolved, colloidal and suspended fractions in water, sediment, and biota. It is important to understand these processes, as a theoretical basis for scenarios, transport and exposure modelling, to estimate the contribution of upstream and inland sources to downstream and marine pollution before developing efficient management solutions at River-Sea System scale, for example in sediment management. Further, we need to determine how navigation channels, reservoirs, river fragmentation, floodplain and marshes reduction, decoupling and restoration, and sediment relocation influence the transformation and retention capacity of nutrients and pollutants.

Multidisciplinary approaches are required to enable an environmental risk assessment of pollutants linking exposure patterns, levels of concentration, the simultaneous presence of several pollutants, harmful effects across various biological levels and bioaccumulation/ biomagnification. How efficient are specific eutrophication and pollution reduction measures? What are the time lags of responses from the catchment to the coastal sea? We currently lack scenario models to assess the quality status of River-Sea Systems, and as decision-support tools for sustainable management.

Biodiversity and Ecosystems

There is ample evidence of a global decline of biodiversity, which is most pronounced in freshwaters[102,103,104,105]. Direct drivers with the largest impact on biodiversity in the last 50 years on freshwater ecosystems have been land-use change, water extraction, exploitation of resources, pollution, climate change and invasive species[106]. In marine waters, the largest impacts on biodiversity have resulted from overexploitation of fish, shellfish and other organisms, land- and sea-based pollution including from river networks, and land-/sea-use change, including coastal development for infrastructure and aquaculture[106]. The Aichi Biodiversity Targets for 2020, to protect at least 17% of inland water areas and 10% of coastal and marine areas will not be met[106].

Ecosystem Functioning

Biodiversity ensures effective ecosystem functioning via species richness, functional groups, and communities and their interactions across ecosystems[107,108,109,110] and thus provides ecosystem stability in response to pressures. Resistance and resilience to pressures are key components for determining ecosystem stability after disturbances[111] due to an ecosystem structure that allows a return to an original state. A healthy ecosystem is considered stable and sustainable in maintaining self-organisation and recognisable emergent properties over time[112]. Highly stressed ecosystems are often unable to maintain these properties, shifting to new stable states within the new boundary conditions[113], which may have profound consequences for the provision of ecosystem services.

The interdependencies between biodiversity and ecosystem functions and services[114,115] along the River-Sea continuum, under accelerated changing environmental and increasingly climatic conditions, can be described using functional approaches. Keystone species play a crucial role in ecosystem structure and functions, determining food webs and matter fluxes (e.g., top predators or abundant grazers[116] or ecosystem engineers shaping the habitat structure[117]). Diverse ecosystems, whose components have co-evolved, promote efficiency in energy transfer from lower to higher trophic levels and provide a capacity for resistance to or recovery from pressures[118,119,120]. While research into trophic dynamics and ecosystem functions has a long history in lakes[121,122,123,124], interest in relating structure to function in rivers and estuaries is more recent[125,126]. Science 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[127,128,129]. While these techniques provide an increasing understanding of ecological functions, the response of ecosystems to multiple human pressures largely remains to be investigated[130].

Ecosystems are connected by abiotic and biotic factors in River-Sea Systems, through the flow of water and sediment (quantity), the associated transport of organic matter, nutrients and pollutants (quality), migration and dispersal of organisms (native and non-native species). Connectivity along the River-Sea continuum is therefore crucial to maintain ecosystem structure and function. Human alterations of morphology such as damming, dredging and channelisation disturb environmental gradients, eliminate upstream-downstream linkages and isolate river channels from riparian/floodplain systems and their connection to the sea, and contiguous groundwater aquifers. These alterations interfere with successional trajectories, habitat diversification, migratory pathways and other processes, thereby reducing biodiversity[131]. Sustainable ecosystem management of River-Sea Systems needs to include: (1) re-establishing environmental gradients along longitudinal, lateral, and vertical dimensions across a range of scales; (2) re-establishing ecological connectivity between landscape elements; and (3) reconstituting some resemblance of the natural dynamics, while balancing it with human uses.

Research Needs

Research into the link between biodiversity and ecosystem structure and function across different scales along the River-Sea continuum under changing environmental conditions and multiple pressures: There is an urgent need to identify how multiple pressures and their interaction change biodiversity and ecosystem structure and functioning. Shifting climatic conditions can amplify these impacts. Developing indicators for multiple pressures will benefit from new tools, like environmental DNA (eDNA), and spectral species analysis based on light detection and ranging (LIDAR). Earth observation tools must be incorporated into assessments of biodiversity along the River-Sea continuum.

Research into regime shifts in ecosystem functioning, into resilience against stressors, thresholds and early warning indicators and, hence, how to increase the resistance and resilience of River-Sea Systems against pressures is required. Longitudinal, lateral and vertical ecological connectivity along the River-Sea continuum is a precondition to maintaining ecosystem functioning. A priority need is to develop realistic strategies to define, mitigate and re-establish connectivity and understand the effects on biodiversity in heavily engineered and managed systems. This will inevitably involve smart and acceptable nature-based solution.

Develop citizen science to build greater awareness and effective engagement strategies involving policy makers and the interested public. Citizen science is increasingly seen as a mechanism both to collect useful data for management and to increase the environmental awareness of citizens. Both approaches have been subject to intensive research and debate in recent years[132,133,134]. Key issues revolve around data reliability, data governance and agency and citizen motivation. The potential for citizen science as part of the evaluation, and management, of River-Sea Systems and its ecosystem services requires further exploration and development.

Ecosystem Services

Ecosystem services reframe the relationship between humans and their natural environment. That implies changing the way we look at River-Sea Systems is essential for solving the problems of how to build a sustainable and desirable future for humanity[135]. In River-Sea Systems, provisioning ecosystem services represent ecosystem goods such as water, fish, habitats and sediments. Regulating services are benefits such as flood regulation, water purification and climate regulation. Supporting services are benefits for other ecosystems services and include nutrient cycling and primary production. Cultural services are, for example, recreation and tourism[136]. To deliver these services in a certain quantity requires an adequate ecological structure and functioning of the respective habitats as well as suitable hydromorphology[137].

In River-Sea Systems, ecosystems like rivers, floodplains, banks, marshes, deltas, beaches, and coastal seas, are connected hydrological units, although differing in their ecological properties. Their ecological state is affected by upstream-downstream political relationships, socio-economic development, culture, and diverse, or even contradictory policies that affect basin management as shown for the Danube River[138]. At the river mouth, 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. For example, upstream impoundments can dramatically affect sediment state and a lack of sediment can cause coastal erosion affecting a combination of provisioning, regulating, supporting and cultural ecosystem services.

Land use changes affect ecosystem services, through fundamental shifts in the structure and functioning of freshwater, transitional water and coastal ecosystems, and not exclusively in terrestrial ecosystems. Wetland transformation to cropland, for example, while generating an increase of food production can have widespread negative impacts on wetland habitats, floodplain nurseries for fish[139,140] and the nutrient retention function and other regulating services.

One of the aims of DANUBIUS-RI is 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[141]. Research therefore needs to address the link between biodiversity and ecosystem function to investigate the connection with sustainable societal and economic welfare more closely.

Research Needs

Implications of global trends for the functioning of River-Sea Systems and related ecosystem services. Mapping ecosystem services and analysing their drivers within the River-Sea System, complemented by monitoring social, traditional physical, chemical and biotic indicators, are key to identifying priority action. Research is needed to understand the effects of altered regulating services on provisioning services and potential trade-offs with other service categories. There is an urgent need to identify and improve realistic indicators for ecosystem health and ecosystem services that complement existing systems, for example the ecological quality assessment undertaken for the Water Framework Directive. This includes the development of indicators of ecosystem integrity and risk. Cross-sectoral indices and thresholds indicating tipping points for ecosystem health are needed to avoid over-exploitation of ecosystem services.

The value of ecosystem services in economic and non-economic terms is often not incorporated in decision making[110]. Assessing and valuing the ecosystem services is critically important for improving management and for designing better policies, as River-Sea Systems are facing increasing pressures for conversion to economic activities. The economic valuation of ecosystem services, and the development of models to assess the value of especially non-use services, are a key step in understanding how human drivers alter ecosystem structure and functioning, and thus the ecological production of important ecosystem services for human benefits[142]. Furthermore, to understand feedback processes, the social dimension of the use of ecosystems and a more integrated approach viewing River-Sea Systems as social-ecological systems is needed for a holistic view of River-Sea System changes.

Without employing ecosystem service values appropriately in management and planning, evaluating the impact of the worldwide degradation of River-Sea Systems will be difficult. New approaches such as nature-based solutions need to be tested for their effects on ecosystem service provision and biodiversity and need to include analyses of trade-off and multifunctionality to identify management priorities, as shown for example for a restoration framework for Danube floodplains[143]. Alternatively, quantitative assessment tools for ecosystem services and their value beyond economic terms require further development because attributing value needs to go beyond the standard economic valuation models[110].

Responding to Complexity

River-Sea Systems of the future will be the product of the combined influence of climate change and human activities. Climate change is projected to exacerbate the consequences of human activities at different spatial and temporal scales[144]. Human action in many respects amplifies the consequences of climate change. Compelling examples of the inherent complexity of cause and effect on River-Sea Systems, and the interconnectedness of human activities and changing climate, provide southern European Deltas[61]. These were formed almost synchronously during the Roman Empire and the Little Ice Age despite contrasting climates, due to deforestation and increase in population in river catchments. This has been followed by delta retreats due to river regulation and sediment trapping behind dams. The effects of reduced sediment fluxes to the coast are amplified by the sinking of deltas due to land subsidence and sea level rise which increase the vulnerability of the coastal zone to erosion and flooding. DANUBIUS-RI's research and the sustainable management of River-Sea Systems have to take into account these interrelationships.

Human activities interfering in climate forcing, land use and the water cycle are interconnected[28,6]. While humans can mitigate the effects and impacts of natural forces such as climate variability, extreme events and geologic forces like land subsidence and earthquake-mediated tsunamis, they can hardly intervene directly with these natural drivers. Man-made climate change and natural climate variability affect River-Sea systems on long temporal and at global scales with often locally differing impacts, while human activities are occurring over shorter timescales, with local to regional impacts. The anthropogenic influence on climate change is superimposed on natural, low-frequency climate variability (e.g. decadal or multi-decadal climate oscillations like the North Atlantic Oscillation), which makes a clear distinction challenging. However, distinguishing between the contribution of climate and human drivers is crucial for effective prevention and mitigation measures[145] and demands interdisciplinary approaches at multiple scales.

Climate change is here to stay due to the thermal inertia of the water volumes on Earth, even if greenhouse gas emissions were to stabilise[38,146,147]. Sea level rise in particular is likely to keep increasing for centuries. Relative to today, the IPCC projects by 2300 an almost 1 m increase in a low emission-high mitigation future, and an up to 3.5 m increase in a high emission-no combatting policies scenario[18]. Hence, human and climate driving forces continue to converge on a narrow fringe of territory: the land-water interface where the level of conflicting uses will increase, particularly near large urban areas, and in areas subject to multiple pressures such as combined riverine and coastal flooding[148].

The impacts of sea level rise on coastal ecosystems include habitat contraction, geographical shift of associated species, and loss of biodiversity and ecosystem functionality. Anthropogenic barriers prevent landward shift of marshes and mangroves[18]. In addition, many large coastal deltas are subject to shrinking as consequences of reduced sediment loads due to damming and water use land subsidence resulting from groundwater abstraction, and aquaculture[28]. Saltwater intrusion into groundwater bodies will be a consequence, amplified by rising sea level. Increased nutrient and organic matter loads provided by rivers to estuaries and coastal seas since the 1970s from intensive human development have exacerbated the effects of ocean warming on bacterial respiration, leading to the expansion of hypoxic areas in coastal seas[18]. Human development will continue with significant differences in climate commitments depending on countries, their economic situation and social development. This situation is likely to exacerbate assuming increase in population and intensification of land use in river catchments and coastal zones[149].

Research Needs

Attributing impacts on the social-ecological system in River-Sea Systems to natural, climate and other human drivers will be a major challenge for research as effective prevention and mitigation measures crucially depend on it. Deltaic/estuarine systems as represented by several DANUBIUS-RI Supersites are suitable testbeds to analyse sustainability in the face of increasing climate change and human pressures and identifying solutions to current and emerging societal problems.

The implications of global change and megatrends will develop in different ways in different parts of River-Sea Systems. How are environmental and social-economical changes propagating through the River-Sea System and at what timescales? What are the ranges of climate and human induced changes to which River-Sea Systems are able to adapt while maintaining ecosystem functioning and services? What are the key thresholds for the functioning of entire River-Sea Systems?

Essential for the development of effective prevention and mitigation measures is the understanding, how climate change, as an amplifier of human pressures, will affect the River-Sea continuum functioning, in different environmental and societal settings. What will be the combined effects of climate change with hydromorphological changes, diffuse nutrient and pollutant input on ecosystem health? What will be the costs of mismanaged River-Sea Systems that have lost their ability of sustaining ecosystem services?

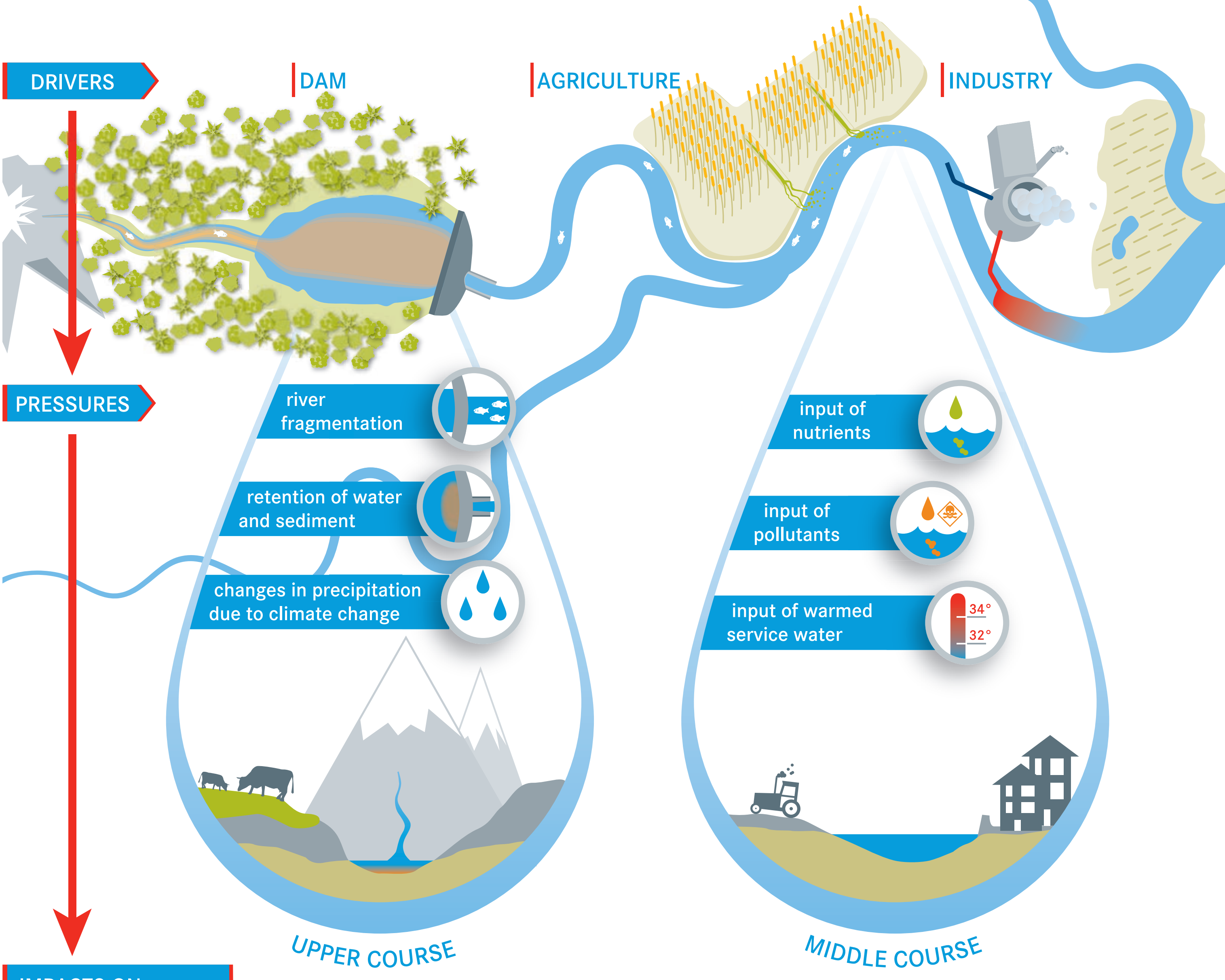
The development of scenario models combining climate variability, climate change and human induced changes is essential to develop solutions to address the main conflicts and challenges resulting from complexity in the River-Sea continuum. Here, the monitoring and data analysis from Supersites, complemented by tools from the Modelling Node, will be the basis for analysing the efficiency of solutions. 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.

The impacts of a non-resilient social-ecological River-Sea System on societal wellbeing can be severe; it can influence and in the worst case trigger societal failures[6]. Therefore, the ultimate goal in the Anthropocene is to develop resilient River-Sea Systems, applying resilience-building principles: manage connectivity, maintain diversity, manage slow variables and feedbacks, foster complex adaptive systems thinking, encourage learning, broaden participation and transboundary management[150].

Research on adequate solutions to prevent overexploitation of ecosystem services of River-Sea Systems and disaster prevention should integrate water resource management and landscape planning through increased protection of freshwater ecosystems, nature-based solutions, improving transboundary water cooperation and management, addressing impacts of fragmentation due to dams and diversions, and incorporating regional analyses of the water cycle[106]. Approaches to sustainability further require mainstreaming of practices that reduce soil erosion and pollution run-off, improving sediment management, reducing the fragmentation of water policies, applying nature-based solutions, and integrating ecological functionality concerns into the planning of river and coastal construction[106].

From the River Source to the Sea

Rivers transport water, sediment and other material from their source to the coastal sea. This lifeline between the land and the sea has been profoundly altered by human activities, with consequences for humans and nature. DANUBIUS-RI is researching these changes and is developing science-based solutions for the sustainable management of River-Sea Systems.



DRIVERS

DAM

AGRICULTURE

INDUSTRY

PRESSURES

river fragmentation

retention of water and sediment

changes in precipitation due to climate change

input of nutrients

input of pollutants

input of warmed service water

UPPER COURSE

MIDDLE COURSE

IMPACTS ON RIVER AND SEA

Human activities have multiple and often compounding effects, propagating through the River Sea System and with impacts that are sometimes visible at points far from the point of origin.

temperature stress for native species

habitat loss

spread of invasive species

land subsidence

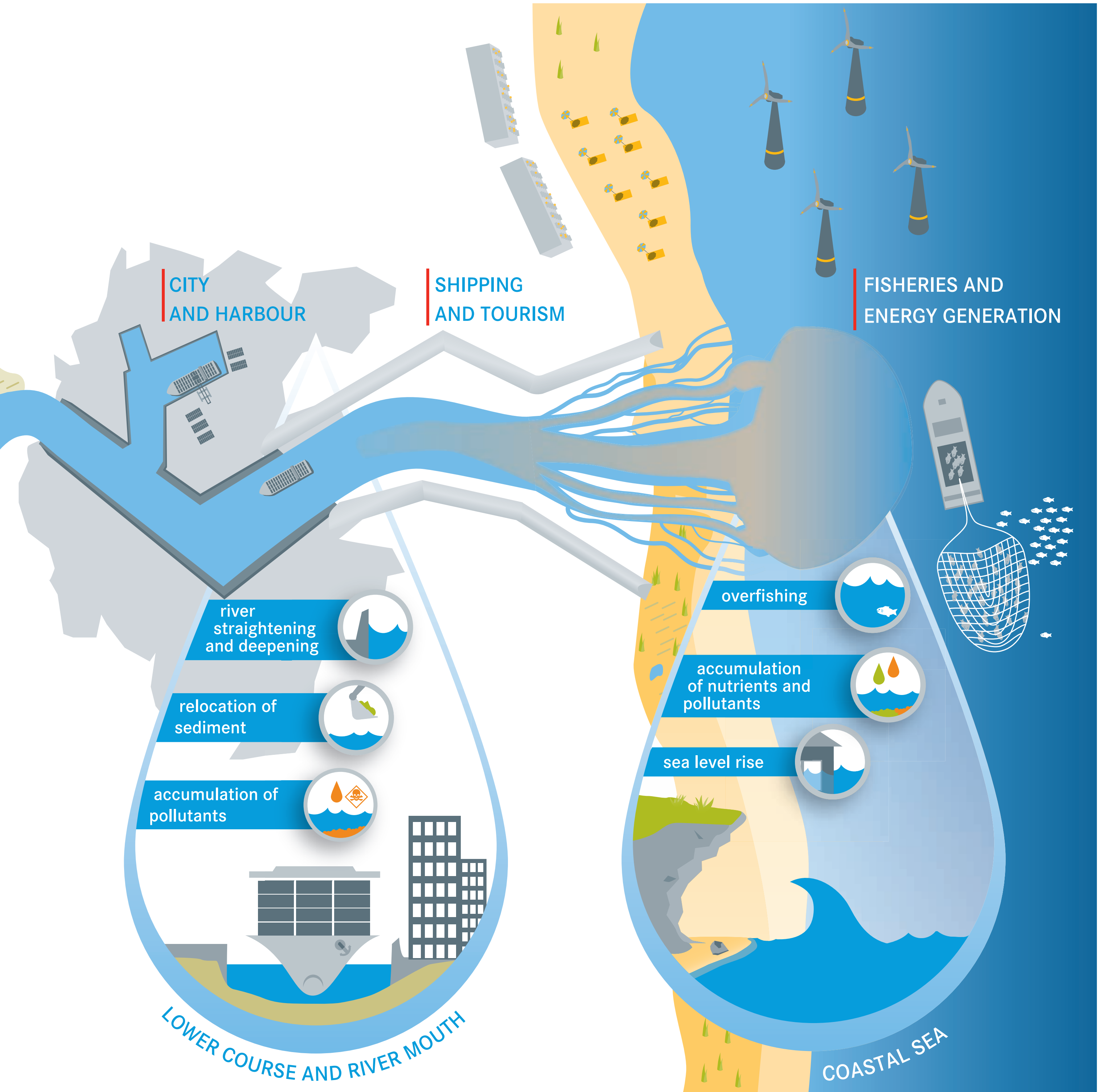
decline of fish stock

hydropeaking

extreme floods/low waters

impaired fish migration

insufficient floodplains



decrease in self-purification capacity

bank and coastal erosion

sediment starvation on coasts and in deltas

altered hydrological conditions

surplus algae growth in the rivers and seas

decrease in water and sediment quality

low-oxygen zones

groundwater salinisation

accumulation of pollutants in organisms and damage

biodiversity loss

4.

Our Strategic Research Priorities

4. Our Strategic Research Priorities

This chapter presents DANUBIUS-RI's research priorities for the first five years, which will guide DANUBIUS-RI's starting activities as it proceeds to operation. Our research priorities will be regularly updated to assure maximum societal impact over time. Societies and their economies are embedded parts of River-Sea Systems. DANUBIUS-RI believes that healthy River-Sea Systems are both directly and indirectly the basis to fulfill the SDGs of the United Nations[16]. Consequently, DANUBIUS-RI's strategic research priorities for the first five years are of societal relevance and in line with upcoming mission areas of Horizon Europe, applied to River-Sea Systems:

Achieving healthy inland, transitional and coastal waters.

Adapting to climate change: enhancing resilience of River-Sea Systems.

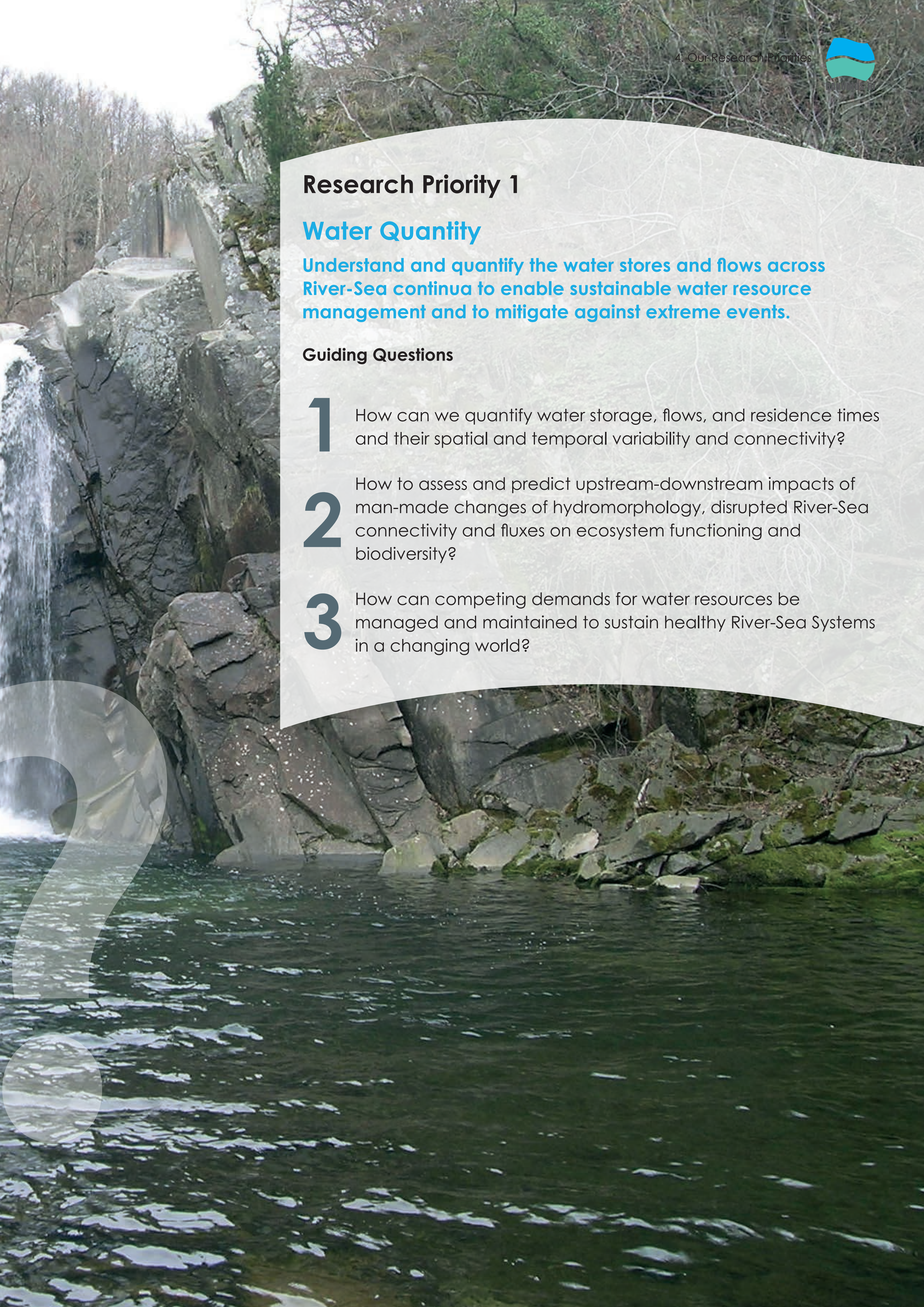
Addressing these mission areas, **DANUBIUS-RI's strategic research priorities** are based on the following criteria:

- Topics of societal and environmental urgency, where answers can be facilitated within five years;
- Topics of societal and environmental urgency that must be tackled now, although providing answers may take longer than five years;
- Require a source-to-sea perspective along the chain of integrating existing data – observation – analysis – modelling – socio-ecological impact;
- Facilitate system understanding, and identify management options and solutions;
- Require interdisciplinary and cross-sectorial approaches.
- Topics, which can be facilitated by research infrastructure that is already available at the DANUBIUS-RI components, while developing the new components step by step according to upcoming research needs.

One prerequisite for adopting truly integrated source-to sea approaches is innovative methodological solutions. Consequently, the development of automated state-of-the-art observation systems, combining in-situ and remote sensing, freshwater-seawater analytical methods, integrated modelling tools, nature-based solutions, advanced methods and concepts for impact and risk assessment and stakeholder engagement will form an intrinsic element of DANUBIUS-RI's research and development.

Achieving Healthy Inland, Transitional and Coastal Waters

Water is indispensable for Earth`s resilience and sustainable development[6]. There is broad agreement globally, across social classes and across disciplines, that solving problems related to water resource use will be of paramount importance in coming decades. The capacity of social-ecological systems to meet the many water resources challenges will fundamentally depend on healthy ecosystems which can sustain their core functions under conditions of global change. Given that many River-Sea Systems worldwide have been irreversibly changed by humans, understanding the constraints on ecosystem functioning is critical for conservation and restoration. These targets have to be in line with societal, economic and cultural expectations. Hence, without a profound understanding of what constitutes a healthy River-Sea System in the Anthropocene, it is impossible to set targets and assess whether management actions have been effective.



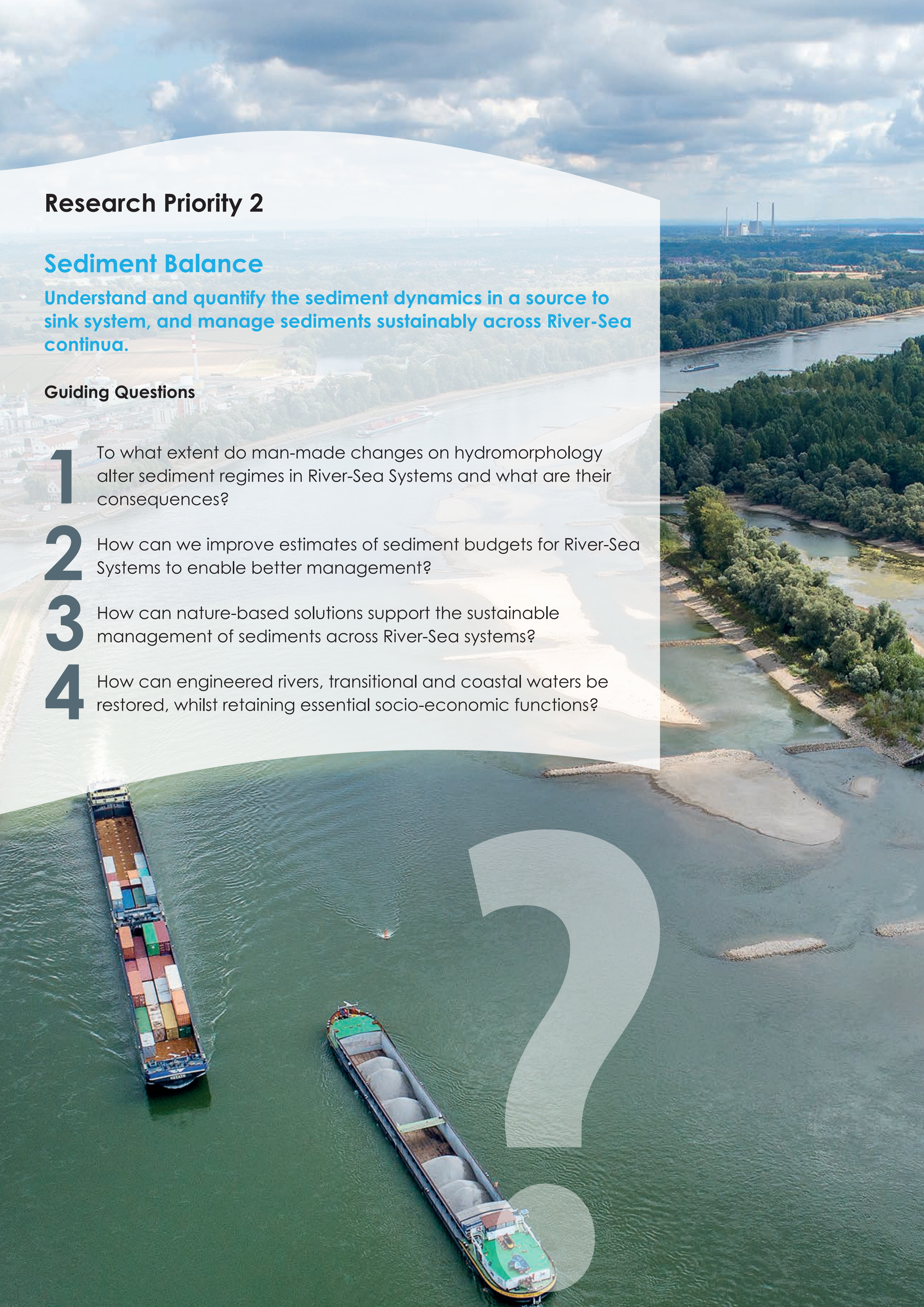
Research Priority 1

Water Quantity

Understand and quantify the water stores and flows across River-Sea continua to enable sustainable water resource management and to mitigate against extreme events.

Guiding Questions

1. How can we quantify water storage, flows, and residence times and their spatial and temporal variability and connectivity?
2. How to assess and predict upstream-downstream impacts of man-made changes of hydromorphology, disrupted River-Sea connectivity and fluxes on ecosystem functioning and biodiversity?
3. How can competing demands for water resources be managed and maintained to sustain healthy River-Sea Systems in a changing world?



Research Priority 2

Sediment Balance

Understand and quantify the sediment dynamics in a source to sink system, and manage sediments sustainably across River-Sea continua.

Guiding Questions

1. To what extent do man-made changes on hydromorphology alter sediment regimes in River-Sea Systems and what are their consequences?
2. How can we improve estimates of sediment budgets for River-Sea Systems to enable better management?
3. How can nature-based solutions support the sustainable management of sediments across River-Sea systems?
4. How can engineered rivers, transitional and coastal waters be restored, whilst retaining essential socio-economic functions?

Research Priority 3

Nutrients and Pollutants

Understand and quantify the singular and combined effects of nutrients and pollutants in water and sediments to establish critical thresholds to support the achievement of good status at the scale of the River-Sea System.

Guiding Questions

1. What are the sources, pathways, transformations and sinks of nutrients and pollutants from current and legacy sources in River-Sea Systems?

2. How do eutrophication and hypoxia upstream impacting ecosystem state downstream, in estuaries/deltas and coastal seas, and how can we create effective nutrient retention zones in River-Sea Systems?

3. What are the thresholds for estuarine and coastal ecosystems resilience against single and multiple pollutant exposures from upstream and updrift, and what interdisciplinary approaches would enable a comprehensive environmental risk assessment of pollutants across River-Sea Systems?

4. How can new contaminant classes, such as plastics and pharmaceuticals, be detected and the impacts on water and sediment quality and ecosystem health be assessed?

5. How can science help to integrate economic strategies such as green economy, closed material cycles, technological advances, and changes in human behaviour to mitigate, control and manage pollution across River-Sea Systems?

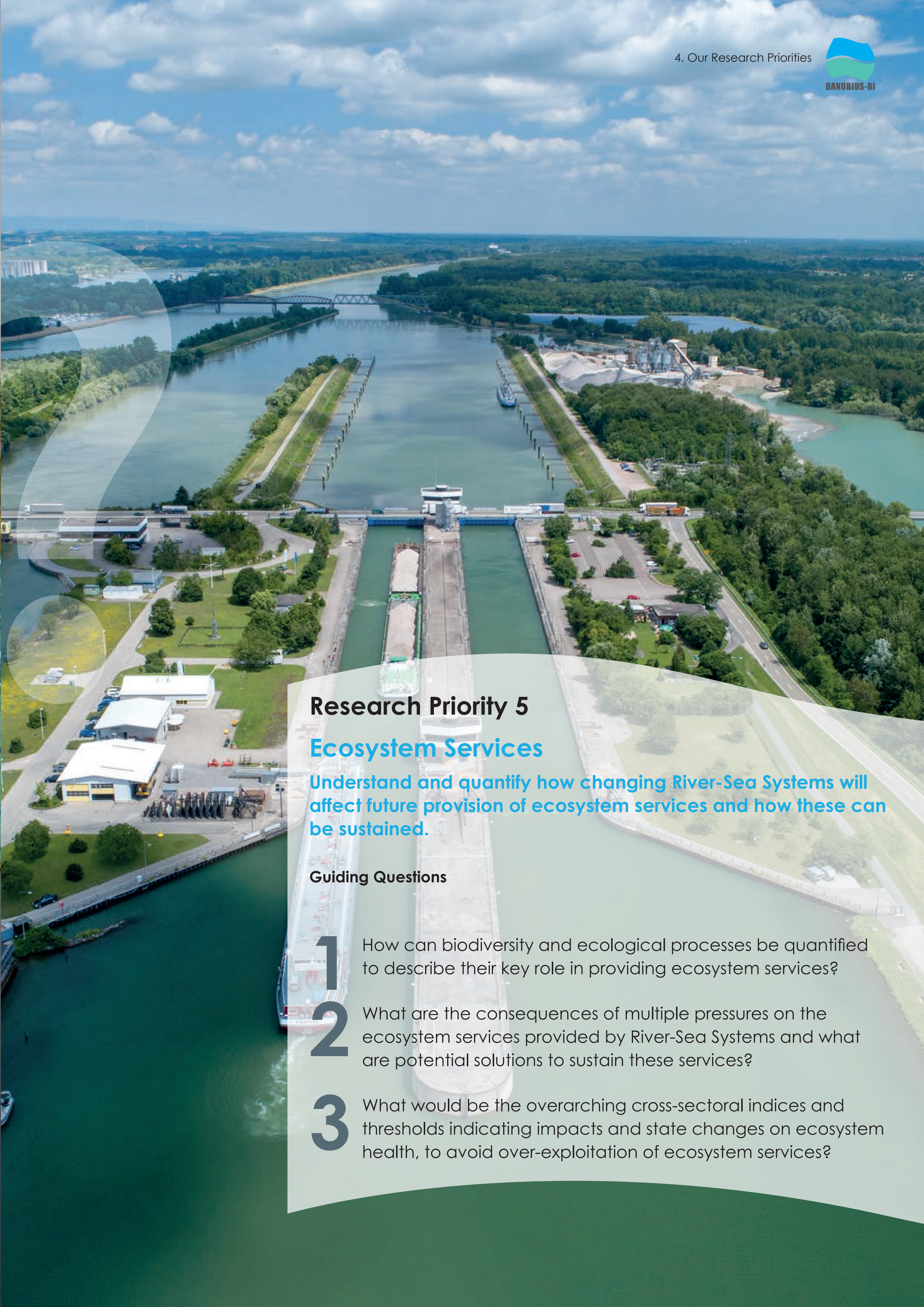
Research Priority 4

Biodiversity

Understand the relationship between biodiversity and connectivity across River-Sea Systems and its response to multiple stressors to support conservation and restoration.

Guiding Questions

1. How can the upstream and downstream impacts of man-made changes on biodiversity and ecosystem functioning in River-Sea Systems be assessed and predicted?
2. What risks do invasive species pose to ecosystem health and resilience and how can these be assessed?
3. What causes regime shifts in ecosystem structure and functioning and what are early warning indicators?
4. How can we maintain sufficient longitudinal and lateral ecological connectivity along the River-Sea continuum to protect and restore ecosystem health?



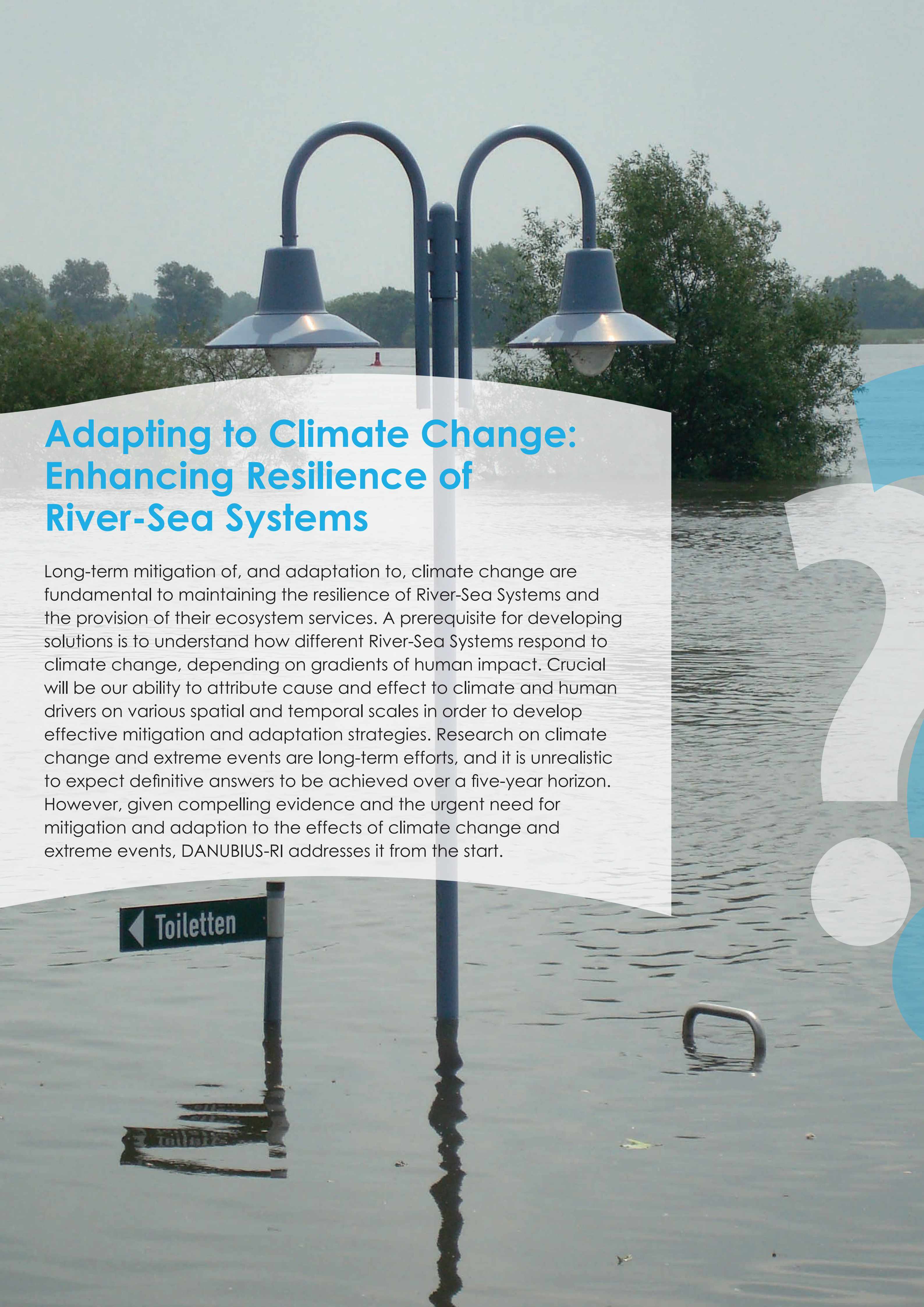
Research Priority 5

Ecosystem Services

Understand and quantify how changing River-Sea Systems will affect future provision of ecosystem services and how these can be sustained.

Guiding Questions

1. How can biodiversity and ecological processes be quantified to describe their key role in providing ecosystem services?
2. What are the consequences of multiple pressures on the ecosystem services provided by River-Sea Systems and what are potential solutions to sustain these services?
3. What would be the overarching cross-sectoral indices and thresholds indicating impacts and state changes on ecosystem health, to avoid over-exploitation of ecosystem services?



Adapting to Climate Change: Enhancing Resilience of River-Sea Systems

Long-term mitigation of, and adaptation to, climate change are fundamental to maintaining the resilience of River-Sea Systems and the provision of their ecosystem services. A prerequisite for developing solutions is to understand how different River-Sea Systems respond to climate change, depending on gradients of human impact. Crucial will be our ability to attribute cause and effect to climate and human drivers on various spatial and temporal scales in order to develop effective mitigation and adaptation strategies. Research on climate change and extreme events are long-term efforts, and it is unrealistic to expect definitive answers to be achieved over a five-year horizon. However, given compelling evidence and the urgent need for mitigation and adaption to the effects of climate change and extreme events, DANUBIUS-RI addresses it from the start.

Research Priority 6

Climate Change

Support the collection of data and the development of innovative methods and tools to assess the effects of climate change and to improve adaptation measures within and across River-Sea Systems.

Guiding Questions

1 How will human pressures amplified by climate change affect the river-sea continuum functioning, in different environmental and societal settings?

2 How will climate change and extreme events influence water & sediment quantity and quality throughout River-Sea Systems?

3 How will climate change affect key socio-economic benefits of River-Sea Systems?

4 How should climate change uncertainties be accounted for in occurrence and magnitude of extreme events regarding mitigation measures?

Research Priority 7

Extreme Events

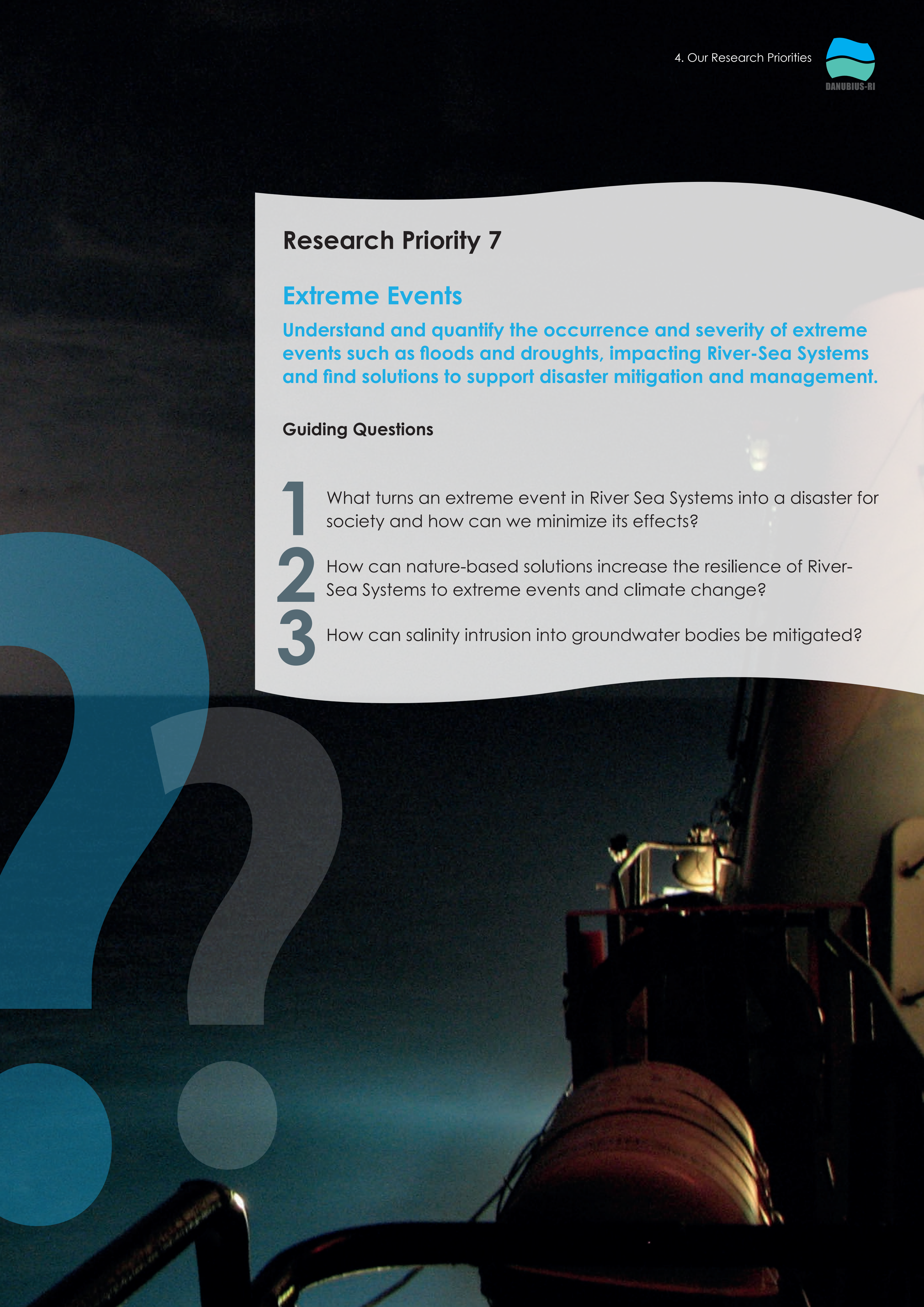
Understand and quantify the occurrence and severity of extreme events such as floods and droughts, impacting River-Sea Systems and find solutions to support disaster mitigation and management.

Guiding Questions

1 What turns an extreme event in River Sea Systems into a disaster for society and how can we minimize its effects?

2 How can nature-based solutions increase the resilience of River-Sea Systems to extreme events and climate change?

3 How can salinity intrusion into groundwater bodies be mitigated?



5.

Our Modus Operandi

5. Our Modus Operandi

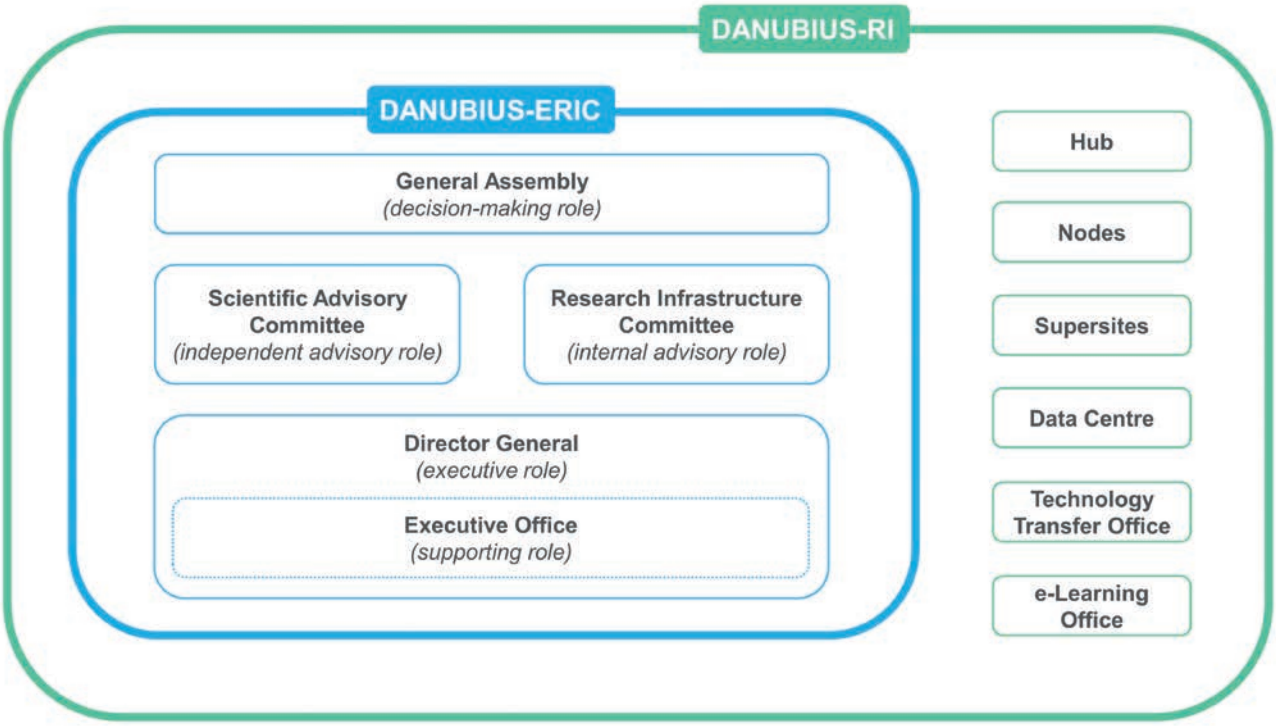
In this chapter we illustrate how we work. DANUBIUS-RI expects and welcomes collaboration with specialists from science related to River-Sea Systems, particularly regarding the interfaces with the atmospheric, marine, biological, terrestrial, geological domains and social sciences. Access for users to DANUBIUS-RI will be based on proposals, which will be evaluated for scientific excellence and social-economic relevance.

DANUBIUS-RI's Structure and Components

The DANUBIUS Research Infrastructure (DANUBIUS-RI) is coordinated by the International Centre for Advanced Studies on River-Sea Systems - European Research Infrastructure Consortium (DANUBIUS-ERIC). DANUBIUS-RI comprises the components: Hub, Nodes, Supersites, Data Centre, e-Learning Office and Technology Transfer Office. The DANUBIUS components will complement each other in their competencies, with tools and expertise.

DANUBIUS-ERIC will provide the governance framework. It will coordinate, manage, and harmonise the activities carried out by the DANUBIUS Components. It will provide a single point of access for applications to use the DANUBIUS Components. DANUBIUS-ERIC, through its Components, will coordinate and provide access to facilities, services, advice and data to promote interdisciplinary research and innovation within and across River-Sea Systems.

DANUBIUS ERIC Headquarters with a Director General and Executive Office will be **hosted by the Hub,** located in Romania. The Hub is also the Hosting Institution of the Danube Delta Supersite. The Hub also hosts the Centre of Eutrophication Research, to develop an integrated interdisciplinary approach to research on eutrophication of freshwater, marine and transitional ecosystems.



DANUBIUS-RI governance and structure.

The Nodes, coordinated by Leading Institutions in Europe, provide state-of-the-art facilities, interoperable methods and expertise regarding (1) **Observation** and (2) **Analysis**, (3) **Modelling** and (4) **Impact**. Their expertise and interaction are essential for holistic understanding of River-Sea Systems and to advance sustainable management of River-Sea Systems. Accredited Service Providers will complement the Leading Institutions of the Nodes, if specific required methods are not available there.

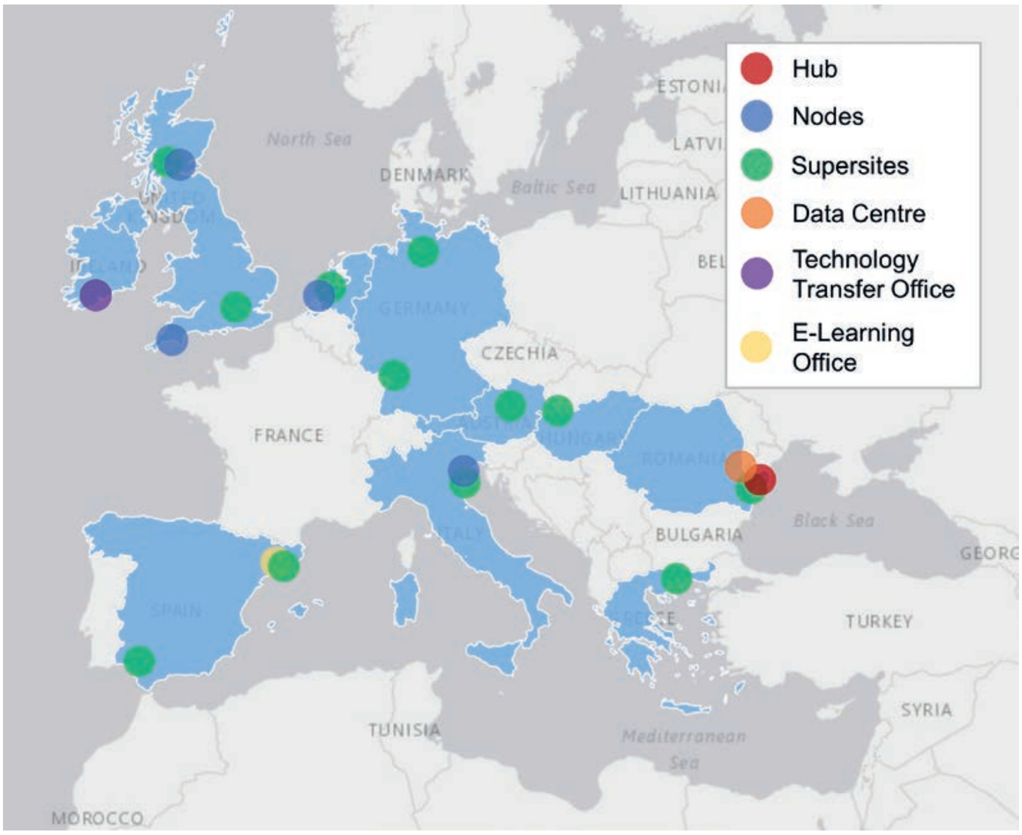
The Observation Node provides a) expertise and facilitates on hydrometric and optical sensor-driven in-situ and satellite observations ranging from catchments to coasts, in line with the Earth observation calibration and validation, b) develops methods and builds capacity for satellite data processing in near real-time coupled to in-situ data, and c) advises the Supersites in their observation activities. Quality control ensures data collection according to the standards and protocols of the DANUBIUS Commons. The Observation Node provides synoptic overviews of the Supersites from near-real time Earth observation images, enabling insight into catchment scale drivers, and time-series of archived satellite imagery for effective model calibration and validation. Satellite imagery will be distributed via the data centre to facilitate informed decision making by end-users.

The Analysis Node provides scientific expertise, concepts and technical know-how on interoperable methods, instrumentation and quality assurance procedures for sampling, field and laboratory analysis across five major scientific disciplines: hydromorphology, chemistry, biology, ecotoxicology and hygiene. In close cooperation with the Observation Node responsibilities are defined in detail at the interfaces between in-situ and laboratory analyses, and methodological support is provided in calibration and validation of remote sensing data. A core activity of the Analysis Node is the development of fit-for-purpose new methodologies on sampling, analysis and measurement techniques across environmental gradients occurring in River-Sea Systems, e.g. salinity gradients, and to identify and quantify parameters or effects, e.g. new harmful substances, which have not been considered so far.

The Modelling Node provides expertise and modelling tools to represent the physical, chemical and ecological status and related processes within a River-Sea System. Expert support for researchers, numerical codes, training and tailored modelling applications will be provided to allow evaluation scenarios for regional and local studies (e.g. at individual Supersites) and support management issues for stakeholders. A major focus will be the development of modelling tools to reproduce the feedback and interconnections between physical, biogeochemical and ecological processes along the entire River-Sea continuum, and connect the environmental results to the social-economic impacts to investigate what-if and climate scenarios. This will be achieved by a) creating a modelling community, building on the modelling capacity of DANUBIUS-RI partners, b) defining baseline processes that a River-Sea System model must resolve, c) coupling complementary and multi-resolution process models and geographical domains from catchment to coast, d) improving data assimilation into models, e) improving model capabilities for large-scale simulations by collaborating with high-performance computing centres and computing infrastructures. The Modelling Node will focus on both developing suitable numerical tools to satisfy the need of complexity (full process reproduction) and improving the simplicity of interfaces (usability).

The Impact Node develops methodologies and practical tools for sustainable management of River-Sea Systems, facilitates knowledge exchange at the interface between natural and social sciences, and transfers the scientific output to users. The Node provides expertise on developing, measuring and monitoring of societal impact. It provides impact assessment, i.e. assessing the potential societal impact and the evaluation of impact generated. Furthermore, it supports the design of stakeholder participation processes and interdisciplinary learning processes to optimise their impact and transfers questions from society (policy, industry, citizens) into scientific research questions and transfer of scientific findings of DANUBIUS-RI into practical, operational perspective. The Impact Node develops impact guidelines and handbooks for optimizing societal impact and provides training and capacity building to achieve societal impact.

The DANUBIUS-RI Supersites are representative areas of River-Sea Systems to: a) advance process and system understanding and diagnose cause-effect relationships, b) assess impacts and risks from external (natural, climate) and internal (human) drivers, and c) develop and test potential measures to address common challenges in River -Sea Systems. As such, Supersites serve as natural laboratories or "test beds" for observation, analysis, modelling and social-economic impact studies. Supersites cover a range of climatic, environmental and socio-economic gradients, as well as gradients of human impact. Supersites either cover an entire (small) River-Sea System or several Supersites may be located within a large River-Sea System. Each Supersite is coordinated by a Hosting Institution. The Hosting Institution coordinates and provides research infrastructure for field observations (e.g., automated stations like ferry boxes, research vessel), laboratory analyses, computing infrastructure and modelling tools, according to their field of expertise. The Nodes provide the required expertise on technologies, methods, models and training supporting the activities within the Supersites, as needed.



Map showing the locations of the DANUBIUS-RI Components.

The Data Centre provides access to data and meta-data from Supersites and Nodes, stores and classifies the data as required, and provides additional functionality for search and access. The data portal will be the gateway to DANUBIUS-RI, covering digital data from remote sensing, automatic stations, cruises, computer models, and the results of other laboratory analyses. The Data Centre will also give access to the metadatabase concerning the non-digital data existing in various components. DANUBIUS-RI's data management plan and data policy follows the FAIR (findable, accessible, interoperable and re-usable) principles.

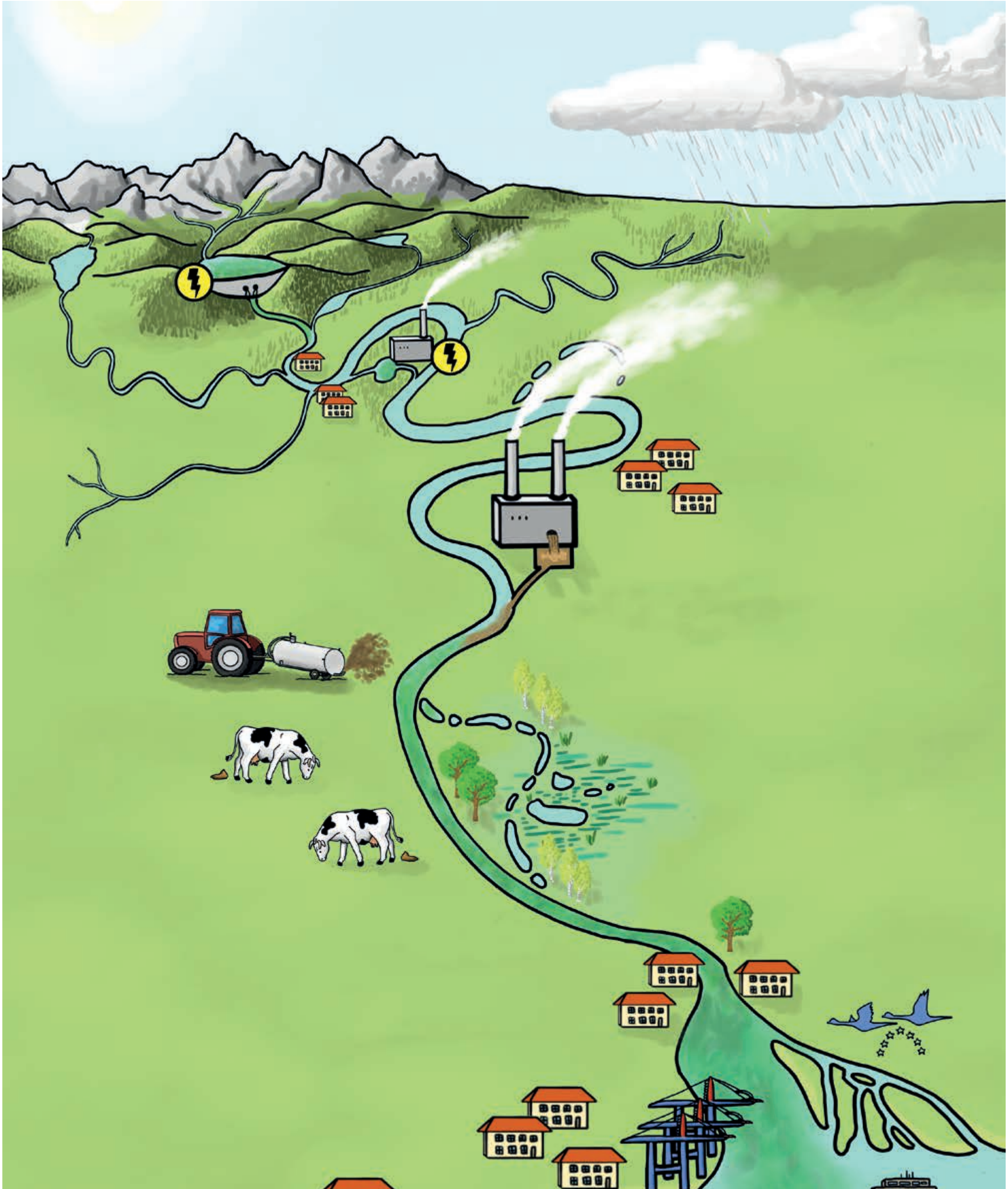
The e-Learning Office will use Information Communication Technology for training and education in the field of River-Sea Systems of the next generation of researchers and practitioners, including: a) organising Master programmes with a blended learning approach recognised by several European universities; b) organising courses and summer school programmes on aspects of River-Sea Systems (e.g. assimilation of data, early warning systems, solutions based on natural processes); c) organising e-learning programmes for postgraduate students on issues in observation, analysis, modelling, and impact; d) developing plans for Master and Doctorate research projects jointly supervised by DANUBIUS-RI Partners; e) developing ad-hoc training courses for administrators or third party interested in sustainable management; and f) offering a virtual meeting point for academia, administration and industry.

The Technology Transfer Office will protect and leverage intellectual property rights and infrastructural resources to successfully engage 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 research infrastructure as a whole, and thus maximise DANUBIUS-RI's overall impact. A distributed model has been proposed for the Technology Transfer Office across jurisdictions to satisfy intellectual property (rights) requirements with respect to the policies and legislation of member countries.

DANUBIUS COMMONS. Integrated and interdisciplinary research across Europe requires a common approach and language, as well as common principles, standards, and methods. Hence, a key element of DANUBIUS-RI will be the **DANUBIUS Commons**: a set of harmonised regulations, methods, procedures and standards for scientific and non-scientific activities, to guarantee the integrity, relevance, consistency and elevated quality of DANUBIUS-RI's products. The DANUBIUS Commons will provide the framework to ensure that the outputs of DANUBIUS-RI are compatible, comparable, and exchangeable throughout the research infrastructure, and within the user community. They will be continually reviewed and revised while established quality assurance and control mechanisms (e.g. ring tests) will ensure comparability between the different facilities of DANUBIUS-RI.

Map with River-Sea Systems and their catchments (hatched), where the current DANUBIUS-RI Supersites are located. The locations of the Hosting Institutions are indicated by green dots. The Supersites coverage within the River-Sea Systems is highlighted by the green-blue bars.

River-Sea System	**Headwaters**	**Middle Waters**	**Lower & Transitional Waters**	**Coastal Waters**
Danube-Black Sea	🟩	🟩	🟦	🟦
Elbe-North Sea			🟦	🟦
Rhine-North Sea		🟩	🟦	🟦
Thames-North Sea			🟦	🟦
Tay-North Sea	🟩	🟩	🟦	🟦
Guadalquivir-Atlantic Ocean			🟦	🟦
Ebro-Mediterranean Sea			🟦	🟦
Po-Adriatic Sea			🟦	🟦
Nestos-Aegean Sea	🟩	🟩	🟦	🟦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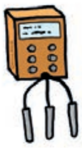


Supersites provide

- access to study sites covering (1) a whole River-Sea System or several sites within a River-Sea System and (2) a range of River-Sea Systems along climatic, environmental and socio-economic gradients
- access to specific field equipment, research platforms and laboratories within Supersite
- expert support and training for specific field campaigns and laboratory studies
- in situ and ex situ data encompassing key variables in River-Sea Systems
- interface between local and regional expertise as well as national and international expertise in other Supersites and Nodes

Observation Node

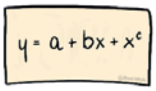
- expert support and training for processing, calibrating and validating Earth observation data incl. deployment of sensors
- development of algorithms, sensor and machine learning technologies
- earth observation and in situ data over large areas and over time
- citizen science in collaboration with Impact Node; validation of data from Supersites and Modelling Node; identification of sampling locations for further analysis

Analysis Node

- access to "beyond state of the art" analytical facilities
- expert support and training for sampling and analysis to assure quality and intercomparability
- development of methods and standards
- ex situ data at representative locations over time
- validation of data from Supersites, Observation and Modelling Nodes

Modelling Node

- expert support and training for the use of modelling software, model applications, good modelling practice, standardisations
- development and access to model codes and manuals, coupled models (e.g. "from catchment to coast") and "what if?" scenario applications
- modelled data filling gaps within data from Supersites, Observation and Analysis Nodes
- integration of data and knowledge from Supersites and other Nodes; identification of locations for further Observation and Analysis



Impact Node

- expert support and training on impact design, assessment and guidelines
- development and access to concepts, methods and tools to support governance, policy-making and management
- integration of data and knowledge from Supersites and other Nodes; co-creation of scenarios and solutions with stakeholders, as well as research questions for further observation, analysis and modelling

Data Centre

- aggregation of data from Supersites and Nodes
- storage and preservation of data
- access and download of data through data portal
- data visualisation and analysis tools

What DANUBIUS-RI can offer to users.

Services

The DANUBIUS-RI service line-up spans a range of disciplines, all of which are needed to address the major questions and challenges of River-Sea Systems. The services address five categories of users:

- Researchers: academic and scientific users
- Businesses and professionals: companies and charities
- Students: pupils and students
- Authorities: local, national and transnational authorities
- Citizens: the public at large.

Seven categories of services have been developed: (1) digital and non-digital data; 2) tools, methods and expert support; (3) study and measurements; (4) diagnostic and impact; (5) solution development; (6) tests, audit, validation and certification; and (7) training.

(1) **Digital and Non-Digital Data**: This category encompasses services that offer access to metadata, data and samples produced or collected by DANUBIUS-RI. Most of these services are e-services, but some require a physical access, such as the sample and sediment core repositories. The DANUBIUS-RI platform, hosted by the Data Centre, will offer users data from observations (in situ and remotely), analyses (ex situ) and modelling along the River-Sea continuum and from a wide range of River-Sea Systems.

(2) **Tools, Methods and Expert Support:** This category includes services that provide access to facilities and equipment, specific methods and tools, and provide expert support. Methods and tools are related to observation, sampling and analysis according to the DANUBIUS Commons, to models codes, coupled and scenario models, data processing and visualisation. Expert support assists users in the use of facilities, equipment, methods and tools.

(3) **Study and Measurements:** This category encompasses services associated with undertaking analyses and measurements with users or on their behalf. Most services in this category can be rendered on-site or remotely. The range of analyses and measurements is large, including physical, chemical, biological, biogeochemical, ecotoxicological, hydromorphological, sedimentological, and bathymetric analyses. The service range also includes assessments of water and sediment quality. This service category involves collaboration with users beyond technical assistance but does not include work from DANUBIUS-RI experts on interpretation of the results.

(4) **Diagnostic and Impact:** This category includes services that entail data analysis by DANUBIUS-RI specialists beyond the analyses and measurements obtained in the services category. Data analysis can be performed by comparing data with previous or expected results (diagnostic) or with forecasts (from models). This category range implies a level of involvement of DANUBIUS-RI beyond technical support and requires DANUBIUS-RI experts to assist users in interpreting the analyses and studies carried out in collaboration with users. This whole category of services is based on DANUBIUS-RI expertise in modelling and impact assessment, for example impact assessment of pollutants, nutrients and alien species.

(5) **Solution Development:** This category comprises services addressing users – mostly from the private sector – looking for a scientific partner with wide-ranging expertise to develop solutions for specific challenges in River-Sea Systems. Unlike other service categories, this service category is defined in terms of development rather than data, tools, methods and models.

(6) **Tests, Audit, Validation and Certification:** This category includes validation and quality assurance of observation, analysis and modelling, the accreditation of the DANUBIUS Commons and certification of Accredited Service Providers.

(7) **Training:** This category is not restricted to students and includes all the potential trainings and courses that DANUBIUS-RI can offer, for example to companies and authorities in the four areas of expertise (Observation, Analysis, Modelling, and Impact). This service category also includes organising conferences and workshops.

Access to Services (on-site, remote or on-site and remote services) requires users to submit an application describing the purpose of the request, the work to be done, the resources to be mobilised (on the user side), the methodology and the expected outcome and impact, and the acceptance of the terms of access at DANUBIUS-RI (including the availability of data generated or used during the access, and the commitment to publish and credit DANUBIUS-RI – infrastructure and researchers – in the publications based on the results of the work). A panel of experts will be charged to review all applications, and rank applications by level of scientific interest. Applications with the highest scientific interest will be granted access to DANUBIUS-RI with the full support of experts and technicians, irrespective of the user affiliation or origin, and at no cost for the user.

DANUBIUS-RI on the international stage

River-Sea Systems are connected to other parts of the Earth system, such as land, open ocean, atmosphere, biosphere and the geosphere. These natural connections reflect DANUBIUS-RI's interface with other research infrastructures, programmes and initiatives. Here, cooperation is crucial to explore and exploit synergies, to include different research perspectives, to share infrastructures and to avoid duplication. DANUBIUS-RI will monitor activities and opportunities within and between research infrastructures, lead initiatives and openly display opportunities for collaboration with relevant scientific communities.

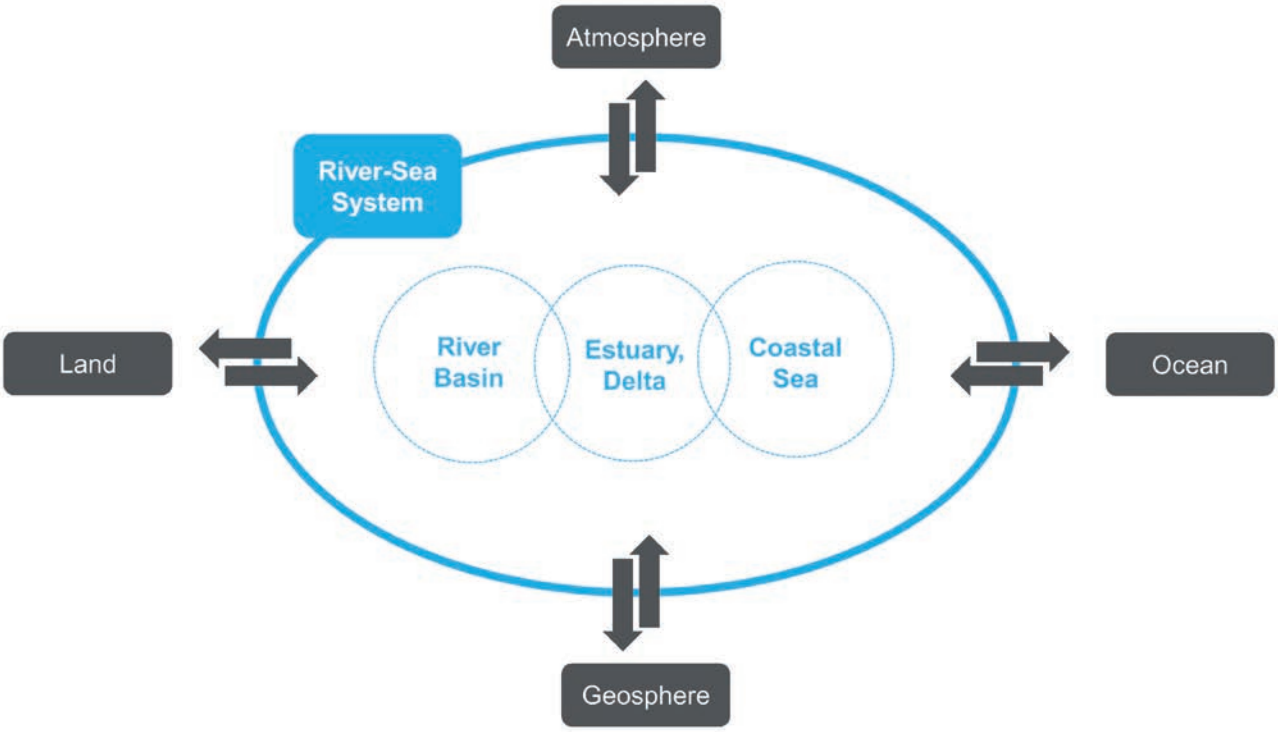
Cooperation with other Research Infrastructures
DANUBIUS-RI is part of the environmental research infrastructure (ENVRI) community, where it fills the gap in the aquatic domain between fresh- and marine water, and research infrastructures dedicated to the atmospheric, marine, terrestrial and geological domains. In the atmospheric domain, we will cooperate with ICOS-ERIC by providing data on greenhouse gas emissions in wetlands in selected Supersites. There is also a strong potential to cooperate with ACTRIS and IAGOS. In the marine domain, we will cooperate with EMSO-ERIC to provide an upstream continuation of observations in basins of mutual interest. EMSO-ERIC has offered its full support during the development of DANUBIUS-RI. There is also a strong potential to cooperate with EURO-ARGO ERIC. In the geological domain, we will cooperate with EPOS-ERIC to provide supplementary expertise on sensitive parts of the solid earth. This includes rivers, deltas, estuaries and coastal seas, which are affected by active tectonic and other geological processes (e.g. subsidence). In the biosphere domain, there is a potential to cooperate with LifeWatch ERIC and eLTER. Some Supersites coincide with eLTER sites even though they have different characteristics. A harmonization of parameters and methodologies has been agreed on both sides. There is also a strong potential to cooperate with DiSSCo, EMBRC, AnaEE.

Cooperation with Networks of Research Infrastructures

There are several networks of research infrastructures, which have a potential for cooperation. For example, DANUBIUS-RI and HYDRALAB have agreed on the need for strategic cooperation given the complementarity of the two initiatives. On the one hand, HYDRALAB needs high quality in situ data to integrate and adapt their physical modelling experiments which could be provided by DANUBIUS-RI's Observation and Analysis Nodes. On the other hand, HYDRALAB's data would provide a major input for the complex numerical models developed by DANUBIUS-RI's Modelling Node. Cooperation is also possible with JERICO and AQUACOSM due to areas of mutual interest. For example, JERICO could provide additional data from coastal observatories, which are situated further away from river mouths, while DANUBIUS-RI could provide data from transitional waters: estuaries, deltas and lagoons.

Cooperation with Research Programmes & Initiatives

Cooperation with different research initiatives is crucial for DANUBIUS-RI. These include the Joint Programming Initiatives (JPI) which are instruments for implementing European Research Areas. Both JPI Water and JPI Oceans could serve as valuable platforms to initiate research calls within the scope of DANUBIUS-RI. This could foster scientists to apply for research grants to be conducted within the respective research infrastructure. Furthermore, DANUBIUS-RI could support the implementation of both JPI Water and Oceans since their scientific agendas have many points of mutual interest. Finally, research projects funded under Horizon 2020 and Horizon Europe could extend their research with the support of DANUBIUS-RI. Contacts with other funding programmes (e.g. LIFE, Interreg, COST) will be established to support the practical implementation of environmental research. Collaboration with Future Earth is foreseen as well.



River-Sea Systems are located at the interface between land and ocean, geosphere and atmosphere.

Cooperation with Data Programmes & Initiatives

DANUBIUS-RI will benefit from access to data (and models) that are hosted or supported by existing or planned large scale programmes on national, European and global levels. There will also be the possibility for data generated from DANUBIUS-RI to be provided to existing public data portals. DANUBIUS-RI will interact with international programmes including, primarily, the European Copernicus programme given the political linkages, data availability and technical requirements. Copernicus will be the main European contribution to the Global Earth Observation Systems of Systems (GEOSS) and a principal provider of Earth observation and model data for near-real time observation as well as long climate data records and future forecasts; hence, Copernicus will be a key input to DANUBIUS-RI's Nodes and Supersites. Similarly, linkages with the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT) and other major European and International Programmes such as SeaDataNet and EMODnet are discussed from both practical as well as political perspectives.

Cooperation with River Basin & Regional Seas Commissions

International river basin and regional seas commissions, such as the International Commission for the Protection of the Elbe River (ICPER), the International Commission for the Protection of the Rhine (ICPR), the International Commission for the Protection of the Danube River (ICPDR), the Black Sea Commission, the Inter-Mediterranean Commission, and the OSPAR Commission for the North-East Atlantic have been effective fora of political and practical transboundary cooperation throughout Europe for many years. DANUBIUS-RI is striving for a close partnership with these organisations on research questions on observation, analysis or modelling and by providing the Supersites as test beds for new forms of monitoring, data integration or stakeholder involvement. DANUBIUS-RI will benefit from the longtime existing cooperation framework, expertise, monitoring and data in these commissions.

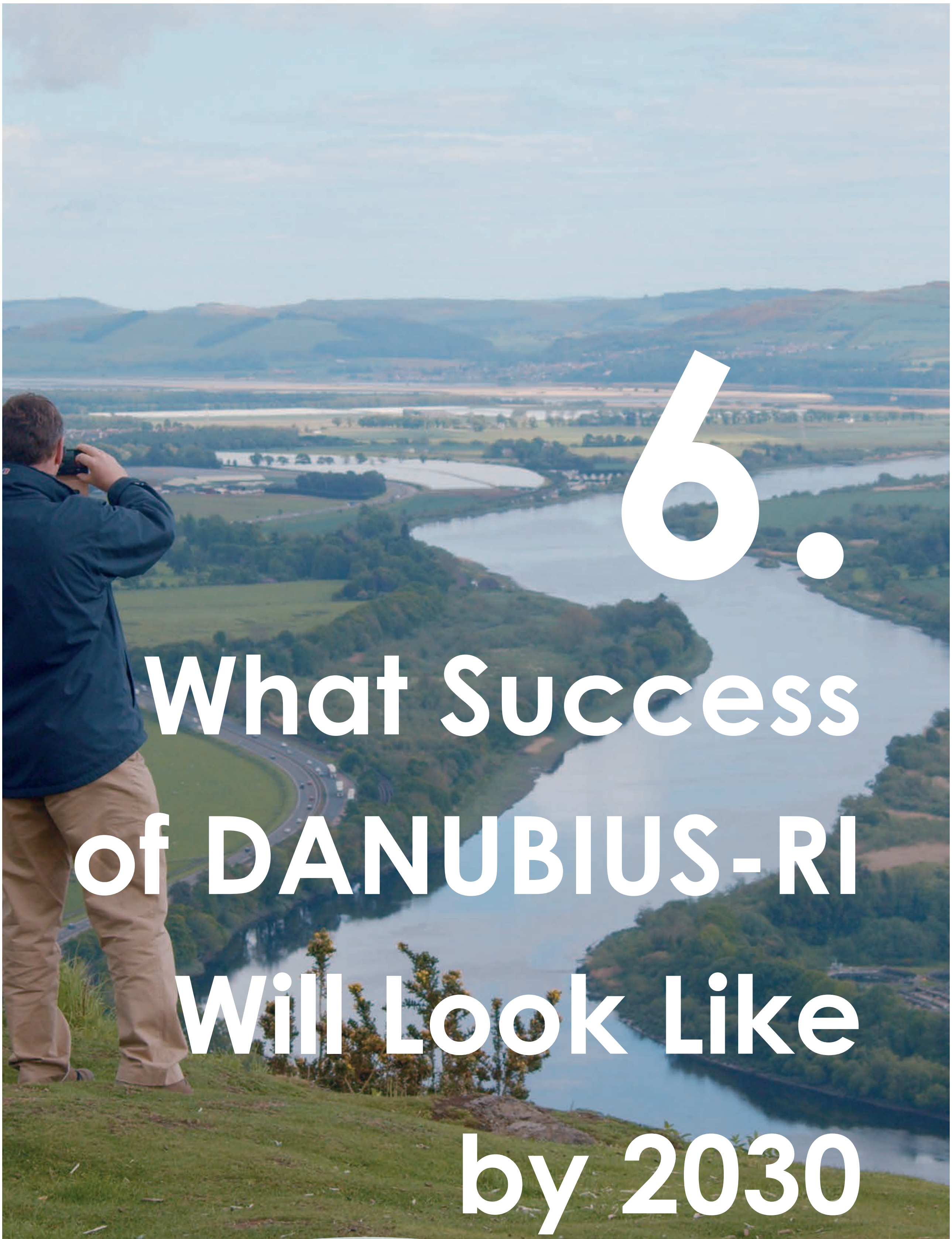
Cooperation with Other Programmes & Initiatives

DANUBIUS-RI will actively engage with international initiatives led by WMO, GCOS, WWAP, UNESCO, UNEP and the United Nations e.g. Decade of Ocean Science for Sustainable Development) Examples of other cooperations includes

- Networks such as International Union for Conservation of Nature (IUCN) and Wetlands International which can increase the visibility of both initiatives and tighten the connection between EU-related and worldwide thematic challenges.

- EU internal connection to policy networks (public and civil society networks): Cooperation can help to improve understanding of the needs of policy makers and to harmonise activities on regional, national and EU wide levels.

- Cooperation with relevant current and past European projects may add expertise to the knowledge pool of DANUBIUS-RI and help to avoid redundancies (e.g. AQUACROSS, DANCERS, EUROCAT, MARS, PERSEUS, REFORM, SESAME, WISER).



6.

What Success of DANUBIUS-RI Will Look Like by 2030

6. What success of DANUBIUS-RI will look like by 2030

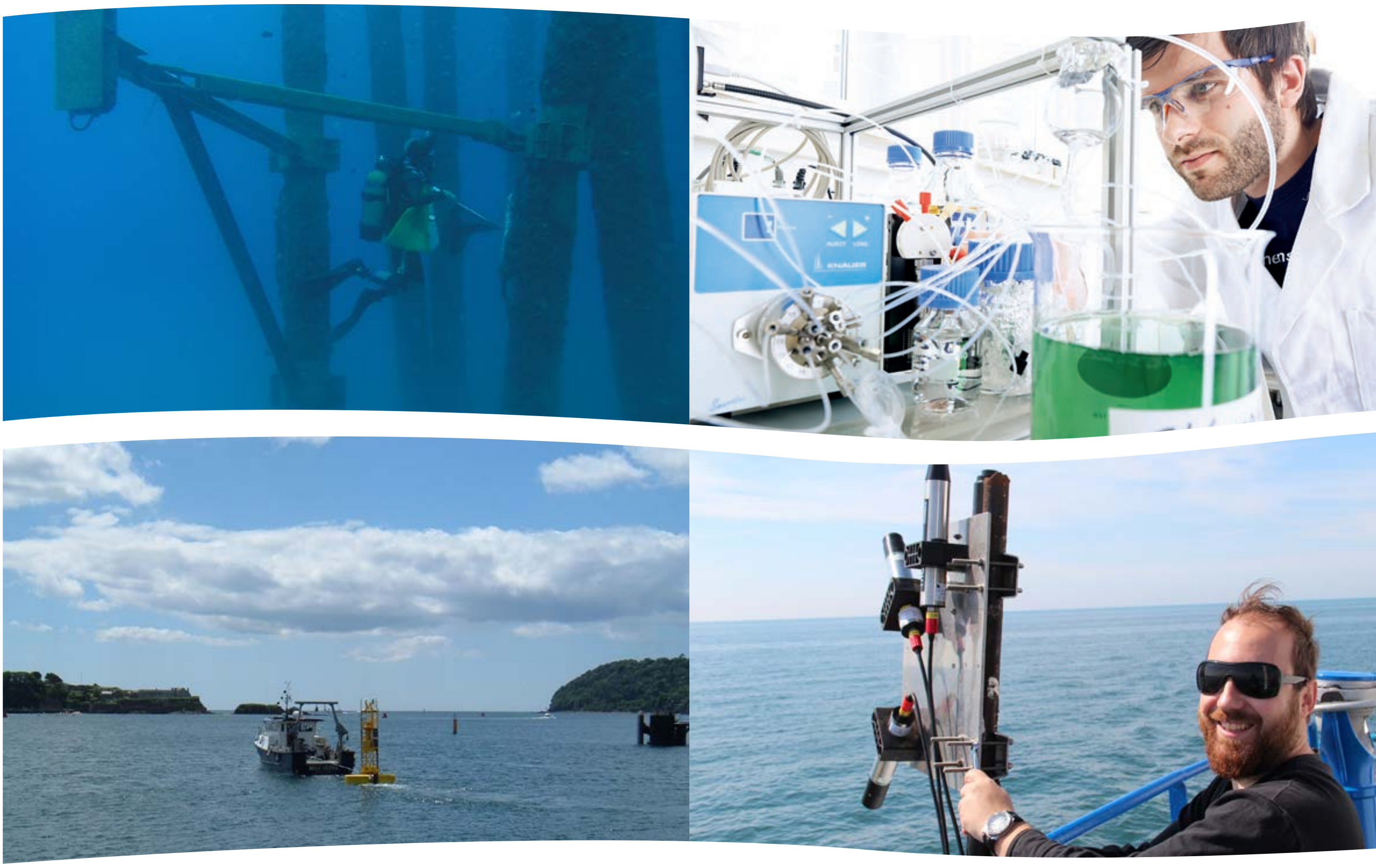
DANUBIUS-RI delivers an interdisciplinary approach with world leading science to address the challenges of a changing environment within River-Sea Systems:

- providing state-of-the-art services and data that facilitate collaboration between stakeholders in research, industry, policy and third sector organisations
- bringing about new understanding, developing and implementing effective innovation, interventions and policy instruments that mitigate against the impacts of extreme events, promotes a (net) zero carbon economy and ensures the sustainable functioning of River-Sea Systems and ecosystem service provision.

DANUBIUS-RI will be:

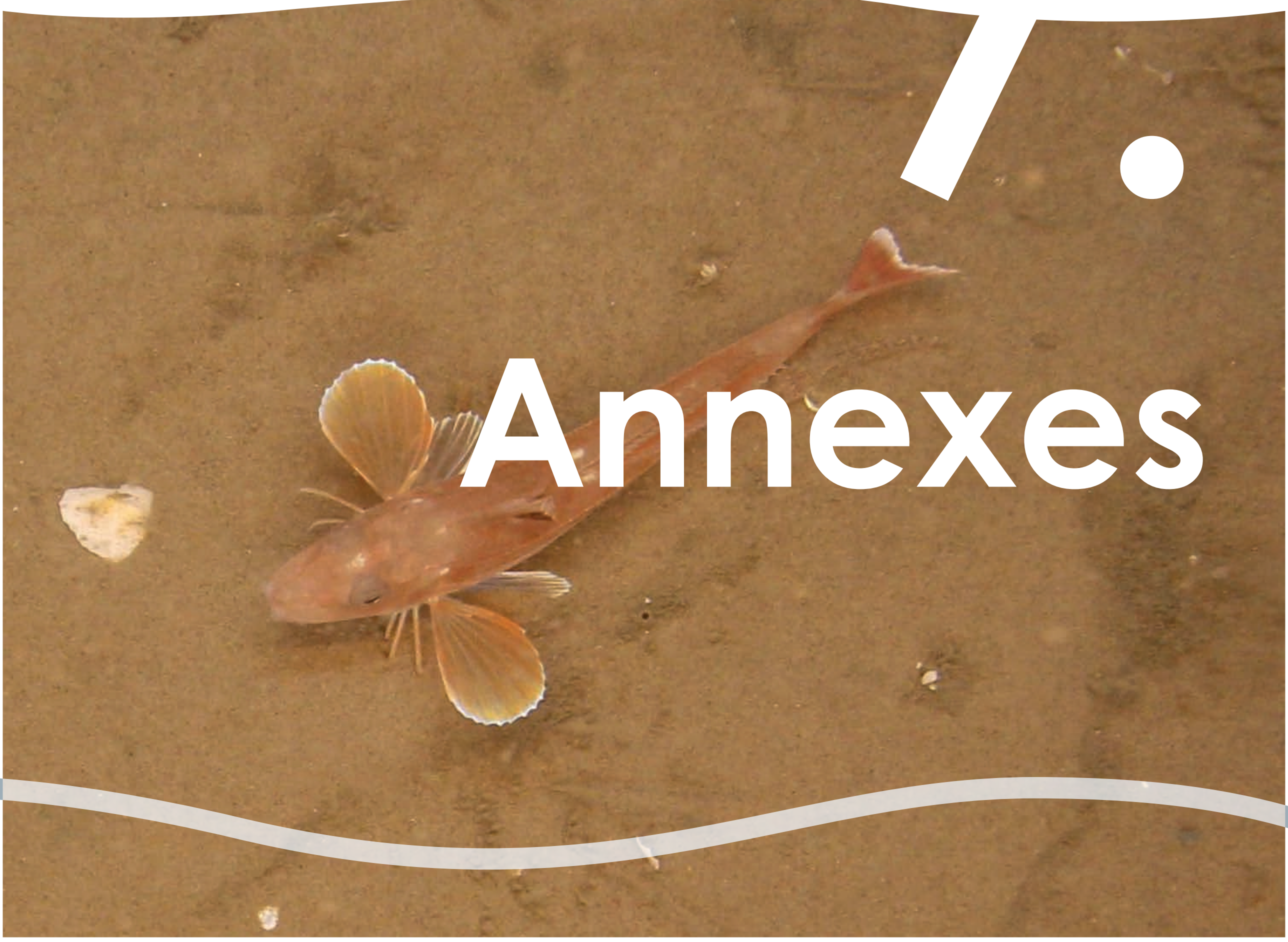
- **established,** with a respected identity and position in the European landscape of Environmental Research Infrastructures, cooperating with the related other research infrastructures
- **growing** with international partnerships facilitating data and knowledge exchange and best practice within a growing global community
- **reputationally excellent** in interdisciplinary research in River-Sea Systems around the world and the preferred partner infrastructure supporting international initiatives and agendas including SDGs and evidencing IPCC
- **harmonised through the DANUBIUS Commons** that ensures consistency, quality, reproducibility and accessibility of data across the RI, that supports research and innovation in Europe
- **integrated through an open access system** of observation, analysis and modelling providing a well characterised framework to test new interdisciplinary concepts, deliver new data sets that facilitate new understandings of the river sea continuum, testing management scenarios and mitigate against the impacts climate change
- **utilising over 95%** of the available DANUBIUS infrastructure by users from within partner countries, across Europe and Internationally
- **oversubscribed,** with access granted to users through science excellence and impact driven research, supported by a financially secure programme of work that supports the sustainability of the RI
- **attracting scientists** to engage with DANUBIUS-RI to facilitate world-leading science, undertake state-of-the-art training and to grow research opportunities, collaboration and capacity building activities internationally
- **providing a productive programme of stakeholder engagement** to ensure a clear prioritisation of research and innovation needs and the effective uptake of evidence to support policy implementation, innovation to support industry that collectively reduces emissions and protects natural capital and in turn supports economic prosperity and human well-being
- **delivering complete, easy to use, freely available data** bridging the knowledge gap for River-Sea Systems and increasing the possibility of intercomparability of river-sea system behaviour at the Pan-European level for research, policy and industry, and linking to Copernicus Services and GEOSS
- **enabling skills development and education** through a fully functioning e-learning environment that also promotes wider societal engagement
- **exploiting an established curriculum for a multi-centre masters programme** through DANUBIUS-RI partner institutions that is attractive to the international community and promotes better management of River-Sea Systems

- **home to a well-supported and vibrant PhD programme** and community that delivers the skills in research and innovation founded on the sustainable opportunities within the River-Sea Systems
- **responsible for enabling the science** and data that generates high impact scientific publications on River-Sea Systems
- **delivering a new generation of skilled scientists** that are imbedded within research, industry and policy to affect better management of River-Sea Systems, enabling societal resilience to climate change and extreme events
- **communicating a strategy** that helps promote the issues, challenges, research needs and solutions that promote the maintenance of healthy, functional River-Sea Systems
- **setting internationally accepted standards** for harmonised and quality-controlled, state-of-the-art research infrastructure for river to coastal sea research through the DANUBIUS Commons
- **benchmarking methodologies** that assess, support and implement the MSFD, WFD and shape the development of the next generation of directives in a source to sink approach



7.

Annexes



Annex I: List of Abbreviations

ACTRIS	European Research Infrastructure for the Observation of Aerosol, Clouds, and Trace Gases
AnaEE	European Research Infrastructure for Analysis and Experimentation on Ecosystems
AQUACOSM	European network of mesocosm facilities for research on marine and freshwater ecosystems
AQUACROSS	Knowledge, Assessment, and Management for Aquatic Biodiversity and Ecosystem Services across EU policies
C	Carbon
COST	European Cooperation in Science and Technology
DANCERS	Danube Macroregion: Capacity Building and Excellence in River Systems (Basin, Delta and Sea)
DiSSCo	European Research Infrastructure Distributed System of Scientific Collections
eLTER	European Long-Term Ecosystem Research Infrastructure
EMBRC	European Marine Biological Resource Centre
EMODnet	European Marine Observation and Data Network
EMSO	European Multidisciplinary Seafloor and Water-Column Observatory
ENVRI	Community of environmental research infrastructures, projects and networks
EPOS	European Plate Observing System
ERIC	European Research Infrastructure Consortium
ESFRI	European Strategy Forum on Research Infrastructures
EU	European Union
EUMETSAT	European Organization for the Exploitation of Meteorological Satellites
Euro-ARGO	European Research Infrastructure for Argo Floats
EUROCAT	European Catchments, Catchment Changes and their Impact on the Coast
FAIR	Findable, Accessible, Interoperable and Reusable
GEOSS	Global Earth Observation System of Systems
GCOS	Global Climate Observing System
HYDRALAB	Advanced network of environmental hydraulic institutes
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
ICPR	International Commission for the Protection of the Rhine
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
IUCN	International Union for Conservation of Nature

JERICO	Joint European Research Infrastructure of Coastal Observatories
JPI	Joint Programming Initiative
LifeWatch-ERIC	European research infrastructure providing e-science research facilities for understanding biodiversity organisation and ecosystem functions and services
MARS	Managing Aquatic Ecosystems and Water Resources under Multiple Stress
MEA	Millennium Ecosystem Assessment
MSFD	Marine Strategy Framework Directive
N	Nitrogen
OSPAR	Oslo and Paris Convention
P	Phosphorus
PERSEUS	Policy-Oriented Marine Environmental Research in the Southern European Seas
PP	Preparatory Phase
REFORM	Restoring Rivers For Effective Catchment Management
RI	Research Infrastructure
SDG	Sustainable Development Goal
SESAME	Southern European Seas: Assessing and Modelling Ecosystem Changes
Si	Silicon
UN	United Nations
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
WFD	Water Framework Directive
WISER	Water Bodies in Europe: Integrative Systems to Assess Ecological Status and Recovery
WMO	World Meteorological Organization
WWAP	World Water Assessment Programme
WWF	World Wide Fund For Nature

Annex II: Glossary of Key Terms

Anthropocene
The term 'Anthropocene' refers to the current geological epoch, where human activities are exerting increasing impacts on the environment on all scales and are outcompeting in many ways natural processes[1].

Ecosystem Services
Ecosystem services are the direct and indirect contributions of ecosystems to human well-being. Ecosystem services can be categorized in four main types. (1) Provisioning ecosystem services represent goods such as water, fish and sediments; (2) regulating services are benefits such as water purification and climate regulation; (3) supporting services are benefits for other ecosystems services and include e.g., nutrient cycling and primary production; and (4) cultural services include e.g. recreation and tourism.[1]

Global Change
Global change encompasses planetary scale changes, which may alter the Earth's capacity to sustain life e.g. by impacting the climate system, carbon and nitrogen cycles, food webs, biodiversity. While global change is not solely caused by a byproduct of human activities, humans have vastly accelerated the pace of change. Humans are driving global change due to e.g., increasing population, economic growths, unsustainable resource use, transport, land use and urbanisation.[2]

Interdisciplinary
Interdisciplinary research has been defined 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"[10].

Megatrends
The Earth's resilience will be significantly affected in coming decades by 'large-scale, highimpact and often interdependent social, economic, political, environmental or technological changes', commonly referred to as global megatrends. Megatrends that are important for Europe's environment are for example demographic changes, urbanisation, disease burdens and health risks, accelerating technological change, continued population and economic growth, intensified resource use, climate change, increasing pollution, and diversifying approaches to governance[22].

Nodes
DANUBIUS-RI's Nodes, coordinated by leading institutions in Europe, provide state-of-the-art facilities, interoperable methods and interdisciplinary expertise regarding (1) Observation and (2) Analysis, (3) Modelling and (4) Impact. Their area of expertise and interaction are essential to advance the research, understanding and management of River-Sea Systems.

Research Infrastructure
Research infrastructures are facilities that provide resources and services for research communities to conduct research and foster innovation. They can be used beyond research e.g. for education or public services and they may be single-sited, distributed, or virtual. They include major scientific equipment or sets of instruments; collections, archives or scientific data; computing systems and communication networks; and any other research and innovation infrastructure of a unique nature which is open to external users.[3]

River-Sea System
River-Sea Systems encompass (1) freshwater, transitional waters, e.g. estuaries and deltas, and coastal seas (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 ecosystems are connected by abiotic and biotic factors e.g. through the flow of water and transport of 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). The wider boundaries of River-Sea Systems are the catchment on land and the region of freshwater influence in the sea.

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[1] https://biodiversity.europa.eu/topics/ecosystem-services

[2] http://www.igbp.net/globalchange/earthsystemdefinitions.4.d8b4c3c12bf3be638a80001040.html

Social-Ecological System
River-Sea Systems are shaped by humans while humans are depending on the ecosystems and the services they provide. Due to this strong coupling, DANUBIUS-RI regards River-Sea Systems as social-ecological systems.

Supersites
DANUBIUS-RI's Supersites are representative areas of River-Sea Systems for observation, analysis, modelling and impact studies. Supersites either cover an entire (small) River-Sea System or several Supersites may be located within a large River-Sea System. The current set of Supersites covers a wide range of climatic, environmental and socio-economic gradients, as well as gradients of human impact.

Sustainable Development Goals
The Sustainable Development Goals (SDGs) were adopted by all United Nations Member States in 2015 as a universal call to action to end poverty, protect the planet and ensure that all people enjoy peace and prosperity by 2030. The 17 SDGs are integrated so that action in one area will affect outcomes in others, and that development must balance social, economic and environmental sustainability.[4]

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[3] https://ec.europa.eu/info/research-and-innovation/strategy/european-research-infrastructures_en

[4] https://www.undp.org/content/undp/en/home/sustainable-development-goals.html

Annex III: List of Pictures

Annex IV: References

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Annex V: List of DANUBIUS-PP Consortium

Partner Institution	Abbreviation	Country
National Institute for Research and Development on Marine Geology and Geo-ecology	GeoEcoMar	Romania
National Institute of Research and Development for Biological Sciences	INCDSB	Romania
Executive Agency for Higher Education, Research, Development and Innovation Funding	UEFISCDI	Romania
Agency for Administration of the National Network for Education and Research (RoEduNet)	ROEDU	Romania
WasserCluster Lunz – Biological Station	WCL	Austria
Bulgarian Academy of Sciences	BAS	Bulgaria
South Bohemian Research Center of Aquaculture and Biodiversity of Hydrocenoses	CENAKVA	Czech Republic
Institute of Global Change Research, Academy of Science of the Czech Republic (CzechGlobe)	CZE	Czech Republic
Integrated Carbon Observation System	ICOS-ERIC	ERIC
European Multidisciplinary Seafloor and Water-column Observatory	EMSO-ERIC	ERIC
Europportunities	EUROP	Estonia
Université de Lorraine – Interdisciplinary Laboratory for Continental Environments	UL	France
Federal Waterways Engineering and Research Institute	BAW	Germany
German Federal Institute of Hydrology	BAFG	Germany
Helmholtz-Zentrum Geesthacht, Institute of Coastal Research	HZG	Germany
Hellenic Centre for Marine Research	HCMR	Greece
Széchenyi István University	SZE	Hungary
University College Cork	UCC	Ireland
National Research Council - Institute of Marine Sciences	ISMAR-CNR	Italy
Consortium for Coordination of Research Activities Concerning the Venice Lagoon	CORILA	Italy
Academy of Science of Moldova	MAS	Moldova
Deltares	DLT	Netherlands
Polytechnic University of Catalonia - Maritime Engineering Laboratory	UPC	Spain
Port Authority of Seville	POS	Spain
IHE Delft Institute for Water Education	IHE	Netherlands
University of Stirling	USTIR	UK
University of Birmingham	UOB	UK
Natural Environment Research Council (NERC) - Centre for Ecology and Hydrology	CEH	UK
Plymouth Marine Laboratory	PML	UK
Odessa State Environmental University	ODESSA	Ukraine
Democritus University of Thrace	DUTH	Greece

UPC
UNIVERSITAT POLITÈCNICA
DE CATALUNYA
BARCELONATECH

UNIVERSITY OF
BIRMINGHAM

UNIVERSITY of
STIRLING

PML | Plymouth Marine
Laboratory

CEH
Centre for
Ecology & Hydrology
NATURAL ENVIRONMENT RESEARCH COUNCIL

GeoEcoMar®

UNIVERSITÉ
DE LORRAINE

bfg Bundesanstalt für
Gewässerkunde

BAW
Federal Waterways Engineering
and Research Institute

UCC
University College Cork, Ireland
Coláiste na hOllscoile Corcaigh

Helmholtz-Zentrum
Geesthacht
Zentrum für Material- und Küstenforschung

Deltares
Enabling Delta Life

ISMAR
CNR - Istituto di Scienze Marine
Venezia

UNESCO
IHE
DELFT

european
multidisciplinary
seafloor & water column
observatory
emso

ICOS
INTEGRATED
CARBON
OBSERVATION
SYSTEM

Port Authority
Seville

Omne vivum ex vivo
INSB

BULGARIAN
ACADEMY
of SCIENCES
1869

hcmr
ΕΛΚΕΘΕ

ΔΗΜΟΚΡΙΤΕΙΟ
ΠΑΝΕΠΙΣΤΗΜΙΟ
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DANUBIUS-PP

The DANUBIUS-PP Consortium is led by Romania and is currently composed of 31 partners from 16 countries, with expressions of interest and support from the scientific community in many other countries in Europe and worldwide. The Consortium provides a well balanced mix of competencies required to build DANUBIUS-RI, in terms of both scientific and administrative domains, as well as geographical coverage.

DANUBIUS-RI

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DANUBIUS-RI

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