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

# Review report on environmental, societal and policy challenges in on river-sea systems and emerging research and legislation needs - final version

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# Environmental, societal and policy challenges in River – Sea systems and emerging research and legislation needs

## Introduction

DANUBIUS-RI is an initiative to develop a pan-European distributed research infrastructure (RI) dedicated to Research & Innovation (R&I) on river-sea systems (RSS). The RI was accepted on the ESFRI[1] roadmap in 2016 and will comprise **facilities, resources and services** to enable R&I spanning the freshwater – marine continuum[2]. DANUBIUS-RI aims to achieve a step-change in RSS understanding by facilitating interdisciplinary R&I.

At present research facilities devoted to rivers and seas are fragmented with no R&I facilities that span freshwater and marine systems. This is becoming increasingly problematic given the scale of current and emerging environmental problems that require: 1. new approaches to observe, understand, and model the environment; and 2. enhanced links between academic communities and the wider society (policy makers, politicians, industry & business, and the general public) to improve the management of these highly dynamic and important environments. A more holistic, integrated, entire river-sea oriented focus is also needed for effective, joint, implementation of key environmental policies and to address key current and emerging societal challenges related to river-sea systems[3].

In this context, and as articulated in the Science & Innovation Agenda (SIA), the DANUBIUS-RI vision is to '***make river-sea systems work***' by securing the knowledge to inform:

i. the sustainable use of the key ecosystem services provided by river-sea systems;
ii. opportunities for Knowledge Exchange and Transfer with business and society; and
iii. environmental policy development, regulation, societal well-being, economic growth and river-sea system management.

This document outlines the wider justification for the RI by summarising the environmental, societal and policy challenges confronting RSS. It is not intended to be exhaustive in scope, but draws selectively upon recent literature to highlight the current RI gap in this area and complements the scientific case for the RI (submitted to ESFRI in 2016), the synthesis of Research Needs in River-Sea systems produced in May 2018, and the SIA, published in Nov. 2019 (the latter two were amongst the outputs of the preparatory phase of the project). The following sections outline the geographical scope of the project and define the concept of River-Sea systems, before summarising the environmental, societal, and policy challenges

[1] European Strategy Forum for Research Infrastructure.
[2] Bradley C, MJ Bowes, J Brils, J Friedrich, J Gault, S Groom, T Hein, P Heininger, P Michalapoulos, N Panin, M Schultz, A Stanica, I Andrei, A Tyler & G Umgiesser. 2017. Advancing integrated research on European river-sea systems: the DANUBIUS-RI project. **Int. J. of Water Res. Dev**. doi: 10.1080/07900627.2017.1399107.
[3] Illustrated by the large number of sectorial European river and sea system-related policies: the Water Framework Directive (WFD), the Flood Directive(FD), the Urban Waste Water Treatment Directive (UWWTD), the Marine Strategy Framework Directive(MSFD), the Maritime Spatial Planning Directive (MSPD), the Nitrate Directive (ND) and the Habitats Directive (HD).

that confront these systems today. Emerging research needs are then summarised (drawing upon the Research Needs synthesis) within the context of a wider argument for mission-orientated inter-disciplinary research, before discussing emerging societal needs with respect to environmental policy and legislation. In so doing, the intention is to make the wider case to support the development of the pan-European distributed Research Infrastructure, DANUBIUS-RI.

## 1. Scope and Compass of DANUBIUS-RI

DANUBIUS-RI conceives River-Sea systems to comprise river catchments, estuaries/deltas, lagoons and coastal seas. While focussing in particular on transitional areas, the scope of DANUBIUS-RI encompasses the entire river basin and coastal sea, extending from catchment to coast and spanning freshwater, marine and transitional environments (Fig. 1). River-Sea systems thus extend from the river headwaters, through alluvial reaches and floodplains, to estuaries, deltas and shallow seas downstream. Their upstream extent is defined by the surface-water (or groundwater) boundary of the catchment, while their marine boundary is more variable and is envisaged as the furthest extent of riverine influence on individual parameters of interest.

River-Sea systems encompass a diversity of environments across marked elevational gradients. The **central nexus** (i.e. link or connection) is the movement of water, sediment, contaminants, through the RSS from source to sink. These material fluxes are highly variable, both in time and space; they are affected by river and catchment management, by agricultural practices, urbanisation and river regulation (e.g. for hydropower and navigation) and coastal engineering works. As a result, the state of a RSS at any point in space and time reflects the dynamic product of interacting environmental and socio-economic processes. Given this complexity, holistic understanding and management of these systems requires innovative approaches to cross-disciplinary R&I, at a number of levels.

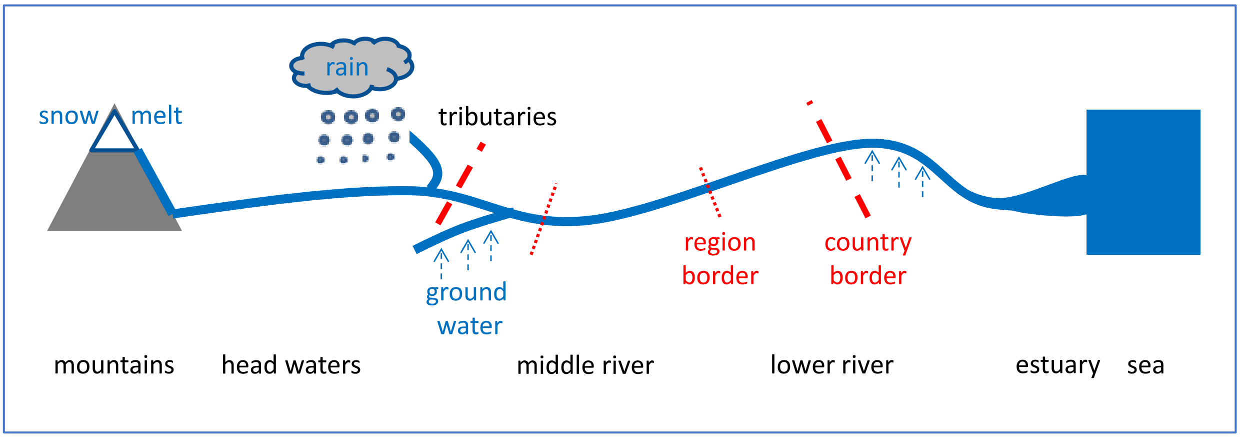


**Fig. 1. River – Sea systems: spanning the river basin, transitional waters, and the sea (from DANUBIUS-PP D9.1. (the Ontology reference document).**

The complexity of River-Sea systems globally, has significantly constrained our ability to understand and manage the evolution of these dynamic environments. This reflects the multi-dimensional nature of inter-related environmental, social and economic processes that influence how these systems are changing over time. Given this seemingly intractable problem, and the breadth and the scale of individual systems, **the key challenge** is how to identify tangible and achievable ways to facilitate R&I on River-Sea systems that can help provide solutions to current and emerging societal problems. In this context, there is increasing recognition of the value in Mission-Orientated R&I[4] which offer a means to addressing projects through R&I missions which should be tangible, measurable and achievable. These missions should provide opportunities for stakeholder engagement through cross-disciplinary, cross-sectoral and cross-actor R&I. Missions should be societally relevant, with transformative impacts that can leverage private sector investment to enable activities that would otherwise be unfeasible and which span traditional approaches to innovation, education and research. Missions should also engage with national strategies (including industrial strategies) and foster economic growth, by providing a problem-solving approach that encourages innovation and collaboration. This provides a wider context in which to develop an RI dedicated to inter-disciplinary R&I on European River-Sea systems. The goal is to provide the framework that enables the research community to collaborate on interdisciplinary projects that address key challenges that extend across the freshwater-marine continuum and provide a strong basis for stakeholder engagement, and provide solutions to environmental problems that have immediate societal relevance.

As a Research Infrastructure, DANUBIUS-RI will not directly fund itself, but will provide the facilities to enable a wide community of users to undertake externally funded research on River-Sea systems. The RI will also advance our understanding of these systems by improving educational provision. As such, the research facilities will be designed so that they closely align with national and international funding opportunities, and they will provide an opportunity to complete interdisciplinary scientific programmes that can underpin improvements in environmental regulation and policy development at the interface between freshwater and marine environments.

One of the key motivations for developing DANUBIUS-RI is the current lack of inter-disciplinary research facilities that span the freshwater – marine continuum: from catchments to coasts and seas. Such facilities are essential for holistic understanding of RSS, to encourage Knowledge Exchange and Transfer, and identify encourage new approaches to knowledge and understanding that transcend traditional disciplinary boundaries and which have tangible benefits for society. At the same time, DANUBIUS-RI offers the opportunity to apply new developments in earth observation, analytical techniques and modelling that together represent a cross-disciplinary toolbox that can be utilised in undertaking mission-orientated

[4] Marianna Muzzucato. 2018. Mission orientated Research and Innovation in the EU. A problem-orientated approach to fuel innovation-led growth: https://ec.europa.eu/info/sites/info/files/mazzucato_report_2018.pdf

research that has the potential to address the key environmental challenges confronting River-Sea systems summarised in the following section (as well as societal and policy-related challenges discussed subsequently).

**Environmental Challenges**

River-Sea systems represent a fundamental global resource supporting diverse habitats and important ecosystems; they have a key function in global biogeochemical cycles and are core to food and energy production. Hence River-Sea systems are central to societal wellbeing, yet they face multiple and confounding pressures from climate forcing, eutrophication and other natural and anthropogenic-driven environmental perturbations at various scales. This is evident in heavily managed catchments globally where increasingly many population centres have developed on coastal margins, near estuaries and tidal rivers at the freshwater – marine interface. In some cases, these present real opportunities for economic growth as centres of innovation, such as the Thames Gateway project: Europe's largest regeneration project that extends 65 km along the Thames Estuary[5] (and which promotes carbon neutral improvements to housing stock, the use of renewable energy and new technologies, with the vision of transforming brownfield sites into an 'eco-quarter'). Elsewhere, in Europe, there are challenges in how to conserve and enhance biodiversity, in the context of accelerating environmental change. Here there are uncertainties over the resilience of key habitats and their potential vulnerability to irreversible changes. This is illustrated by global concerns expressed that many coastal deltas and estuaries are at 'tipping points' due to progressive changes in water and sediment regimes, land subsidence, and changes in sea level[6]. The concern is that at present, our knowledge of the wider functioning of River-Sea systems is insufficient to assess their resilience, and from this to determine how management interventions might enable deltas such as the Ebro, the Rhine-Meuse, or the Danube, to persist and maintain their current structure and function in a highly modified state and avoid a potential state of 'collapse' (similar concerns exist elsewhere, for example, in the Ganges, Indus, and Mississippi basins).

Globally the tools required to quantify environmental system dynamics at different scales and across disciplinary boundaries is lacking, despite growing evidence of our inability to manage environmental processes at the freshwater – marine interface. This is illustrated in:

[5] Further information on initiatives, South of the Thames are available at: http://www.tgkp.org (Kent) [accessed 27.11.19]

[6] Renaud FG, JPM Syvitski, Z Sebesvari, SE Werners, H Kremer, C Kuenzer, P Ramesh, A Jeuken & J Friedrich. 2013. Tipping from the Holocene to the Anthropocene: how threatened are major world deltas. Current Opinion in Environmental Sustainability 5: 644-654

- N. America by the Mississippi Delta, where regulation of the Mississippi-Missouri system has reduced sediment flux, affecting accretion rates in coastal wetlands, and with developing hypoxic zones in the Gulf of Mexico.
- Australia, by the impacts of diffuse pollution associated with sugar cane cultivation in catchments associated with deterioration of the Great Barrier Reef.
- N Africa, by the Nile and the Nile Delta given upstream river regulation (Aswan High Dam), coastal erosion of the Delta, and proposals to develop irrigated agriculture in the upper catchment.
- The Indian sub-continent in the trans-boundary basins of the Indus, Ganges, Brahmaputra rivers, where high population densities in their lower basins present growing challenges in ensuring agricultural sustainability (salinization; groundwater abstraction), and in increasing resilience to environmental hazards (fluvial and coastal flooding).

These examples illustrate the global scale of environmental problems affecting River-Sea systems, which are emerging with increasing population pressures (and per capita resource demand) as river catchments, freshwater – marine transitional zones and shallow seas are impacted by development. In Europe, pollution from agriculture and hydraulic engineering (for navigation, water supply, hydroelectricity and flood control), are seen as the two main factors inhibiting the achievement of good ecological status of European river basins. In addition, water is both an input to many industrial processes and a sink for pollutants, while households consume water whilst also contribute to pollution where wastewater is inadequately treated. Economic activities such as navigation and hydroelectric power depend on minimum water levels for their functioning, and similarly while freshwater systems are damaged by changing water quantity and quality, requiring proscribed environmental flow criteria.

The scale of these problems is such that generally, the prices that consumers pay for their water is in many cases too low, and water-efficient technologies and practices are not yet fully implemented. Additional factors such as population growth, economic growth, and possible effects of climate change on river flow are expected to increase existing pressures on river basins. In fact, current global climate projections anticipate crucial changes regarding extreme weather conditions, oceanographic conditions and in the water regime of rivers. These changes will, in turn, severely modify riverine processes inducing important physical, geochemical and biological responses.

Whilst these problems have significant implications for environmental health, and present challenges with respect to biodiversity conservation and habitat restoration, they also have the potential to affect human health more directly (e.g. Methyl mercury and arsenic contamination). In this respect, there is an urgent need for chemical and effect-based monitoring tools that can inform new models of exposure and risk assessment. These require improved understanding of sources, transport pathways, and ultimately the fate of pollutants. This is particularly challenging given the scale of new and emerging pollutants which present considerable challenges for catchment managers; for example, in identifying and monitoring specific compounds, determining their sources, and designing methods for control and mitigation of effects.

The problems are cumulative with implications at the drainage basin boundary downstream in the freshwater – marine transition zone, in transitional estuarine environments and shallow seas. For example, transitional and marine systems have been impacted globally by reductions in catchment sediment fluxes as a result of river regulation. Deltas, estuaries and coastal seas are further affected by increases in relative sea level and temperature, by changes in salinity, acidification and de-oxygenation that impact marine pelagic and shallow benthic ecosystems. Potential effects are magnified by changes in the quality and quantity of the freshwater input to marine systems, by algal blooms and eutrophication, and by environmental pollutants that accumulate in marine food webs. In many cases, shallow seas represent the ultimate fate of emerging pollutants with consequences for public and environmental health that have yet to be fully quantified. However, the combination of changes in climate and in the physical degradation of coastal areas is increasing the pressure on marine food webs globally. At the same time, there are potential impacts of oil and gas extraction and the development of new sites for renewable energy generation (wind farms; tidal barrages) and uncertainties over the consequences of new initiatives relating, for example, to methane hydrates. Moreover, given projected population, particularly in coastal areas, there is an urgent need to ensure sustainable food production by integrating fisheries and aquaculture research with environmental, social and economic research (JPI-Oceans, 2015), although inevitably this relies upon improved understanding of processes (and fluxes) that link freshwater and marine systems.

**Societal challenges**

Social challenges in River-Sea systems are inextricably linked to the environment and to the problems summarised above. This reflects the multi-faceted and interconnected problems that in many respects are difficult to resolve [e.g. lack of data and understanding; the problems span traditional disciplinary boundaries] with a social and economic context that is fundamental to understanding potential trajectories of change in River-Sea systems. In many respects, therefore, the challenges exemplify those of 'wicked' problems[7]: characterised by uncertainty, limited understanding, differing viewpoints and perspectives. However, novel ways of addressing these problems, and provide opportunities to undertake socially relevant R&I is essential in making progress towards achieving the UN Sustainable Development Goals (SDGs) which reflect a desire for society to live safely within current constraints, whilst retaining the aspiration of continuing to increase human wellbeing. The SDGs were intended

[7] The concept was originally outlined in HWJ Rittel & MM Webber, 1974. Wicked problems. *Man-made Futures*, *26*(1), 272-280.

to be action-orientated, universally applicable, goals to secure sustainable development. They were presented as integrated and indivisible goals, which were developed in consultation with stakeholders, and for them to be achieved, active an continued stakeholder engagement is required. River-Sea systems span several SDGs (i.e. SDG 6 – clean water and sanitation; SDG 14 life below water; SDG 15 life on land), and progress towards fulfilling the proscribed goals has been limited by the constraints of traditional, sector-specific approaches to the management of freshwater and marine systems, and fragmented governing structures (illustrated by the classic problems of international ocean governance, and the difficulties of managing international river basins such as the Danube). These challenges have spawned initiatives including green growth (to foster economic growth and development whilst ensuring that natural assets continue to provide the resources and environmental services on which human well-being relies') and blue growth (viz. the economic and social importance of the ocean and inland waters). This supported internationally: the Food and Agricultural Organisation (FAO) has launched a Blue Growth Initiative to protect 'the potential of the oceans, lagoons and inland waters by introducing responsible and sustainable approaches to reconcile economic growth and food security with the conservation of aquatic resources'.[8]

Clearly, however, there are many challenges in achieving these aspirations (i.e. the SDGs and green & blue growth) with significant attendant risks, both to human well-being and the environment, which are at least partly dependent upon the policy and decision-making responses. Further complications may arise given uncertainties over environmental resilience particularly in the context of abrupt, non-linear change. The latter may lead to non-linear transitions in system functioning as summarised in the emerging Planetary Boundary concept when rapid environmental change poses an unacceptable risk to society[9]. Proposed planetary boundaries (in addition to climate change) include changes in phosphorus and nitrogen cycling, global freshwater use, changes in land-use, loss of biodiversity, chemical pollution and ocean acidification. These problems are ubiquitous, and in some cases the consequences have been so severe that river basins have effectively become 'closed' with insufficient water available either to satisfy anthropogenic demand or sustain 'natural' ecosystems.

The concept of Planetary Boundaries has been widely adopted internationally, for example, by the UN High Level Panel on Global Sustainability. PBs have been criticised recently, however, as the majority of associated processes and boundaries do not necessarily operate at the scale of the river basin, rather than at globally and more corroborating evidence (of their global applicability) is needed[10]. Indeed, it has been suggested that their basis for policy

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[8] Eikeset AM, AB Mazzarella, B Daviosdottir, DH Kliner, SA Levin, E Rovenskaya & NC Stenseth. 2018. What is blue growth? The semantics of "Sustainable Development" of marine environments. Marine Policy. 87: 177-179.

[9] Rockström J, W Steffen, K Noone et al. 2009. Planetary boundaries: exploring the safe operating space for humanity. Ecology and Society 14 (article 32);
Steffen W, W Broadgate, L Deutsch, O Gaffney & C Ludwig. 2015. The trajectory of the Anthropocene: the Great Acceleration. The Anthropocene Review, 2(1): 81-98.

[10] Heistermann, M. 2017. HESS opinions: A planetary boundary on freshwater use is misleading. Hydrology & Earth System Science 21: 3455-3461.

and management 'should be actively refuted by the hydrological and water resources community. However, River-Sea systems exemplify the diversity of problems that can arise when environmental management fails to acknowledge the wider geographical and social context; e.g. catchment processes contributing to ocean acidification; or regional environmental stress threatening the provision of key ecosystem services downstream.

Rockström et al.[11] argue that water has a critical role in determining the resilience of socio-ecological systems at different scales, with emerging challenges over increasing food and biofuel production, highlighting the importance of environmental stewardship in protecting ecosystem function (and emphasizing the need for green water management). Hence, while the Planetary Boundary concept provides the science-based analysis of risk to earth system functioning, key questions, over how society responds and addresses these global problems, remain. For example, the need for a new paradigm of water governance has been put forward, that specifically accounts for the many faceted uses of water, and interactions at different scales. It should also recognise the importance of Human Agency at points extending through the river – catchment – coast – sea continuum.

Integrated management of River-Sea systems is challenging in a number of respects given their multi-disciplinary nature, the difficulties in defining their physical boundaries and in attributing cause- and effect. They are potentially characterized by significant instabilities, with responses to pressures that are to a certain extent unpredictable, yet they perform essential ecosystem services which are vital in delivering the sustainable development goals and harbour sensitive and highly threatened species. Hence the use of River-Sea systems should be regulated by three interlinked principles: first, management should: i. be well-informed; ii. conform to the accepted ideals of adaptive management; and iii. follow a participatory approach[12]. Ultimately this requires environmental research that has societal relevance and impact and spans traditional boundaries both disciplinary and geographical. These goals have yet to be addressed in detail for River-Sea systems: while the principles of integrated catchment management are generally acknowledged, they have yet to be applied within a wider physical context that spans the freshwater – marine environment and considers the full impact of catchment processes on environments downstream.

Further difficulties in achieving these goals arise with the essential importance of linking biophysical processes to the behaviour and impact of humans. This is explicitly recognised in the increasing literature devoted to the concept of the Anthropocene, the key characteristics of which are: human agency, social and economic networks that have global reach, and an 'environment' which is the product of extensive feedback between human systems and

[11] Rockström J, M Falkenmark, T Allan, C Folke, L Gordon et al. 2014. The unfolding water drama in the Anthropocene: Towards a resilience-based perspective on water for global sustainability. Ecohydrology 7: 1249-1261

[12] Brils J, W Brack, D Muller-Gragherr, P Negrel, J Vermaat. 2014. Risk-informed management of European River Basins (395pp) Heidelberg: Springer.

environmental processes. In response, Donges et al.[13] (2017) advocate a new Earth System science paradigm that builds upon a deeper understanding of the physical and biological 'environment' and of the economic, social and cultural forces that are intrinsically part of it. In practise this requires R&I that seeks to understand and quantify a diversity of socially and structurally-differentiated human behaviours, in a social-environmental system characterised by a variety of feedback loops, and exhibiting a range of different behaviours. The consequences are complex and chaotic trajectories of environmental change, in which socially-differentiated agency, and social and economic networks exhibit complex co-evolutionary dynamics. These processes are evident today in River-Sea systems globally and can explain their spatial and temporal evolution through catchments to coast and sea, and provide the context for the specific research needs in European River-Sea systems which are summarised in the following section.

**Synthesis of research needs in European River-Sea Systems**

This summary of research needs in European River-Sea-Systems has been produced by DANUBIUS-PP. It is envisaged as a living summary which has been incorporated into the strategic Science and Innovation Agenda (SIA) for DANUBIUS- RI and is derived: first, by reviewing the academic literature; and second, by applying a Driver – Pressure – State Change – Impact – Response (DPSIR) model to investigate overarching research challenges in European River-Sea Systems. Progressive modification of rivers and seas have resulted in fundamental changes in individual catchments, coasts and seas which potentially jeopardises the continued provision of key ecosystem services provided by River-Sea systems. This requires new approaches to interdisciplinary R&I that seeks to link, *inter alia*, anthropogenic, social, ecological, climatic, catchment, and marine processes to provide systemic understanding, provide the basis for sustainable adaptive management, and the development of informed environmental policies and regulations.

Drawing upon potential user input across Europe (including 14 countries), DANUBIUS-RI has put forward seven strategic research priorities in River-Sea systems that will inform the development of the RI as it proceeds through to the implementation phase:

i. Water Quantity; ii. Sediment Balance; iii. Nutrients and Pollution; iv. Biodiversity; v. Ecosystem Services; vi. Climate Change; and vii. Extreme Events.

[13] Donges JF, R Winkelmann, W Lucht, SE Cornell, JG Dyke, J Rockström, J Heitzig & HJ Schellnhuber. 2017. Closing the loop: reconnecting human dynamics to Earth System science. The Anthropocene Review: 4(2): 151-157.

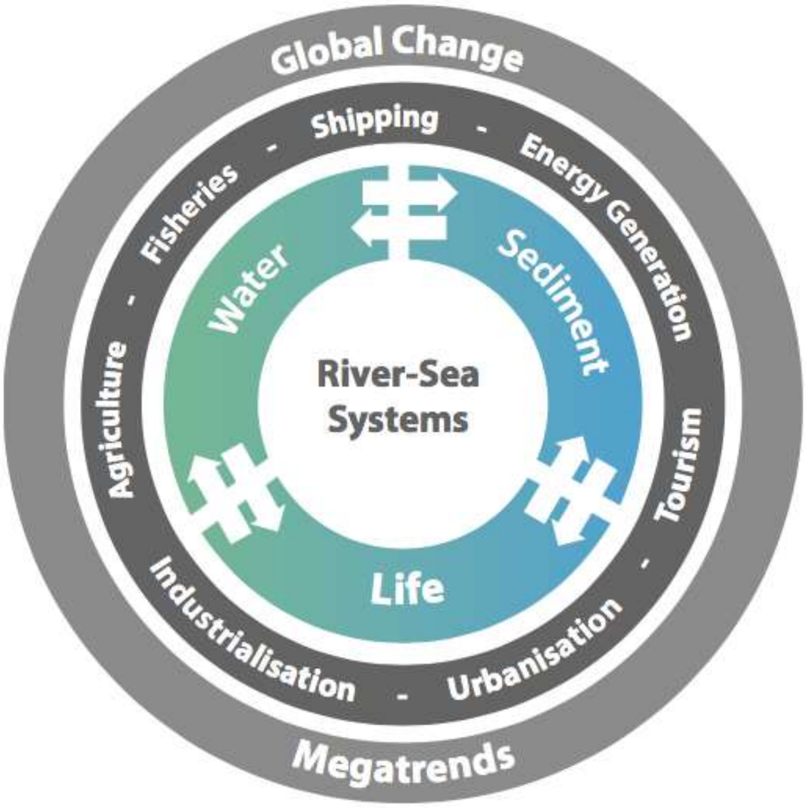


**Fig 2. Schematic representation of research themes on River-Sea systems proposed by DANUBIUS-RI (from the Science & Innovation Agenda, Nov. 2019)**

**Climate change** is contributing to an intensification of the hydrological cycle and an increase in the frequency of extreme events (floods & droughts), with effects that are exacerbated in coastal areas by sea level rise, and land subsidence. Inevitably there will be considerable social and economic impacts: on agriculture, on urban and peri-urban areas, communications and transport, industry and business. Hence long-term mitigation and adaptation will be crucial to maintaining key ecosystem services currently provided by River-Sea systems. This, in turn, requires greater holistic understanding of River-Sea systems, particularly in our ability to attribute 'cause and effect' recognising how these systems are evolving in response to a variety of 'drivers' at different spatial and temporal scales.

Water is an essential resource, and DANUBIUS-RI considers the challenge of **water quantity** as being how to ensure continued water availability for both anthropogenic and environmental needs. It embraces both quantity and quality, of both surface-water and groundwater, along the continuum from catchment-to-coast. The challenge of water sufficiency lies in addressing problems such as eutrophication and hypoxia, changes in river (and tidal river) regime and sea level in the context of increasing water abstraction, river regulation (for hydropower and navigation), salinization and changing catchment land-use. Individually and collectively, these affect the hydrogeomorphology of individual rivers which have been increasingly isolated from their floodplains, and modified by extensive engineering. In some parts of Europe, the potential for increasing coastal flooding is of concern, while there are general questions over how an increasingly scarce resource (water) can be allocated equitably between different uses.

The continued functioning of River-Sea Systems is heavily dependent upon maintaining the **sediment balance** through catchment-to-coast. River-Sea Systems are characterised by the routing of sediment from source to sink through erosion, deposition and remobilisation. While 'natural' rivers should persist in a state of dynamic equilibrium, the movement of sediment through modified rivers, to transitional waters, coasts and seas, is significantly affected by catchment, river and coastal management. This threatens the continued availability of sediment, which is itself a resource: whether for sustaining farmland, or enhancing flood protection (via aggradation of floodplains, deltas and coasts). Sediment dynamics is also key to safeguarding the morphological dynamics of River-Sea systems, which are essential for biodiversity conservation. Erosion and sedimentation occur over different scales, and as for the other challenges, holistic approaches are required to research on River-Sea systems to deliver integrated sediment management plans which are fully supported by key stakeholders at different levels.

River-Sea Systems are complex and heterogeneous, and encompass diverse habitats in freshwater, terrestrial (i.e. floodplains), transitional zones (deltas, estuaries) and marine environments. **Healthy ecosystems** are those that are resilient, stable and sustainable, and maintaining their organisation over time. Biodiversity is the foundation for ecosystem structure and function and underpins the provision of key ecosystem services (such as fish production, habitat provision, flood and storm protection). Ecosystem health is threatened by habitat fragmentation, poor water quality, changes in river regime, and river management. Across Europe, lateral connectivity between rivers and floodplains has been lost, while longitudinal connectivity has been affected by dam construction and navigation. These (catchment) changes, threaten highly productive and biodiverse environments downstream: in estuaries, deltas and shallow seas. Given progressive changes in these environments, there are key challenges in determining how changing ecosystem structure and function will impact ecosystem health and the future provision of key ecosystem services. It is also unclear how River-Sea systems will evolve, given the multiple pressures on aquatic ecosystems, and the rates at which some of these systems are changing.

These challenges summarised here, are inter-related. However, they highlight the importance of interdisciplinary R&I at different scales across the freshwater-marine continuum. The vision of DANUBIUS-RI is to provide a Research Infrastructure that addresses this need and hence '***makes river-sea systems work***' by ensuring the sustainable use of the key ecosystem services provided by river-sea systems and enabling environmental policy development and regulation to secure societal well-being and economic growth.

**Policy challenges**

At present, there are a number of practical problems in implementing environmental policies within European River-Sea systems and fulfilling the EU's aspirations for blue-green growth. Environmental policies and regulations have developed in an ad-hoc manner and have a largely sectoral basis which limits their effectiveness when considering the functioning of River-Sea systems along the nexus from catchments to coasts and seas. Their fundamental purpose is to address problems arising through adverse environmental impacts, howsoever caused. Within the wide geographical boundaries of RSS, key environmental policies include the Water Framework Directive (WFD), the Flood Directive (FD), the Urban Waste Water Treatment Directive (UWWTD), the Nitrate Directive (ND), the Habitat Directive (HD) and Natura 2000 [for terrestrial / freshwater environments], and the Marine Strategy Framework Directive (MSFD), the Maritime Spatial Planning Directive (MSPD) and Recommendations for Integrated Coastal Zone Management [for marine environments]. River and coastal zone management is governed by the WFD (WFD – 200/60/EC) while management of European marine waters is subject to the MSFD (MSFD – 2008/56/EC) and the more recent MSPD (2014/89/EU). The difficulties presented by the disjunct in regulatory structures are compounded by the multi-dimensional diverse and dynamic process drivers, both natural and anthropogenic, that govern River-Sea systems, which highlights the case for a harmonization process between individual directives in future. While ecosystem-based management is explicitly referenced in a number of the directives, there are significant constraints at the interface between freshwater and marine environments, particularly in transitional zones (estuarine and deltaic systems), as well as a number of differences in interpretation. These are illustrated below, after first summarising the scope of two of the directives: the WFD and the MSFD:

***The Water Framework Directive***

The WFD focuses on the protection of groundwater, inland and transitional waters. It seeks to prevent any further deterioration in their status, but also aims to protect and enhance aquatic ecosystems generally, as well as associated wetlands and terrestrial ecosystems. The WFD emphasizes the importance of ecological status, defined as the 'quality of the structure and functioning of aquatic ecosystems associated with surface waters' and changes in ecosystem structure and functioning are attributed to anthropogenic pressures. Implementation of the WFD, advocates water management at the basin scale, which in some cases will transcend political boundaries.

The WFD requires EU member states to develop river basin management plans with a view of achieving good (or improving) ecological status in all water bodies. These management plans are required to consider all activities in the river basin that could impact the status of a water body and must be continually monitored and updated to take account of continued environmental change, and economic activity. The WFD draws heavily upon the tenets of ecosystem-based management, although as noted below, currently there are a number of practical constraints have limited the effective implementation of the WFD in individual catchments.

### *Marine Strategy Framework Directive*

The MSFD requires that all European marine waters should obtain (or maintain) good environmental status by 2020. In common with the WFD, the MSFD also envisages ecosystem-based management to support the blue economy, achieve the sustainable use of associated goods and services whilst maintaining ecosystem integrity. The ecosystem approach implies the integrated management of human activities, their dynamics and interactions which requires collaboration and interdisciplinary research to provide the toolbox necessary for environmental assessment and management at the basin and ecosystem level. The MSFD requires EU coastal member states to take specific actions to achieve this, but as for the WFD, there are significant constraints that affect the implementation of the MSFD. For example, what are the impact of catchment processes on the functioning of marine systems and vice versa? How can we distinguish human-induced changes from those driven by natural processes (including climate-induced variability)? How can we manage marine systems sustainably and can we predict the natural and human-influenced evolution of these systems?

## Discussion

The wider argument for greater integration of environmental Directives is generally accepted[14]. Borja et al. discuss the practical difficulties of integrating elements of the MSFD and the WFD, where there are significant differences in approach (WFD: structural approach; advocating good ecological status; MSFD: functional approach; good environmental status). While a complete analysis of methodological differences within and between environmental policies are outside the scope of this paper, there are three primary difficulties that constrain the implementation of environmental policies, that bridge the main environmental policies: these relate to i. terminology; ii. data; and iii. understanding (i.e. avoiding an overly sectoral approach, with R&I that spans the River – Sea continuum.

**Terminology:** DANUBIUS-RI seeks to develop a common language across RSS that transcends disciplinary boundaries, and proposes a consistent ontology that spans freshwater and marine environments. The need for a common terminology and consistent use of definitions

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[14] Borja, A, M Elliott, J Carstensen, A-S Heiskanen & W van de Bund. 2010. Marine management – Towards an integrated implementation of the European Marine Strategy Framework and the Water Framework Directive. Marine Pollution Bulletin: 60: 2175-2186

and concepts is exemplified by the use of terms such as 'coastal seas', and the need to use 'coastal waters' and 'territorial seas' in preference.

The WFD defines 'coastal water' as 'surface water on the landward side of a line, every point of which is at a distance of one nautical mile on the seaward side from the nearest point of the baseline from which the breadth of territorial waters is measured, extending where appropriate up to the outer limit of transitional waters'. While 'territorial waters' are defined as 'bodies of surface water in the vicinity of river mouths which are partly saline in character as a result of their proximity to coastal waters, but which are substantially influence by freshwater flows'.

However, the WFD usage of 'coastal waters' is difficult to relate to the MSFD, which focuses on 'marine waters': i.e 'waters, the seabed, and subsoil on the seaward side of the baseline from which the extent of territorial waters is measured extending to the outmost reach of the area where a Member State has and/or exercises jurisdictional rights, in accordance with the UNCLOS'.

**Data**: increasingly common indicators of the state of the environment, across RSS are needed. Data **quality control** and **quality assurance** are of fundamentally important, particularly given the increasing availability of 'big data' that present new opportunities to quantify the spatial and temporal dynamics of environmental change, but which also present new challenges (verification and the validity of environmental proxies). These challenges are particularly acute at the interface between rivers and seas, and here the intention is that by developing the DANUBIUS Commons (including common protocols of data collection, and processing), key stakeholder communities will have access to real-time data to strengthen environmental policy frameworks and governance. This will address a widely recognised need to provide free and unrestricted access to data that, on implementation, will enhance the wider applicability of environmental research, and the translation of research results into policy-making[15].

**Understanding**: DANUBIUS-RI aims to advance systemic understanding along the continuum from catchment to coast and sea. This will be achieved by reframing broad challenges within the context of specific missions, to identify appropriate policy responses to bridge the gaps between existing European environmental policies (i.e. the WFD, the MSFD, and EU biodiversity policies)? By focusing on the 'whole system', the initiative will build upon recent reviews that highlight problems with policy formulation and implementation[16]. This is essential to reconcile intensive human use and environmental protection in European RSS, and requires holistic approaches to research to deliver enhanced system understanding. This, in turn, requires studies that span the freshwater and marine sciences to ensure environmental protection of River-Sea systems, and maintain their ecosystem functioning.

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[15] Beniston M, M Stoffel, R Harding, M Kernan, R Ludwig, E Moors, P Samuels, & K Tockner. Obstacles to data access for research related to climate and water: Implications for science and EU policy-making. Environmental Science & Policy: 17: 41-48.

[16] Voulvoulis N, KD Arpon & T Giakoumis. 2017. The EU Water Framework Directive: From great expectations to problems with implementation. Science of the Total Environment: 575: 358-366.

**Summary**

In conclusion, it is critical that R&I priorities in River-Sea systems need to align with EU research funding policy and priorities, whilst also meeting stakeholder needs. This alignment is essential if future R&I is to support sustainable development, protecting the environment whilst also realising social and economic expectations. Moreover, inter-disciplinary research is required to address current and emerging environmental problems to deliver sustainable and innovative solutions to major societal challenges, including environmental protection and job creation (e.g. EU Blue and Green Growth initiatives).

It is also important to move beyond a relatively narrow approach to integrated water resource management (IWRM) and recognise the interconnectedness of social, economic, hydrological and ecological needs in river basins and associated coastal zones. The IWRM uses the basin as the managed unit and recognises the dynamic relationships between stakeholders and central governments who must work together to meet the goals of sustainable development. This highlights the fundamental importance of improving environmental governance, and interdisciplinary (or transdisciplinary) cooperation, as argued recently by Kurian[17]. The intention is that DANUBIUS-RI will facilitate the interdisciplinarity required, for R&I along the River – Sea continuum, addressing the gap identified in a recent review by Granit et al[18]. They highlight problems with current approaches to achieve environmental protection, specifically in the context of a source-to-sea system, which they attribute partly to understanding (i.e. more research is needed) and partly to fragmented governance and management systems at different levels (i.e. relating to policy and socio-political structures).

As noted above, one of the main ways in which DANUBIUS-RI will aim to achieve its mission of 'making river sea systems work' is by facilitating interdisciplinary collaboration, developing a **common terminology** and modus operandi (e.g. through the DANUBIUS commons), **advancing data access**, and **understanding** across the River – Sea continuum between freshwater and marine environments. The intention is that the RI will also aid Knowledge Exchange (KE) and Knowledge Transfer: within and between academic communities; business, government and the wider public. The following paragraph illustrates some of the wider benefits of facilitating KE with respect to environmental legislation and the implementation (and policing) of environmental policies.

In many respects, environmental legislation presents many opportunities to deliver tangible improvements in River-Sea systems and promote sustainable development. As outlined by

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[17] Kurian, M. 2017. The water-energy-food nexus. Trade-offs, thresholds and transdisciplinary approaches to sustainable development. Environmental Science & Policy: 68: 97-106.

[18] Granit J, BL Lymer, S Olsen, A Tengberg, S Nommann & TJ Clausen. 2017. A conceptual framework for governing and managing key flows in a source-to-sink continuum. Water Policy, 19: 673-691.

Chapron et al**[19]**, environmental laws and regulations provide unique, binding, and enforceable tools to limit adverse environmental impacts. Further, they provide a practical way in which society can satisfy international obligations (e.g. under the Aarhus Convention), and to enable government to hold polluters to account where environmental standards have been breached. Chapron et al. suggest that environmental legislation, where properly drafted, can prevent planetary boundaries being breached. However, the challenge in enabling this lies in providing more opportunities for KE with the legal profession (lawyers, lobbyists), and in addressing the three key challenges constraining the management of River – Sea systems noted above (i.e. **Terminology**; **Data**; and **Understanding**).

A topical example of the need for enhanced interdisciplinary understanding of River-Sea systems that informs environmental policy and regulation in this area is provided by the increasing need for effective legislation to address plastic waste in marine (and freshwater) environments[20]. Here the difficulties of environmental regulation reflect a combination of incomplete understanding of the pollution pathways and the fragmented nature of aquatic legislation. In their recent review, Black et al. highlight the need to integrate policy and legal instruments and to explicitly acknowledge the importance of geographical connectivity: viz. the mechanisms of transport from catchment to sea. While there are specific difficulties with plastics (as the WFD does not cover plastic litter), the example emphasises the need for targeted research to inform improvements in 'monitoring and in the legislative framework, connecting river basin management to coastal and marine water management.'[20]

[19] Chapron G, Y Epstein, A Trouwborst & JV López-Bao. 2017. Bolster legal boundaries to stay within planetary boundaries. Nature Ecology & Evolution. 1 doi: 10.1038/s41559-017-0086

[20] Black, JE, K Kopke & C O'Mahony. 2019. A trip upstream to mitigate marine plastic pollution – a perspective focused on the MSFD and WFD. Frontiers in Marine Science 6, art. 689 doi: 10.3389/fmars.2019.00689.

DANUBIUS-PP

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