Advancing the basis for integrated research on (European) River – Sea systems: the DANUBIUS-RI project

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European research at the interface between terrestrial, riverine, estuarine and marine environments is frequently constrained by disciplinary and geographical boundaries. This is problematic given the need for holistic environmental management. This paper introduces DANUBIUS-RI: a project which aims to facilitate inter-disciplinary research on river-sea systems and which was accepted onto the European Strategy Forum on Research Infrastructures roadmap in 2016. Its scope spans the environmental, social and economic sciences and seeks to facilitate cross-disciplinary research on European rivers and seas. The project will offer researchers access to facilities, to European River–Sea systems, providing a platform for multi-disciplinary research and training.

Keywords: Research infrastructure; Environmental Research; River-Sea systems

Introduction

River catchments and coastal areas globally are experiencing multiple pressures relating to freshwater availability. This is increasingly threatening our ability to provide human water security, given increasing anthropogenic water demands at a time of changing catchment water balances (Vörösmarty et al. 2010). In many cases the effects of increasing water management are cumulative: propagating downstream, and in coastal areas the effects are further exacerbated by changes in relative sea level (Nicholls & Casenave, 2010; Weisse et al., 2014) and high (and increasing) population densities. The problems are compounded by concurrent concerns over surface-water and groundwater quality and potential implications for public and environmental health. The breadth and potentially wider impact of these pressures present increasing problems for catchment and river managers, given the increasing frequency of extreme flows and environmental hazards, the loss of biodiversity, and the many difficulties in identifying sustainable solutions to dynamic and widespread problems that have increasing societal impacts.

There is an urgent need for new and innovative approaches to environmental research that span the freshwater and marine sciences. With some notable exceptions (e.g. Ericson et al. 2006), research at the River – Sea interface is significantly constrained by disciplinary and geographical boundaries. Consequently, at present there is a particular lack of knowledge and research that covers the full continuum of terrestrial, riverine, estuarine and marine systems, linking catchments, to transitional environments (coastal deltas, estuaries), coastal areas and shallow seas. This is particularly significant when considering the river – sea continuum given the lack of truly inter-disciplinary approaches to environmental management and the imposition of rigid geographical boundaries at different levels, both physically and politically from catchments-to-coast. The pressures are particularly marked in coastal areas given widespread population pressures: currently half Europe's population are estimated to live within 50 km of the coast and coastal areas support key industries and activities including aquaculture, fisheries and tourism. There are also significant infrastructural assets (valued at €500 - €1,000 million) situated within 0.5 km of Europe's coastline (European Environment Agency, 2012). Consequently, any environmental change, whether natural or anthropogenic, can have significant societal implications, with increasing vulnerability to riverine and coastal hazards (e.g. Güneralp et al. 2015; Hinkel et al. 2014) which has global implications (Newmann et al. 2015).

To address this need, and to advance a more integrated approach to environmental research across the river – sea continuum, a pan-European distributed research infrastructure DANUBIUS-RI is being developed which is dedicated to the integrated study of European River – Sea systems. The title (DANUBIUS[1]) reflects the development of the initiative which was initially proposed following workshops bringing together freshwater and marine scientists and which sought to integrate studies of the Danube River, the Danube Delta and the Western Black Sea. Discussions at these meetings concluded that, notwithstanding the scale and complexity of the Danube River Basin and Black Sea (a drainage basin spanning 19 countries with a complicated geopolitical history; a unique wetland Biosphere Reserve; a semi-enclosed sea dependent on riverine inputs of freshwater and nutrients), the problems of the Danube River – Delta – Black Sea were common across Europe and globally. The challenges are compounded by extensive anthropogenic changes to river catchments, coasts and shallow seas which potentially compromise their ability to continue to provide key ecosystem services. Solutions to these problems require innovative approaches to environmental research and water resources management to enhance the capabilities of existing facilities and take full advantage of new and emerging developments and capabilities in the environmental sciences. In particular, cross-disciplinary research that spans traditional disciplinary boundaries is required at several levels: for example from freshwater to marine; river to floodplain; and surface-water to groundwater.

DANUBIUS-RI was accepted onto the European Strategy Forum on Research Infrastructures (ESFRI) roadmap in 2016. The initiative is currently (2017) in its implementation phase, and plans detailing the architecture and funding model(s) for the RI are being developed with support from a 3-year H2020-CSA project. DANUBIUS-RI seeks to build upon existing expertise and facilities across Europe, to facilitate world-leading interdisciplinary research on river – sea systems. The scope of the project

[1] From the Sanskrit for fluid: 'dãnu'

spans the environmental, social and economic sciences seeking to facilitate integrated approaches to environmental research, management and education. As a distributed infrastructure, it will offer researchers field access to facilities and research services across a range of European River – Sea systems. The vision, is that when fully functioning, DANUBIUS-RI will provide a ‘one stop shop’ for Knowledge Exchange, and access to harmonized data, which will assist in developing new scientific approaches to cross- and trans-disciplinary research and a platform for education, research and training.

The scientific case to support and underpin the development of the infrastructure development will be refined during the implementation phase of the project. In this article we explore some of the key challenges confronting River - Sea systems, which provided the initial motivation and rationale for DANUBIUS-RI, and outline the proposed structure of the research infrastructure (RI). In so doing, we highlight the degree to which the RI can build upon existing research capabilities by enhancing our ability to undertake environmental research, and in so doing, identify solutions to emerging environmental problems. While here we focus mainly on water resources, the intention is that the RI will have a wider scope within the environmental sciences, recognizing the need for any facility to enhance interdisciplinary collaboration and research across the freshwater – marine continuum. Importantly however, the actual architecture of the RI may still change from that summarised in this paper, and there are opportunities for the wider community to engage with the development process to influence the infrastructure design as the RI moves forward to the implementation phase from 2019 onwards.

The Scientific Challenge

Rivers, lakes, deltas, estuaries, coastal wetlands and coastal seas are the dynamic product of interacting environmental processes and are subject to continuous natural alterations. This presents significant management challenges: both in understanding 'natural' environmental dynamics at different spatial and temporal scales, and in quantifying the implications of anthropogenic impacts which may contribute to 'change' at a variety of scales. Fundamentally, interdisciplinary studies of River – Sea systems need to integrate the biological, chemical and physical sciences, and recognize the significance of interacting social and economic processes. Physically, the system boundaries extend from the 'aqua incognita', or 'unknown waters', of the catchment headwaters (Bishop et al. 2008) to coastal seas which rely upon riverine nutrient and sediment fluxes to maintain productive fisheries, provide flood protection and sustain coastal deltas. Globally, rivers and seas are threatened by direct and indirect effects of increasing population densities, including widespread changes in land use and land cover, and increases in the frequency of high and low flows (Palmer et al. 2008). Freshwater and marine systems thus face multiple pressures from both natural drivers (e.g. climate forcing) and anthropogenic drivers (e.g. urbanization, hydro- and wind power generation, and shipping / navigation) at scales ranging from local to regional and global (Omerod et al. 2010). These pressures are ubiquitous and contribute to problems such as eutrophication, hypoxia, pollution, loss of biodiversity, habitat depletion, and ultimately loss of ecosystem services. Inevitably, the pressures are likely to increase in future with implications that extend throughout the catchments-to-coast continuum with unknown consequences for the resilience of often vulnerable ecosystems. For example, there is growing concern that coastal deltas and estuaries are currently at 'tipping points' as these systems evolve from their 'natural' state in the early Holocene, to a heavily modified (Anthropocene) state at present. The concern is that these systems may potentially progress to a state of ‘Collapse’ in future as the effects of rising sea level and land subsidence are compounded by changes in river flow and sediment fluxes (Renaud et al. 2013; 2014; Walling, 2006). These problems are symptomatic of wider concerns that at present our knowledge of system functioning is insufficient to inform levels of resilience and determine the likelihood of ‘collapse (Syvitski et al. 2011).

In a number of respects societal responses to the challenges confronting River – Sea systems have been fragmentary, constrained to a significant extent by disciplinary and geopolitical boundaries. This has contributed to the hitherto limited scope of inter-disciplinary initiatives to undertake, develop and apply the fundamental and integrated research required for the holistic study of River Sea systems. One of the key challenges in managing the river – sea continuum is how to reconcile the need to ensure security of water supply without compromising the provision of other key ecosystem services, e.g. provision of water for industry and transport or to support biodiversity. These challenges are compounded by the uncertainties of environmental functioning, particularly at disciplinary interfaces: longitudinally (freshwater to marine), laterally (river to floodplain; coast to sea), and vertically (surface to groundwater). The problems are further impacted by, in some cases, inappropriate current and historic catchment and coastal management, which to a considerable extent has lacked the integrated approach required given ongoing increases in population densities as explicitly acknowledged in recent debates and syntheses exploring the developing concept of the Anthropocene (Ruddiman, 2013). While a more holistic approach to the study and management of the River – Sea continuum is urgently required, the problems and contradictions of current approaches are best illustrated by first considering the contradictions of current catchment management practices, before examining the implications downstream for freshwater-marine transitional zones and shallow seas.

Globally river catchments are experiencing substantial and ongoing changes in catchment water balance, with anthropogenically driven climate change contributing to changes in the partitioning of rainfall between individual catchment water stores and fluxes (Overeem et al. 2013). In some catchments increasing temperatures have led to increases in both rainfall quantity and intensity, while elsewhere, elevation dependent warming has contributed to reduction in seasonal snowfall with an attendant decrease in streamflow (Berghuijs et al. 2014). The tendency towards streamflow reductions has been exacerbated by increased evapotranspiration, and groundwater abstraction, with the cumulative effects of reduced streamflow increased by widespread hydraulic engineering for navigation (e.g. removing river meanders and dredging) and hydropower, which heavily modify river flow regimes and sediment flux (Nilsson et al. 2005). These developments threaten human water security (Vörösmarty et al. 2010), however, the management of many rivers and catchments is characterized by an overly sectoral approach with limited integration and without the holistic focus required. For example, there are considerable management challenges in international river basins such as the Danube River Basin where an increasing proportion of the basin is heavily regulated, and it is difficult to reconcile the conflicting needs of flood management and navigation whilst restoring or conserving the geomorphological and ecological diversity of key freshwater environments (Habersack, et al. 2016; Hein et al. 2016). These concerns are compounded when considering the implications of changes in river water quality: including inadequately treated waste-water, urban runoff, and agricultural effluent (Chapman et al. 2016). Here there is an urgent need for chemical and effect-based monitoring tools to inform new models of exposure and risk assessment.

However, the success of this work (particularly its wider impact) is heavily dependent upon holistic, basin-wide approaches to catchment management and governance. The latter are frequently hindered by political boundaries which contribute to a disjoint in management priorities through the wider basin.

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 (Habersack et al. 2016; Paola et al. 2011; Walling, 2006). 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, potential development of sites of renewable energy (wind farms; tidal barrages) and uncertainties over the consequences of new initiatives relating, for example, to methane hydrates (Ruppell, 2011). Given increases in global population and in the population of 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.

Further complications arise through the growing recognition of limits in environmental resilience given increasing environmental change, particularly in the context of abrupt, non-linear change. The latter may lead to non-linear transitions in ecosystem functioning, which may constitute Planetary Boundaries when rapid environmental change poses an unacceptable risk to society (Rockström et al. 2009; Steffen et al. 2015). 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 (Rockstrom, et al. 2009; Table 1). While these problems are almost ubiquitous, in some case, 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. Rockström et al. (2014) 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 (Steffen et al. 2015). 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 (Rockström et al. 2014).

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 current sustainable development goals (Green et al. 2015; Griggs et al. 2013) and harbour sensitive and highly threatened species, especially those, such as the sturgeon, that migrate over long distances (Banaduc et al. 2016). 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 (Brils et al. 2014). 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.

Resolution of these problems requires novel approaches to environmental management underpinned by scientific understanding. The latter requires innovative approaches to environmental research, and particularly water resources management, are required to enhance existing capabilities and benefit from new and emerging developments in the environmental sciences. In particular, enhanced knowledge exchange and improved communication between environmental researchers and the wider community is needed urgently to address wide-ranging problems relating to environmental management and governance.

DANUBIUS-RI: the architecture of the Research Infrastructure

Given the challenges identified above, the development and implementation of the ESFRI[2] distributed pan-European research infrastructure, DANUBIUS-RI, to advance the integrated study of River-Sea systems is both timely and essential. The research landscape analysis by ESFRI concluded that DANUBIUS-RI is the only (European) research infrastructure to support research on transitional areas between coastal marine and freshwater areas (ESFRI, 2016). The goal of DANUBIUS-RI is to provide enhanced process understanding of: i. environmental system dynamics; ii. the impact of catchment and marine pressures on system function; iii. the consequences of human activities as drivers; and hence, iv. safeguard the ecosystem functions and services provided by River Sea systems. The Research Infrastructure (RI) seeks to quantify environmental system dynamics at different scales and across disciplinary boundaries to enhance our ability to manage environmental processes of freshwater and marine systems. Significantly, in this respect, recent developments in analytical and observation technology, from space-borne to in-situ monitoring, and more advanced modelling capabilities, now provide opportunities to monitor River Sea systems at the entire basin scale and in real-time. However, these developments present their own challenges, requiring quality control to ensure comparability and consistency in environmental monitoring, in analytical procedures, and in enhancing our ability in environmental modelling to utilize these new data sources. DANUBIUS-RI aims to integrate research across the environmental, social and economic sciences. It will provide access to a range of River Sea systems, facilities and expertise, offering a 'one-stop shop' for Knowledge Exchange, access to harmonized data and a platform for interdisciplinary research. DANUBIUS-RI seeks to consolidate European facilities in the freshwater and

[2] European Strategy Forum for Research Infrastructure.

marine sciences by developing (and using) the analytical, observational, modelling and data management facilities devoted to these environments. In so doing the RI seeks to build upon initiatives including Future Earth Coasts (formerly Land Ocean Interactions in the Coastal Zone: LOICZ), the World Climate Research Programme (WCRP) and the Global Environment Facilities' International Waters programme. The RI aims to offer a platform to integrate knowledge and understanding contributed by disciplines spanning the Earth, Environmental, Social and Economic Sciences to encourage a more integrated approach to the study of key societal challenges relating to the linkages within, and between, Rivers and Seas. This integrated approach is essential to deliver holistic understanding of system functioning and change.

The infrastructure is envisaged as a new pan-European distributed research infrastructure dedicated to research in the freshwater and marine sciences. The current architecture of the RI, as accepted onto the ESFRI roadmap, is summarized in Tables 1 and 2. Physically the RI will comprise a 'Hub', 'Nodes' and 'Supersites' distributed across Europe (Figure 1) to optimize the use of existing expertise and facilities in undertaking interdisciplinary research to understand, characterize and manage these diverse systems. The 'Nodes' of the infrastructure will be key facilities, some of which will be virtual in nature, that offer observational, analytical and modelling capabilities across the biological, physical and social sciences (detailed in Table 1):

The **Observation Node**, to be coordinated by the Plymouth Marine Laboratory (PML) in the UK, will build upon PML's experience in developing and testing algorithms to retrieve water constituents using data from remote sensing platforms and wider community developments of in-situ sensing technologies at different scales. The node will recommend procedures for standardization of instrumented buoys across sites associated with the RI and advise on the telemetry that needs to be in place to enable real-time data capture.

The **Analysis Node**, led by Bundesanstalt für Gewässerkunde (BfG), Germany, will work to ensure consistency in analytical techniques through standardized protocols for field sampling and laboratory analyses of key environmental determinants. Quality Control standards will be developed to ensure comparability between data collected at different sites and environments (e.g. freshwater – transitional – marine). The Node will build upon BfG's analytical capabilities spanning the environmental sciences which will be the designated 'lead laboratory' for the RI, but additional 'satellite laboratories' are envisaged to provide additional services and expertise in key areas (both geographically and with respect to different suites of analytical analysis).

The **Modelling Node**, coordinated by ISMAR-CNR, Italy, will draw upon the enhanced availability of environmental data to develop transferable modelling tools to simulate specific processes, interpolate (spatially and temporally) between observation points, and investigate model scenarios. Appropriate numerical modelling tools are key pre-requisites in identifying sustainable solutions to environmental problems spanning River Sea systems and their transitional environments and this work will build upon ISMAR-CNR's expertise in hydrodynamic and biogeochemical modelling, including oil spill scenarios.

The **Impact Node**, to be developed by Deltares, The Netherlands, will aim to integrate technical knowledge on River Sea systems, provided by the RI, with developments in environmental governance and policy making. The node will develop and test concepts, methods and instruments to identify sustainable solutions using innovative approaches: for example, using a 'decision theatre' to enhance spatial planning across the River – Sea continuum. A key focus will be on developing methods and instruments to identify how to address uncertainties in the decision-making process. Furthermore, given the different disciplines associated with the RI, the node will work to develop a common language, or ontology, to enhance communication and Knowledge Exchange.

In addition to the Nodes, a suite of 'Supersites' are envisaged. These will be situated across Europe (Fig. 1) and will comprise 'national laboratories' for observation, research, modelling and innovation at key areas of interest across the River – Sea continuum. Individual supersites will constitute advanced field laboratories which encompass a range of environments at different scales and interfaces. Currently proposed Supersites vary from relatively pristine sites (such as the **Danube Delta**) to areas impacted significantly by anthropogenic processes (e.g. **the Thames Estuary**; **the Elbe**). Freshwater supersites include **Szigetkoz** on the floodplain of the River Danube in Hungary which focuses on characterizing surface-water – groundwater interactions and quantifying the effects of river engineering works (river diversion and realignment), and **Lake Lunz and the Upper Danube** catchment in Austria focusing on Alpine systems. The latter offers long-term observation sites to study ecosystem response to climate change to help attribute cause-and effect given multiple pressures on freshwater environments and the effects on carbon cycling. Additional supersites include the **Ebro Delta** (Spain), **Nestos** (Greece) and the **Po Delta / Venice Lagoon** (Italy) which provide a range of transitional field-sites impacted to varying degrees by climate change, rising sea level and changes in catchment land use. Together, the proposed supersites will provide access to a range of 'field laboratories' experiencing a variety of pressures at different scales and there is the potential to increase or modify details of the Supersites associated with DANUBIUS-RI as the project develops.

In addition to the opportunities provided by dedicated field laboratories (the Supersites) there is a desire to fully realize the benefit from our freshwater and marine resources under the Integrated Management Plan and the Blue Green Agenda at EU level, and associated corresponding national initiatives (e.g. Harnessing our Ocean Wealth in Ireland). Hence it was felt essential that DANUBIUS-RI should have the ability to converse with industry, particularly with regard to Intellectual Property (IP) Rights. Consequently, one of the nodal centres, UCC in Cork, Ireland, will house a dedicated **Technology Transfer Office** charged with maximising the benefits derived from development of the infrastructure to enhance technology transfer and commercialization of IP. It is envisaged that this will create an enabling environment for collaborative working between industry and researchers whilst also building capacity in the research (and industry) communities to identify and fully exploit any IP generated.

The project also proposes a dedicated **Data Centre**, to be situated in Romania that will draw upon existing European e-infrastructures to provide data access and ensure data interoperability. A distributed data archiving infrastructure will be developed to foster sharing of data and computer resources at different levels: from data acquisition, through data processing and storage and ultimately through to data access.

The overall vision of DANUBIUS-RI is that the Nodes will ensure disciplinary rigour whilst benefitting from the potential for inter-disciplinarity provided by the Supersites. The **Hub** of the RI, to be situated in the Romanian Danube Delta, will coordinate the infrastructure and will seek to build capacity in interdisciplinary and transdisciplinary research linking freshwater and marine sciences. A particular focus will be in developing links outside Europe, given the wider international context to these problems..

In its present form, the proposed infrastructure extends across ten European countries with further support provided by institutions in a further eight countries. A significant focus of the project will be to encourage and enhance inter-disciplinarity, which could potentially be compromised by discipline-specific observation and analytical protocols. Hence for the RI to span the freshwater and marine sciences, a harmonized methodology will be developed to ensure the consistency and quality of scientific output.

Discussion

In this paper, we summarize the vision for a distributed pan-European Research Infrastructure, DANUBIUS-RI which, following the ESFRI definition, comprises 'facilities, resources and services used by the science community to conduct research' (ESFRI, 2016). The initiative seeks to avoid duplication wherever possible, but to use the opportunity to develop complementary facilities that enable the research community to address key research and societal challenges that confront River – Sea systems. These challenges are particularly urgent across the River - Sea continuum given the current lack of integrated, participatory and adaptive management in which the river, delta/estuary, coast and sea have not been considered (or managed) as a single entity. The reasons for this are many and include wide-ranging constraints on inter-disciplinary research and the degree to which current regulatory frameworks impede the development of holistic approaches to River Sea systems. In Europe, for example, river and coastal zone management is governed by the Water Framework Directive (WFD – 200/60/EC) while management of European marine waters is subject to the Marine Strategy Framework Directive (MSFD – 2008/56/EC) and the more recent Maritime Spatial Planning (MSP) Directive (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.

The success of DANUBIUS-RI will to a large extent depend upon the degree to which the infrastructure is able to foster inter- and cross-disciplinary research at all levels. The proposal seeks to breakdown the traditional, disciplinary, barriers to environmental research and management by providing state-of-the art facilities for the research community within the Nodes and Supersites. In practice, this requires agreement over a common language, or ontology, to ensure research questions are framed appropriately, with data (field, analytical, model) collected and archived according to agreed protocols to ensure disciplinary rigour. Hence stakeholder engagement is vital in ensuring that the architecture of the RI satisfies the (current) needs of the user community and has sufficient flexibility to adapt in response to future pressures, howsoever these are determined. In the process, the hope is that inter-disciplinary dialogue will encourage cross-fertilisation in approaches to environmental research and management on River – Sea systems that builds upon ongoing advances in field, analytical and modelling capabilities.

For European River – Sea systems, DANUBIUS-RI provides opportunities for the research community to work closely with catchment and river managers, to advance new and transferable solutions to emerging environmental problems. Europe has a long institutional experience in responding to these challenges, evidenced by past actions in response to poor water quality, and developing tenets such as integrated water resources management, adaptive management and ecosystem-based approaches for conservation and restoration (Falkenmark, 2017). The arguments to develop and integrate these new approaches, as part of a wider ‘water paradigm’ are compelling (e.g. Pahl-Wostl et al. 2013; Schoeman, et al. 2014) although the problems are geographically diverse: Europe has a long and considerable institutional experience in responding to water management problems, culminating in the Water Framework Directive. The WFD provides the legal framework to protect water bodies, advocates management approaches focussed on the drainage basin. However, increasingly even where achievable, a drainage basin focus in itself may be insufficient to resolve wider environmental problems, given increasing coastal populations with higher per-capita water use at a time of reduced water availability with concurrent concerns where marine pollution problems (e.g. PCBs; Jepson et al. 2016) can be directly attributed to catchment and river management. It is evident, however, that problems of this scale and complexity require novel approaches to understand, quantify, and manage, emphasizing the need for enhanced communication between researchers, environmental managers and the wider community to understand the rationale that underpins changes in environmental policy and regulation.

These broad goals must be supported by sound science. Here the situation is further complicated by the nature of the River - Sea continuum itself which is characterized by process discontinuities at different scales through fluvial to marine systems (Bentley Sr et al. 2016). Globally, however, River - Sea systems are increasingly important, both with respect to conventional hydrocarbon exploitation and production, and to explore the full potential of emerging development in renewable energy including offshore wind farms, tidal energy (barrages and turbines and wave energy converters) and aquaculture (Buck et al. 2004). At a time of extensive human modification of freshwater and marine systems it is essential that the full potential benefits accruing from cross-disciplinary projects are realized, without jeopardizing the resilience of River - Sea systems in the context of sustained environmental change. This presents significant challenges in which adaptive management requires an accommodation between potentially multiple users as well as recognition of the significance of autogenic process response at different spatial and temporal scales. The latter describes the extent to which River - Sea systems have the ability to self-regulate as they evolve over time, although there are uncertainties with regard to their resilience, for example, over their capacity to assimilate material fluxes (e.g. nutrients, carbon, emerging pollutants, sediment) and their stability in the context of continued environmental change.

Notwithstanding these challenges, there are considerable benefits in ‘working with nature’ to support the natural capacity to deliver key ecosystem services. This requires targeted conservation and restoration of freshwater and marine ecosystems to protect the provision of key services in sustaining ecosystem dynamics and health. Examples include developing concepts in natural flood management and green engineering, which can replace traditional ‘hard’ engineering approaches to catchment, river and coastal management. These changes in approach have been likened to a paradigm change (e.g. Petts et al. 2006), but their implementation in advancing the basis for integrated water resource management present considerable practical problems. This includes the difficulties in reconciling competing demands for water, in sustaining the complexity of freshwater and marine habitats, and quantifying the inter-relationships between biotic and abiotic processes. The problems are further complicated by the potential of non-stationarity (Milly et al. 2015), the global context of water distribution and use with increasingly human mediated changes in water storage and flux (e.g. Kumar et al. 2016), and the urgent need to identify and deliver solutions to environmental problems (Pahl-Wostl, et al. 2013).

For a number of reasons, therefore, this is a timely opportunity to develop an interdisciplinary pan-European RI on freshwater – marine systems. Given the global context of pandemic water problems, and the need to identify solutions, Pahl-Wostl et al. (2013) advocated the setting of 'global water testbeds' for interdisciplinary research, in which the identification of shared problems and development of integrated methodologies can enhance interdisciplinary and transdisciplinary knowledge. While there are practical difficulties in implementing these ideas, DANUBIUS-RI illustrates how a research infrastructure can be designed to build upon new and emerging ideas in the environmental sciences. These include: advances in Earth Observation that build upon the European Commission and the European Space Agency's Copernicus Programme; increasing capabilities in in-situ monitoring technologies (e.g. Blean et al. 2016); recent developments in citizen science (Bonney et al. 2014); and the developing potential for near-real time processing and management of Big Data. These advances provide opportunities to model River Sea systems at spatial and temporal scales that were previously unrealistic given, for example, that our ability to develop complex hydrological models has been constrained by limitations in data availability (Gleick et al. 2013). The challenge for the future lies at the intersection of the pure and applied sciences, in ensuring appropriate quality assurance and control of the new data, in practical applications of our improved scientific understanding, and developing cross-disciplinary communication (Vegteveen et al. 2014). The ultimate challenge is then in applying these new techniques to provide sustainable solutions to new and emerging environmental problems.

Conclusions

Globally Rivers and Seas are confronted by a suite of environmental problems reflecting the current and historic management of catchment, river and marine systems. The dynamics of the water cycle have been increasingly affected by human activities, with effects that in some cases are being compounded by ongoing changes in climate and land use. The scale of these problems is such as to require a stronger inter-disciplinary focus, to develop and apply new ways to integrate environmental research and stakeholder communities. In this paper we summarise a proposed pan-European distributed research infrastructure that seeks to address this need at the freshwater – marine interface: DANUBIUS-RI. This project is dedicated to the integrated study of European River - Sea systems, which was recently accepted onto the ESFRI roadmap. The proposal envisages **nodes**, focussing on **observation**, **modelling**, **analysis**, and **impact**, with (at present) **Supersites** in 8 countries (Austria, Germany, Greece, Hungary, Italy, Romania, Spain and the UK), a **Technology Transfer Office** (in Ireland) and a **Data Centre** and **Hub** (in Romania). As the architecture of the infrastructure is finalized prior to the implementation phase, a consultation process is underway to refine the structure of the RI, and determine the capital and recurrent funding required for the proposal to proceed. Further development of the proposal provides opportunities to widen community engagement and ensure that the research infrastructure provides key facilities to enable the research community to strengthen the basis for trans-disciplinary research on European River – Sea systems.

Acknowledgements.

Many of the costs incurred so far in developing the ESFRI project DANUBIUS-RI were covered by projects PN 09410307/2010, 7S/2013 and PN3-DANUBIUS-Management/2016 funded by the Romanian National Authority for Scientific Research.

Further funding was provided through the FP7 project DANCERS (DANube macroregion: Capacity building and Excellence in River Systems (basin, delta and sea)) contract EC 603805. The authors are grateful for current funding of the preparatory phase, as the project moves towards implementation, provided through the HORIZON 2020 project DANUBIUS-PP (Contract EC 739562).

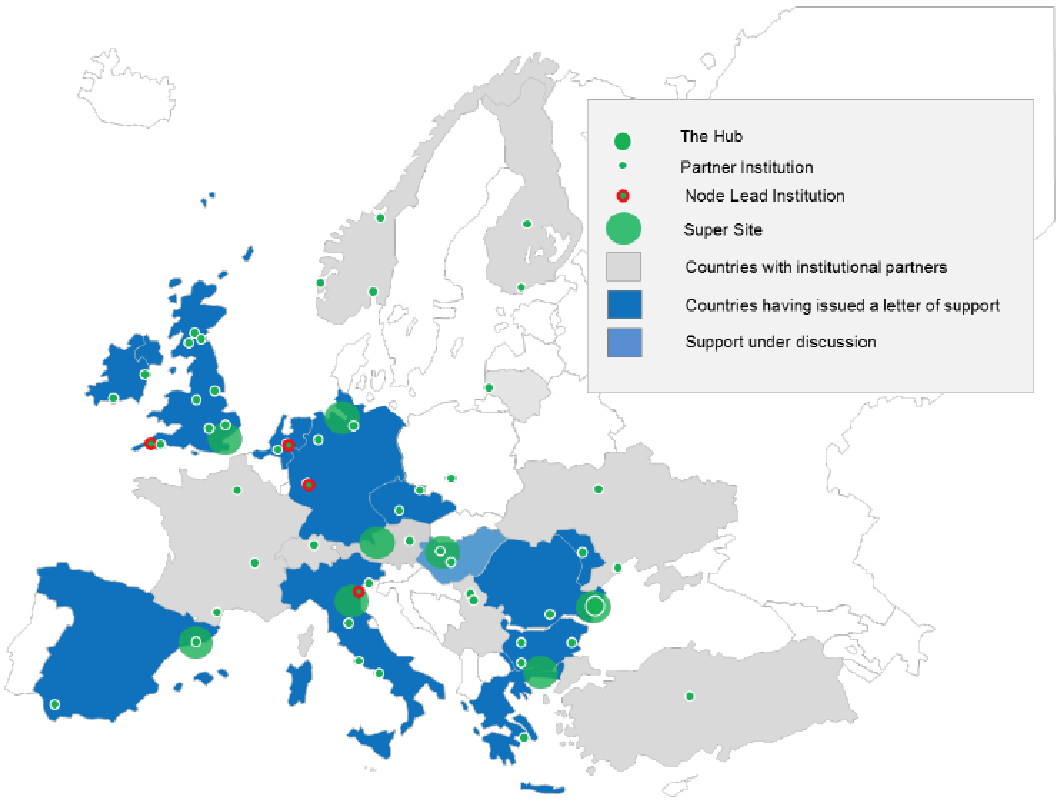
Table 1. Details of the scope of Danubius-RI: Hub, Nodes and Technology Transfer Office.

	Location / Lead institution	Description
The Hub	Danube Delta, Romania	RI management and coordination; stakeholder engagement; capacity building; research dissemination; oversee development of the infrastructure (as an ERIC).
The Observation Node	Plymouth Marine Laboratory, UK	Virtual node to utilize recent developments in satellite and aircraft Earth observation sensors and science, in-situ sensor capabilities for fixed and mobile platforms to provide observational capabilities in real / near-real time. Ensure consistent monitoring of physical and biogeochemical parameters.
The Analysis Node	Bundesanstalt für Gewässerkunde (BfG), Germany	Ensure the consistency in analytical techniques required across the disciplines of Hydrology, Chemistry, Biology, Ecotoxicology. The node will comprise lead laboratories for the major analyses with satellite laboratories providing key services in additional areas.
The Modelling Node	ISMAR-CNR, Italy	Transferable and interchangeable modelling tools will be developed by the modelling node to address challenges across the typology of processes across freshwater – marine systems at different scales.
Social & Economic Node	Deltares, the Netherlands.	Aims to integrate technical knowledge on River Sea systems with governance and policy making; seeks to develop and test concepts, methods and instruments to achieve this goal and improve the decision-making process.
Technology Transfer Office	University College Cork	A dedicated resource designed to ensure that the Intellectual Property generated under Danubius_RI by the research community, or by researchers collaborating with industry, is recognized, protected and fully exploited.
Data Centre		Data archive infrastructure integrated with the European Grid Infrastructure to facilitate data sharing and computer resources.

Table 2. Summary characteristics of Supersites associated with DANUBIUS-RI.

Supersite	Lead Institution	Description
Danube Delta	National Institute for Research and Development in Biological Sciences; GeoEcoMar, Romania	A relatively pristine world heritage site impacted by conflicting pressures from Danube River Basin of >800,000km^2 and Black Sea
Ebro-Llobregat Deltaic system	Politehnic, University of Catalunya, Spain	Large wetland complex in Western Mediterranean with catchment of >85,000km^2.
Elbe Estuary	Helmholtz Zentrum Geesthact & Federal Institute of Hydrology, German	Important transport corridor. Catchment of ~150,000km^2 is primarily in Germany but with headwaters in Czech Republic. Subject to conflicting pressures of navigation and environmental conservation.
Lake Lunz and the Upper Danube Catchment	WasserCluster Lunz, Austria	Long-term experimental and observation facilities to assess ecosystem response to environmental change, analyses of multiple pressures and aquatic ecosystem research.
Nestos	Hellenic Centre for Marine Research, Greece	Relatively pristine and sparsely populated catchment of varying relief spanning Bulgaria and Greece draining into the North Aegean Sea. Extensive microtidal delta and transitional environments, sensitive to changes in catchment biogeochemistry and sediment transport.
Szigetkoz	Széchenyi István University, Hungary	Characterization of surface-water – alluvial groundwater interactions on the Danube floodplain. Investigation of the impacts of river engineering on floodplain hydrology.
Thames Estuary	Centre for Ecology & Hydrology, UK	Highly impacted and modified estuary; catchment of ~13,000km^2, and heavily urbanized floodplain.
Venice Lagoon & Po Delta	Ismar-CNR & CORILA, Italy	Vulnerable coastal systems with alpine catchment headwaters affected by coastal management. Important cultural heritage site vulnerable to pressures of tourism

Figure 1. DANUBIUS-RI: the distribution of facilities across Europe giving the location of the Hub (Romania), Nodes, Supersites and institutions supporting the development of the infrastructure.



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