RIPARIANET - Prioritising riparian ecotones to sustain and connect multiple biodiversity and functional components in river networks

Stefano Larsen[‡], Jose Manuel Alvarez-Martinez[§], Jose Barquin[|], Maria Cristina Bruno[‡], Laura Concostrina Zubiri[|], Luca Gallitelli[¶], Micael Jonsson[#], Monika Laux[¤], Giorgio Pace[«], Massimiliano Scalici [¶], Ralf Schulz[¤]

‡ Research and Innovation Centre, Fondazione Edmund Mach, San Michele all'Adige, Italy
§ University of Cantabria, Cantabria, Spain
| Environmental Hydraulics Institute, University of Cantabria, Cantabria, Spain
¶ University of Roma3, Rome, Italy
# Umeå University, Umeå, Sweden
¤ RPTU Kaiserslautern-Landau, Landau, Germany
« CBMA Centre of Molecular and Environmental Biology, Minho, Portugal

Corresponding author: Stefano Larsen (stefano.larsen@fmach.it)

Abstract

Europe has committed to upscale ecosystems protection to include 30% of land and sea. However, due to historical overexploitation of natural assets, the available area for biodiversity protection is severely limited. Riparian zones are natural ecotones between aquatic and terrestrial ecosystems, contributing disproportionately to regional biodiversity and providing multiple ecosystem functions and services. Due to this and their branching geometry, riparian networks form a vast system of ‘blue-green arteries’ which physically and functionally connect multiple ecosystems over elevation gradients, despite covering a relatively small area of the basin. Hence, RIPARIANET argues that developing approaches able to optimise the spatial conservation of natural stream-riparian networks represent a flagship example of biodiversity protection in the EU. Although the integrity of riparian zones is fundamental for the achievement of multiple EU environmental objectives, the lack of a standardised framework for biodiversity assessment and protection across Member States has led to extensive impairment of riparian areas and frequent stakeholder conflicts.

The main objective of RIPARIANET is to leverage the increasing resolution of remote sensing information to provide practitioners with evidence-based guidance and approaches to biodiversity conservation. Key questions include: i) how can we remotely assess riparian integrity and identify areas which provide effective connectivity allowing species biodiversity and ecosystem functions to persist through meta-ecological processes? ii) how can we disentangle the influence of local- and network-scale stressors and processes on riparian biodiversity to better implement river basin

management schemes? iii) to what extent do currently existing protected areas in rivers account for the geometry of riparian networks and their multifunctionality?

We will address these questions in riparian networks within six river basins in Europe, including Boreal, Continental, Alpine, Temperate and Mediterranean systems. First, we will gather local needs and interests from key stakeholders together with satellite imagery and GIS environmental data for all basins. Then, riparian and river ecosystems functions will be modelled and ecological hotspots will be identified through a GIS-based multi-criteria approach, including stakeholder inputs. Then, we will collect in situ data to assess multiple biodiversity and stressors at the local scale and, subsequently, scale-up this information to the network scale using geostatistical tools and advanced modelling. This knowledge will be conveyed to managers at local and EU scales in the form of decision-support tools allowing decision-makers to identify protection gaps and ecological hotspots along riparian networks, based on multiple biodiversity, functional and connectivity criteria.

Keywords

riparian zones, river networks, remote sensing, bats, microbiome, plastics, contaminants, subsidies, aquatic-terrestial linkages

List of abbreviation

UKL: University of Koblenz-Landau;

FEM: Fondazione Edmund Mach.

Rationale and hypotheses underpinning RIPARIANET

In light of the Biodiversity Strategy 2030, Europe's commitment to upscale protection to at least 30% of land and sea urgently requires approaches able to optimise biodiversity conservation, while meeting the socio-economic needs of current and future generations. For decades, conservation management has been primarily driven by an ‘area-centric’ approach, where large areas and ecosystems supporting high species richness were prioritised. As a result, protected areas globally represent today isolated islands and remain biased towards economically marginal lands mostly at higher elevation (Venter et al. 2017). Despite recent emphasis on expanding protection to networks of areas in order to strategically include metacommunity and ecosystem processes, translating these perceptions into practical guidelines has proven challenging (Cid et al. 2021). This is particularly relevant for the EU, where the available area for biodiversity protection is limited due to historical predation of natural assets, current population density and intensive land-uses.

In this context, we argue that developing approaches to enhance the spatial conservation and prioritisation of natural stream-riparian networks represent an ideal flagship example for improving biodiversity protection in the EU. Riparian zones are natural ecotones between aquatic and terrestrial ecosystems, representing areas of complex environmental and biological transition within a relatively narrow extent. As such, they contribute disproportionately to regional biodiversity (Sabo et al. 2005), while also providing a range of important ecosystem functions and services, such as habitat and resource provision, nutrients and sediment retention, flood and climate regulation amongst others. Importantly, because of their branching, dendritic geometry, riparian networks form a vast system of 'blue-green arteries' similar to the human circulatory system (Weissteiner et al. 2016). Riparian networks thus physically and functionally connect ecosystems across heterogeneous landscapes and over elevation gradients. They also act as buffers of stressors and conveyors of material and organisms between the terrestrial and aquatic habitat; all this despite covering a relatively small area of the basin. The ecological benefits of protecting riparian networks will outweigh the costs of land reclamation. Nonetheless, local and global environmental alterations and climate change are a threat to riparian areas, with up to 90% of European stream floodplains now ecologically degraded. In addition, as emphasised in a recent call from WWF, despite evidence that freshwater habitats are losing biodiversity faster than any other ecosystems (Tickner et al. 2020), the Convention on Biological Diversity still focuses on 'land and ocean' without explicit considerations of freshwater and transitional habitats. Riparian zones are directly relevant to both aquatic and terrestrial EU environmental policies (e.g. Water Framework Directive, Habitat and Flood Directives, European Climate Law). Yet, the assessment of streams and rivers as part of the WFD still focuses exclusively on channel habitats and organisms. Similarly, the Flood Directive concerns riparian floodplains directly, but aims at mitigating flood risks rather than achieving biodiversity objectives. The apparent lack of consideration of riparian ecosystems in EU environmental policy partly stems from the lack of a standardised framework of biodiversity assessment and protection (González del Tánago et al. 2021). As a result, frequent stakeholder conflicts emerge related to conservation and the development of urban, agricultural, farming or forestry activities.

In this project, we hypothesise that an improved understanding of the stressors, functions and spatial constraints of stream-riparian networks can optimise biodiversity management in the EU to benefit both aquatic and adjacent terrestrial landscapes while, at the same time, only a small fraction of the landscape would be directly concerned. To achieve this, environmental decision-makers require tools to assess the integrity of riparian zones at the whole basin scale and identify conservation hotspots, based on multiple socio-ecological criteria. Combining satellite observations, field measurement and geo-statistical modelling in riparian networks over a wide climatic, landscape and vegetation gradient (Sweden, Germany, Spain, Italy and Portugal), RIPARIANET will produce a novel insight into riparian biodiversity, connectivity and multifunctionality at the basin scale. Applied riparian science has lagged behind contemporary ecological frameworks, such as metacommunity and meta-ecosystem theory, despite providing a unique test base for them. Appraisal of riparian conditions has seldom included spatially-explicit approaches able to account for complex spatial patterns. This is relevant for riparian networks, whose geometry influences physical and eco-evolutionary processes (Larsen et al. 2021). RIPARIANET explicitly addresses the dendritic spatial structure of riparian zones within the wider landscape (i.e. meta-ecosystems), a key novelty with respect to previous initiatives. Whether continuous or fragmented, impaired or in reference conditions, vegetated riparian areas are connected along hydrological networks and also laterally to other landscape units. Yet, this is scarcely acknowledged in applied research, where riparian corridors are referred to as *linear* green infrastructure

We will focus on key elements of river-riparian ecosystems that have been hitherto largely neglected and how they are related to riparian structure and composition. First, we will monitor bats as they are amongst the most threatened animal groups, with 45 species in the EU, of which almost 50% are classified as vulnerable, endangered or near threatened according to IUCN. Riparian areas are fundamental for the persistence of bat populations, as they provide habitat, foraging resources (aquatic insects) and are essential for connectivity between patches (Stahlschmidt et al. 2012). Second, riparian areas support hotspots of biogeochemical and hydrological activity (Vidon et al. 2010), which is mainly driven by microbial activity; we will quantify bacterial and fungal biodiversity and organic matter decomposition along the longitudinal and lateral dimensions of stream-riparian networks, while also estimating river metabolism (Rodríguez-Castillo et al. 2018). Third, plastic pollution is an emerging environmental risk of global proportions (Jambeck et al. 2015). While media attention has shed light on plastic islands in the oceans, most plastic is retained in and around rivers and streams (van Emmerik et al. 2022), yet patterns of plastic trapping remain little explored and unquantified. Fourth, the proliferation of chemical contaminants has outpaced other drivers of global change (Bernhardt et al. 2017), but the understanding of their fate and effects across the aquatic-terrestrial ecosystem boundary has lagged behind (Kraus et al. 2020, Lidman et al. 2020). This is a neglected aspect in the assessment of riparian ecosystems with important ecological implications (Schulz et al. 2015, Larsen et al. 2016). Hence, we will quantify the fluxes of waterborne contaminants from aquatic to riparian habitats as transported by emerging aquatic insects, the main biological vectors (Kraus et al. 2020) that also represent the primary prey source for many terrestrial consumers, including bats.

This knowledge will be translated into evidence-based guidelines and tools for policy stakeholders for identifying resilient riparian ecosystems and prioritise conservation and/or restoration efforts in different socio- and eco-regional contexts, while minimising socio-economic conflicts. In doing so, RIPARIANET will formalise synergies amongst Water Framework, Habitat, Birds and Floods Directives. We will address several points relevant to the BiodivERsA call, especially Theme 1, concerning the identification and promotion of priority conservation areas, enhancing connectivity and species protection.

Scientific objectives

The overarching objective of RIPARIANET is to leverage the increasing resolution of remote sensing information to provide practitioners with data-driven guidance and tools to biodiversity conservation (Fig. 1). Our main questions in relation to the BiodivERsA themes include:

1. *how can we remotely assess riparian integrity and identify areas which provide effective connectivity allowing species biodiversity and ecosystem functions to persist through meta-ecological processes?* We aim to develop approaches able to remotely identify and prioritise riparian areas that maximise biodiversity and ecosystem functions. Accounting for the branching geometry of riparian networks and their lateral connectivity to the landscape allows designing solutions that promote and maintain ecological connectivity amongst natural areas while maximising biodiversity potential outside protected areas.
2. *how can we disentangle the influence of local- and network-scale stressors and processes on riparian biodiversity to better implement river basin management schemes?* Stream and riparian areas are embedded within the wider land-use context, where local- and basin-scale factors, including anthropogenic stressors, influence ecological dynamics. By integrating remote sensing, field measurements and geostatistical tools, we will model and upscale riparian biodiversity, functions and the impact of key stressors, from local to basin scale.
3. *to what extent do currently existing protected areas (Natura 2000; local and regional) in rivers account for the geometry of riparian networks and their multifunctionality?* We seek to critically evaluate limitations and gaps in currently implemented protection strategies with respect to linked freshwater and terrestrial ecosystems. Management of riparian areas is still restricted to local actions without explicit consideration of their wider network geometry and their role as conservation corridors and their linkage to processes of the wider landscape.

Major outputs from RIPARIANET will include:

1. State-of-the-art remote sensing mapping of riparian integrity and continuity, diversity and ecosystem functions across six basins in Europe. This will be amongst the first continuous and ground-proofed (see 2) mapping of riparian conditions allowing the identification of conservation priority areas, based on multiple criteria (including stakeholders needs and interests).
2. Field-based assessment and modelling of multiple biodiversity, ecosystem functions and stressors in river and riparian networks from the six study basins.
3. The first EU-wide riparian connectivity mapping and conservation gap-analysis, providing a large-scale identification of riparian green infrastructures as current and potential ecological connectors across protected and natural areas.

4. Provide conservation practitioners and policy-makers with knowledge, GIS tools, data-processing pipelines and standardised approaches to identify functional and resilient blue-green infrastructure across heterogeneous basins.

Detailed approaches and methods

The planned work within RIPARIANET includes seven interlinked work packages (Fig. 2).

WP1 - Participatory conservation planning: Stakeholders involvement

A dedicated WP1 will guarantee continuous stakeholder involvement during the entire life-cycle of the project and beyond. The RIPARIANET consortium has already established relationships with stakeholders in each participant country. The project will further reinforce and expand interactions to widen the stakeholder landscape at national and EU levels. Early collaboration with local stakeholders and experts will occur via focus-groups and larger round-tables to identify key socio-ecological issues and priority areas in each study basin. Such information will feed into WP2 and WP3 aiding field-site selection. This bottom-up approach will enable timely and direct involvement of stakeholders in decision-making and will help appraise socio-ecological similarities and differences amongst countries. Involvement of stakeholders from the environmental, water management and agroforestry sectors will integrate needs from both aquatic and terrestrial perspectives. Targeted focus-groups will allow information exchange relevant to specific stakeholders, while larger round-tables will foster inter-communication amongst diverse groups highlighting synergisms and divergences. To further gather information about the ‘political landscape’ concerning riparian protection as it is currently perceived and to raise awareness about the future role of riparian zones for biodiversity and human well-being, we will propose questionnaires and citizen-science initiatives as detailed below.

Activity 1.1 - Development of a framework for identification and collaboration. Given the diverse nature of local stakeholders and the distinct socio-political landscape of the basins, we will develop a shared participatory protocol to identify, prioritise and interact with stakeholders within each study basin (months 1-3). Stakeholders from the following key sectors will be contacted in each basin: environmental and natural-resources (including NGOs), water and energy management, agriculture and forestry, local authorities and municipalities, plus wider “stream-riparian users” (canoeing and fishing clubs and tourism agencies). Special care will also be taken to include a diversity of public and private riparian landowners. The RIPARIANET consortium has gained substantial experience and skills in the involvement of stakeholders and the wider audience from previous scientific projects (see section “Approach to Stakeholder Engagement”).

Activity 1.2 - Demand and supply analysis. Early stakeholder involvement will rely on small (possible online) focus-groups (months (m) 4-5), where the objectives of RIPARIANET will be explained emphasising the synergies with interests of each target group. This stage will also identify sector representatives (e.g. species protection, fishing, hydropower) and types of riparian land ownership willing to participate in round-table discussions. Larger round-tables (first: m 5-9) will foster two-way knowledge exchange across multiple stakeholder representatives within each basin. The objectives will be:

1. developing a transparent partnership for shared decision-making and
2. the participatory mapping of socio-ecological priorities, based on multi-criteria evaluation.

Participants will be asked to identify and rank riparian segments considered in reference or impaired conditions and to highlight areas deemed critical for their particular sector. These maps will aid subsequent remote analyses of hotspots in WP2 (A2.4). Environmental managers will be asked to reflect on what is needed to better identify priority conservation sites in their areas. To facilitate an agreement in the ranking of priority areas based on potentially contrasting criteria (e.g. environmental vs. economic benefit), decision-aiding tools may be used (e.g. MCDA R package).

Activity 1.3 - Reaching out to the “stream-riparian community”. We will contact riparian landowners, local businesses and the wider riparian community with direct access to and interest in streams and riparian areas. Questionnaires will be distributed (m 13-15) with the objective to:

- gather information about their perception of stream-riparian zones for their activities and
- raise awareness and gather opinions about EU, national and regional policies and legal frameworks concerning the management and conservation of riparian zones in compliance with the European Green Deal.

Emphasis will be given to query how financial incentives and direct payment under the CAP Pillar I (Common Agricultural Policy) eco-schemes for buffer strips meet the local conditions. This would allow comparing the end-users perception of a key environmental policy across Member States. This feedback will be translated into recommendations (policy briefing) of potential changes to EU policies tailored to each country. Given the timeline for the new CAP 2023-2027, these policy recommendations should provide valuable material for the 2025 first performance review of each national strategic plan.

Activity 1.4 - Citizen-science plastic monitoring. We will develop a citizen-science initiative (m 7-8; 18-21) to raise awareness and monitor macro-plastics deposited or trapped in riparian zones. Crowd-based assessment represents a valid means for cost-effective plastic monitoring, with successful examples from the Netherlands and Germany (Kiessling et al. 2019, van Emmerik et al. 2020). We will leverage the recently extended CrowdWater app and the PlasticPirates initiative to engage with local schools and university students, canoeing/rafting and fishing clubs to carry out standardised observations of macro-plastic debris along river banks. Target citizen groups will be identified in the first year during stakeholders round-tables, while monitoring will take place during low-flow periods in the second year. These activities will necessarily take place in areas with easy access to stream banks and riparian zones.

WP2. Riparian Biodiversity and Ecosystem Functions (Remote sensing)

WP2 will apply cutting-edge remote sensing-based modelling approaches to assess how riparian areas interact with the river and the wider landscape (e.g. controlling sediment and pollutant inputs from adjacent terrestrial ecosystems to the river) and to develop an integrative mapping and monitoring protocol of biodiversity and ecosystem functions. Model outputs will be the base for a multicriteria analysis to identify ecological hotspots for landscape management and biodiversity conservation.

Activity 2.1 - Delineation of riparian areas and selection of gradients. NetMap software will be used to define virtual river networks and riparian areas for each study basin (Fernández et al. 2012). This approach uses a digital elevation model (DEM) to depict all river, riparian and terrestrial surfaces and their biophysical connections across the wider landscape. Next, riparian areas and their corresponding river reaches will be classified, based on two criteria:

1. catchment size (5 to 6 classes) and
2. a gradient of riparian forest conservation using latest Corine Land Cover data (CLC18) and pan-European Copernicus Land Monitoring Service products (e.g. Riparian Zones).

In the latter case, we will count up to 7-8 river reaches from the lowest to the highest conservation status of the riparian forest for each catchment area size class. Finally, we will select a minimum of 45 river reaches in each case study representing all possible combinations of catchment size and riparian forest conservation gradient. At each river reach, riparian vegetation will be characterised using available vegetation maps, orthophotos and expert knowledge, as well as specific field surveys (i.e. rapid assessment protocols developed *ad hoc* for riparian areas) to feed into activity A2.2. Within these sites, we will conduct qualitative/semi-quantitative assessment of riparian vegetation, identifying major habitat types, river-reach and bank morphology. This will allow the production of a quick, but large number of semi-quantitative observations feeding into WP3 for more detailed quantitative analyses.

A2.2 - Modelling riparian composition and structure using remote sensing. We will collect a temporal series of satellite imagery derived from Copernicus (i.e. Sentinel 1 and 2 platforms) and Landsat 5 TM and 8 OLI and ancillary GIS data about climate, topography and soil properties for all case studies. Combining these datasets with the in-situ data collected in A2.1, we will:

1. estimate land-use and land-cover (LULC) changes across space and time,
2. classify riparian habitat types following EUNIS level-3 (Álvarez-Martínez et al. 2017) and
3. model major riparian vegetation patterns (e.g. structure, composition, diversity) using spectral indices, such as the Normalised Difference Vegetation Index, the

fraction of absorbed photosynthetically active radiation (fPAR) and the leaf area index (Laliberté et al. 2019) by means of ad-hoc spatial models (Pérez-Silos et al. 2019, Pace et al. 2021).

A2.3. Modelling riparian and river functions within the larger landscape. We will model the biophysical interactions between LULC/habitat features derived from A2.2 and physical processes underpinning key riparian functions, such as thermal loading, erosion and diffuse pollution regulation and C-sequestration. River metabolism will be modelled to estimate riparian control on river functions over the entire river network (Rodríguez-Castillo et al. 2018). Riparian and river functions will be quantified in each functional unit by the magnitude of the physical processes they are regulating (i.e. Generic Erosion Potential Index, Thermal loading, Gross Primary Production).

A2.4 - Identification of ecological hotspots and selection of priority sites for field assessment (WP3). Ecological hotspots will be identified through GIS-based multi-criteria, based upon a Systematic Conservation Planning approach (Dolezsai et al. 2015). We will rank riparian units, based on a range of socio-ecological objectives, targets, constraints and penalties (Billionnet 2013), including key riparian attributes (characterised under A2.2 and A2.3) and stakeholder perceptions collected under WP1. This approach will allow us to identify riparian areas where biodiversity and functions will be maximised by conservation or restoration actions. We will then use prioritisation algorithms (prioritiser R-package) to select and rank between 10 and 20 riparian segments for their ecological importance (hotspots). This remote-based selection will integrate stakeholders meetings and views from WP1 and guide the final selection of field sites for quantitative analyses within WP3.

WP3 - Riparian Biodiversity, Stressors and Ecosystem Functions (Field case studies)

Distribution of field sites for local-scale assessment will be optimised in order to take into account:

1. results from stakeholders input regarding locations in reference vs. impaired conditions (Activity 1.2);
2. the geometry of the river network so as to represent the dendritic structure and the wider landscape matrix;
3. results from the remote analyses (i.e. riparian hotspots Activity A2.4); and
4. the availability of local biophysical and contaminant data (Activity A2.1 & A3.2).

As such, WP3 will feed on information from both WP1 and WP2. Data analyses under this WP3 will feed connectivity and geostatistical modelling performed in WP4. Between 10 and 20 stream-riparian sites will be sampled in each riparian network. WP3 includes five main activities.

A3.1 - Development and validation of field study plan (protocols and methods). To coordinate field activities, detailed protocols will be agreed upon and shared amongst partners. Validation of methods will also be performed. Preliminary assessment of microbial analysis, pesticide quantification and bat detection in representative sites will be carried on during months 1-6. Where required, online training courses on field methods will be held amongst project partners. This will guarantee the correct performance of sampling and analytical methods that will be employed in year 2.

A3.2 - Compiling available biophysical data. The study basins were selected also based on the availability of existing information from previous projects. Macroinvertebrate and fish community data across each basin are available through national monitoring schemes. Information on long-term flow regimes, point or non-point sources for contaminant or plastic input along with data on contaminant use (e.g. pesticide application) will be of importance. We acknowledge that not all this information will be available to the same extent in each basin. We will make use of the available information in both site selection and during the interpretation of results in the light of confounding variables. Although not specifically analysed in the project, these biological elements will be used as important covariates in modelling and upscaling field-based observation to the network scale.

A3.4 - Field-based assessment of riparian biodiversity, stressors and ecosystem functions. A range of biodiversity, functional and physico-chemical elements of stream-riparian ecosystems will be measured and collected across the six basins.

Microbial and fungal communities will be sampled over a lateral gradient (at least six samples per site), from the streambed sediments, biofilm, water, to the wetted banks and vegetated riparian areas (~ 5 m from stream banks). This will allow assessing microbial communities over the longitudinal and lateral riparian dimensions. Standard protocols for soil, biofilm and water sampling and storing will be used, followed by DNA extraction, library preparation, 16s rRNA genes and ITS sequencing in the lab. Total DNA will be extracted and amplified using primers specific to the bacterial and archaeal 16S rRNA gene or the fungal ITS1 region. The amplicon libraries will be barcoded, purified and checked for quality and sequenced on an Illumina® MiSeq (PE300) platform. Raw paired-end reads will be quality checked, filtered and clustered into Sequence Variants (SVs) using standard software pipelines (MICCA). Finally, SVs will be taxonomically classified using sequence databases specific for bacteria and fungi, such as RDP and UNITE. All molecular and bioinformatic analyses will be carried on in the Fondazione Edmund Mach (FEM). Organic matter decomposition will be quantified using wooden (lolly) sticks deployed for 2 months in-stream and in riparian zones. Biofilm biomass accrual will be estimated from chlorophyll-*a* concentration and biofilm biomass in clay tiles deployed for 1 month in the stream. Following widely-used and cost-effective protocols, all decomposition and biomass accrual analyses will be carried by the Fundacion Instituto de Hidraulica Ambiental de Cantabria (FIHAC). River Metabolism will be measured using continuous oxygen and light data loggers placed in the stream and under the riparian canopy, respectively.

Bat communities will be surveyed using field eco-locators deployed for at least three nights in each site. Small portable "Audiomoth" eco-locators will be used, following protocols previously used by the University of Koblenz-Landau (UKL) in other projects (

Stahlschmidt et al. 2017). UKL already owns 50 such eco-locators and additional ones will be purchased at low costs. The focus of these assessments will be on hunting activity of bats in near-stream riparian habitats. Field campaigns will take place in spring/summer of year 2. Aquatic-terrestrial contaminant transfer will be analysed for a wide range of current-use pesticides (i.e. pesticide, pharmaceuticals, biocides) in different biotic and abiotic matrices. Ceramic tiles will be deployed in spring and collected in summer for contaminants assessment in biofilms (m 4-7). Additional collection of riparian spiders (sweep-nets) and emerging aquatic invertebrates will quantify pesticides in animal tissues covering both primary and secondary consumers and the aquatic-terrestrial contaminant transfer pathways. All pesticide measurements will be conducted in UKL with state-of-the-art analytical methods, including UHPLC-MS/MS and GC-MS/MS to account for small sample sizes (~ 5 mg dry weight) in arthropods and for a large spectrum of analytes (Brühl et al. 2021, Roodt et al. 2022).

A key, yet neglected, process associated with riparian zones is the trapping of plastic debris. We will, thus, carry on the first standardised measurement of microplastic (MP; items < 0.5 cm) and macroplastic (MA; > 2.5 cm) along riparian networks across the study basins (Cesarini and Scalici 2022). These measurements are independent from the citizen-science plastic monitoring of A1.4. Microplastics will be sampled at least in 3 replicates of water and riverbank sediment. In addition, several caddisfly cases will be collected and analysed as a comparable indicator of plastic pollution in the biota. Finally, in each riparian site, three random plots of 5 m^2 will be sampled for MA, distinguishing samples trapped in vegetation or sediments. All samples will be stored and shipped to UniRomaTre for laboratory analyses. Laboratory methods will follow state-of-the-art protocols and all necessary equipment and instruments are available to the consortium.

WP4 - Integrated framework for network analysis (Lead FEM)

WP4 will integrate satellite, field case study and GIS data along with geostatistical models to:

1. derive connectivity metrics for each stream-riparian network;
2. quantify the actual and potential contribution of each segment to overall network connectivity;
3. develop predictive modelling and upscaling multiple biodiversity and functional elements (measured in WP2 and WP3) at the basin scale using a variety of modelling approaches.

Activity A4.1 - Gap analysis and riparian network connectivity mapping (study basins). Remotely derived riparian zones (from WP2) will be classified as core and corridor areas across the whole networks using digital image object analysis and graph-theory implemented in the GuidosToolbox software and igraph R-package. The contribution of each riparian segment to overall connectivity will be calculated using the Conferor or the ConScape software providing spatially-explicit ranking of connectivity hotspots. Comparison with ecological hotspots (identified in A2.4) and protected areas (e.g. Natura2000) will provide a detailed protection gap analysis for each study basin. This detailed connectivity and gap analysis at the case study level will be compared with a parallel assessment at the EU scale (see A5.1) based on available pan-European products (Copernicus Riparian Zones).

Activity A4.2 -Integration of remote sensing and field data for network-scale predictions

In a first step, the influence of local and basin-scale drivers on multiple biodiversity and functional elements will be assessed combining remote and field data across the study basins. Generalised mixed-models or structural equation models will be applied. This will provide the quantitative framework for subsequent network scale predictions. Then, a suite of modelling approaches will be explored to upscale local observations to the entire network scale. Depending on the available data in each study basin (including stakeholders input from WP1), we will employ geo-statistical stream-network models (SSN) as well as Random Forest and Bayesian Belief Networks.

WP5 - Support System for riparian network prioritisation and conservation (Lead FIHAC)

Scientific insight produced in WPs 1-4 will be ‘translated’ into practical decision-support tools and conveyed to decision-makers and managers at local to EU scales. Leveraging the international and multidisciplinary partnership of RIPARIANET, WP5 will thus link directly to WP1 through stakeholders capacity building for evidence-based management of stream-riparian ecosystems.

The ultimate aim of WP5 within the project is to develop a framework where environmental decision-makers can learn through user-centred innovations in the form of web tools and interactive maps. WP5 is organised around two main activities at the pan-European scale and the six study basins.

Activity A5.1 Gap-analysis and riparian network connectivity mapping at EU-scale. We will use Copernicus layers on the distribution of riparian zones across Europe (i.e. Riparian Zones), to systematically quantify the structural continuity of riparian areas and their role as ecological connectors across protected areas (Natura 2000; National; Regional). We seek to assess:

1. which and how many protected (or otherwise natural areas) are currently connected with other protected areas through riparian corridors;
2. the proportion of riparian areas that are currently protected in EU;
3. the ecological conditions and biodiversity threats in riparian zones identified as potential connectors.

To that end, we will use and extend remote information on riparian zones integrating the report from the European Topic Centre on Biological Diversity to provide the first large-scale connectivity gap-analysis of stream-riparian networks. Secondly, we will quantify the discrepancies between this large-scale assessment and the fine-scale (study basins) analyses of A4.1, to appraise the extent to which available pan-European products can help local decision-making in identifying riparian areas to be prioritised for protection in selected study cases and beyond.

Activity A5.2 - Development of data layers processing pipelines and GIS tools. Outputs from WP1-4 will be synthesised in multiple thematic GIS layers and maps. These will be integrated into a user-friendly interactive web GIS platform allowing stakeholders to visualise riparian attributes (i.e. river reaches, riparian buffers, floodplains and drainage wings), land cover patterns, biodiversity, functions and contaminant flows at selected locations to guide riparian management, restoration and conservation actions. By spatially-explicit mapping of the integrity of riparian forests and floodplains and their main ecological processes, this platform can be particularly useful to stakeholders for reporting on European Directives (i.e. HD, EC 1992; WFD, EC 2000; Floods EC 2007).

WP6 - Dissemination

The RIPARIANET project will establish communication channels with three main groups to facilitate the interactive use of results:

1. The scientific community, reached primarily through peer-reviewed publications and international scientific conferences. A RIPARIANET website and Twitter account will make available all publications and outcomes to the scientific community. We expect to produce several open-access manuscripts for discipline-specific as well as broad-interest Journals. We also foresee the involvement and productive exchange of students and postdocs, as well as the brief exchange of permanent staff to foster communication across partner institutes. A special session or possibly a technical workshop is also planned at annuals meetings from the International Society of River Sciences (ISRS) and European Federation of Freshwater Sciences (SEFS), to transmit the network perspective for riparian conservation developed in the project.
2. The policy-makers and environmental, river and riparian managers will be reached through participatory mapping, focus-groups, round-tables, questionnaires (WP1), open-access publishing, policy briefing (WP2-5) and our project website. WP1 will guarantee the timely and direct involvement of stakeholders at the very early stage. A showcase of project results, maps and practical tools will also take place towards the end of the project and beyond to make sure decision-makers are provided with all relevant information. Newsletters will be produced every six months in the local language (Spanish, Portuguese, Italian, German and Swedish) to continuously engage with and better inform provincial, regional and national stakeholders. Policy-relevant outreach at the international level will be achieved via interactions with NGOs such as EUROBAT, Pesticide Action Network, WWF and through sharing data and maps across platforms and repositories, such as MAES, BioFresh Freshwater Atlas, GEO BON and FW BON. Final National stakeholders workshops (one in each country) will be organised at the end of the project presenting the major results of RIPARIANET, web-GIS tools (WP5), data-processing pipelines and standardised approaches developed along the project.

3. The local riverside municipalities, schools and the general public, involving citizens of all ages and genders, will be reached through local media including local newspapers, tourism promoters, our website and social media (Facebook, Twitter). Questionnaires (Activity 1.3) and citizen-science initiatives (PlasticPirates) in WP1 (Activity 1.4) are also designed to inform and raise awareness about the ecological significance of riparian areas. Wider scientific dissemination activities will take place during public events, such as Researchers' Night, Science Cafe and press releases. Two reports, one on the "stream-riparian community" perception and the other one on the citizen-science activities will be produced at the end of the project assuring the outreach and the wider societal impact of RIPARIANET.

WP7 - Project management

The project consortium forms a multi-disciplinary team that covers all technical skills, expertise (freshwater - riparian ecology, remote sensing, microbiology, eco-toxicology, sensor-ecology, spatial and statistical modelling) and experience needed to achieve the project's objectives. All needed equipment, instruments and infrastructure to conduct laboratory analyses are available to the consortium.

Overall coordination. The Project Coordinator (Prof. Ralf Schulz; UKL) provides the resources for the effective coordination of all activities, the maintenance of contact with representatives of BiodivERsA and the timely submission of the project's reports. This will be done with the support of the administrative office of UKL. Prof Schulz, who has experience in coordinating numerous national and international projects, will organise the scientific and the administrative work of all actions according to the guidelines of the BiodivERsA. The Steering Committee is chaired by the coordinator and will include all work package (WP) leaders. The role of the steering committee is to make decisions concerning any important scientific and technical issue and to control the WP performance. This Committee will meet at least twice a year favouring virtual meetings. When possible, field visits to study areas will also be organised. A stakeholders group will be created and chaired by the coordinator to include all project members and all core stakeholders (round-tables). The group will be permanently open to interested people/ organisations and will meet before all relevant decision-making processes, favouring virtual meetings.

Monitoring and control. Regular review meetings will be run by WP leaders with individual researchers involved in each Activity to ensure that all deliverables are fully reported and properly formatted for the technical reports at milestone control points. Shared tasks board (in excel) will be used to check bimonthly for advances and delays in the workflow. Technical Progress Reports will be prepared and issued by the WP leaders, with the contribution of Activity leaders, in correspondence with periodical meetings. At months 12 and 24, progress reports will serve as measurement criteria to evaluate the work done in each WP. Meetings will provide the main forum for strategic planning, for presentation of scientific results and of dissemination and for discussion of management issues. All reports will be kept by the project coordinator in a master file sent to all partners and uploaded on the project website with exclusive access to project partners and stakeholders, when appropriate. The RIPARIANET project proposes to address the lack of gender equality by promoting the participation of women. Moreover, flexible working hours and other family-friendly policies will be considered.

Risk management. RIPARIANET will implement a risk management plan to monitor and control risks in a continuous manner. Due to their interdependencies, the following activities will be monitored with special attention: A1.2, A2.3, A2.4, A3.3. Activities linked to WP2 (e.g. A2.3 and A2.4) present low risks, as these are mostly related to the modelling of available data and layers with open-source software. Expertise in remote sensing within the consortium will further minimise any risks. Intermediate risks are associated with activities in WP1 (e.g. A1.2), considering a possible poor participation of stakeholders in the round tables. However, consortium members will capitalise on successful interactions with key stakeholders from previous or ongoing projects (see V.F.). In addition, the multidisciplinary nature of the project allows involvement of a diverse range of stakeholder groups, which will minimise the effect of potential resistance from some groups. Field and laboratory activities related to WP3 (A3.3) present the estimated higher risks of the project, since they can be associated with possible delays (e.g. identification of study sites, feedback from WP1 and WP2) or impediments to field and laboratory work, which would delay subsequent modelling in WP4 and WP5. These could be due to equipment failure or challenging field conditions, including (unlikely) Covid-related restrictions. To minimise the effect of such events, field activities in spring/ summer will span several months reflecting the natural latitudinal/climatic gradient of the study basins. This will guarantee a longer time-window of opportunity and allow laboratory activities to be better distributed and coordinated across partners.

Transnational added value

The outcome of RIPARIANET will have transnational value in terms of both scientific insight and policy relevance. The span of bio-geographic, land-use and socio-cultural character included in the study basins largely reflect the range of conditions present in European landscapes. From a scientific perspective, this will allow identifying how key biodiversity and functional elements (including IUCN listed species, pesticide loads, plastic pollution) differ amongst stream-riparian networks draining basins with contrasting land uses, climate and vegetation. From an applied perspective, the project will contribute to developing standardised approaches to monitor the integrity of riparian systems at the basin scale. Contrary to strictly aquatic and terrestrial ecosystems, a fragmentary approach to the management of riparian zones has been adopted across borders, resulting in discontinuous policies for biodiversity assessments. RIPARIANET will foster synergies amongst countries in tackling common environmental issues and promote the use of Blue and Green Infrastructures to meet the 2030 Biodiversity Targets and EU Directives. Productive interactions amongst project partners will also result from the exchange of post-doc, doctoral students and joint conference sessions, as well as brief research exchange of WP leaders. The project is built around five inter-dependent

WPs and will capitalise on the multi-disciplinary partnership established and the diverse expertise from large scale remote observations to molecular profiling and pesticide quantification.

Data management and sharing of the products of research

Responsible partner: A specialised data manager, Alessandro Cestaro, team-member of FEM, will be in charge of the Data and Digital Outputs Management process (DDOMP). Dr. Cestaro has expertise in data management and will coordinate the work of the data sharing, storage and accessibility for each WPs. A data management plan will be developed and provided to all partners before the start of the project. Dedicated budget is allocated to allow the data manager and coordinator to attend the data management workshops.

Type of data: RIPARIANET will produce multiple quantitative and qualitative data. In the remote sensing WP, we will use layers (e.g. Sentinel 2 images) and calculate several spectral indices (image texture analysis). These data will be stored as shapefiles, raster or NetCDF files. Field activities will generate raw data of species abundances, physico-chemical measurements and genetic sequence data from molecular analyses. Interactions with stakeholders will produce outputs, such as maps, GIS layers and brochures. We will also produce data from questionnaires with stakeholders and from citizen-science activities. General Data Protection Regulations will be followed.

Duration of data value: Raw biodiversity data regarding, for example, invertebrates and bats, as well as microbiological sequences along with contaminant measurement data, have long term value beyond the timeline of the project. Data derived from analyses of remote sensing layers are considered of medium-term value, as the quality and resolution of satellite images is constantly improving.

Data Management: All data and metadata, describing the data and digital outputs, their acquisition (including models, related simulations and workflows) and other details for their use and reuse, will be stored in repositories. Codes and software pipelines will be stored in GitHub, while GIS maps, biodiversity and other environmental data will be made available via Dryad, GBIF, Freshwater Metadata Journal, the Portuguese RepositóriUM and GEO BON. Molecular profiling of microbial communities will produce sequences that will be stored in the European Nucleotide Archive. Specific budget for these activities is allocated. Data fairness will be assured through the implementation and the use of international standards. The overall experimental design will be represented using the ISA-tab paradigm and data, along with associated metadata, will be described and managed by the use of appropriate standards. For example, sampling of metagenomic data will be described using the ENVO approach (https://sites.google.com/site/environmentontology/), while for raw-data (i.e. sequence amplicons), sequence ontology will be used (www.sequenceontology.org).

Approaches to stakeholders engagement and expected societal and policy impact

Due to its multidisciplinary nature, RIPARIANET will include diverse stakeholder groups in the discussion about natural riparian ecosystems, their contribution to biodiversity and human well-being. Examples include regional territorial authorities (e.g. Autonomous Province of Trento [IT]; Città Metropolitana of Rome [IT]; The County Administrative Board [SE]; Ministry of the Environment Rhineland-Palatinate [DE]), agencies for environmental protection (APPA, ISPRA [IT]; ARH Norte/APA [PT]; Swedish EPA [SE]), protected areas officials (Servizio Aree Protette [IT]; ICNF [PT]; UNESCO Biosphere Reserve Palatinate Forest [DE]; Picos de Europa National Park [ES]), the water management (e.g. Tiber River Contracts [IT], ADP [PT]; Confederación Hidrográfica del Cantábrico [ES]), fishing organisations (e.g. Ass. Pescatori val di Sole [IT]; Sävar River Fishing Society [SE]) and agricultural and forestry cooperatives (e.g. Coop. 5 Comuni [IT]; CAP [PT]). The consortium members have already engaged with many of these policy stakeholders in the past. FEM have on-going collaborations with local environment agencies and NGOs (APPA; Free Rivers Italia), water managers (Dolomiti Energia) and tourism organisations (APT val di Sole; Parco Fluviale Alto Nove) through the S-Hydro, REPORT, REDIAFOR prjects. UMinho has collaborations with intermunicipal community of Cavado - CIM CAVADO, water managers (AGERE, APA), farmers confederation Eduardo Oliveira e Sousa (CAP) and with Instituto da Conservação da Natureza e Florestas (ICNF) through the involvement in the Climalert, Streameco and River2Ocean projects. UKL has coordinated several trans-national INTERREG projects, for example, on ecosystem services, which included the Sportfischerverband Pfalz, environmental policy agencies (e.g. SGD Süd, region Grand-Est), as well as the UNESCO Biosphere Reserve Palatinate Forest-North Vosges. FIHAC has ongoing projects from European (Interreg-Atlantic: ALICE) and national projects (Spanish National Research Plan: WATERLANDs) involving a community of stakeholders in the case study including water administrations (CHC), regional government (CCAA Cantabria), local municipalities, private companies and civil organisations (Official School of Forestry Engineers). The relevance of project results will be made clear to representatives of the civil society at the national and international level by involving environmental NGOs (e.g. EUROBATS, Pesticide Action Network; Eurosite; EcoStat; Water JPI) and via posts and data sharing in EU environment forums and repositories. WP1 will coordinate all activities involving stakeholders from the early stage of the project (Activity A1.2). Questionnaires (A1.3) and citizen-science initiatives (A1.4) will further expand the reach of RIPARIANET to the wider riparian community.

Results of RIPARIANET will be of great use to environmental policy since they will:

1. ‘translate’ scientific insights into practical guidelines, maps, tools and leaflets in multiple languages, thereby providing all means to decision-makers to apply evidence-based management of stream-riparian ecosystems.

2. deliver knowledge regarding local stakeholders' awareness of CAP eco-incentives and willingness to contribute to the sustainable management of riparian areas, thus contributing to the EU Eco-Management and Audit Schemes.
3. optimise blue-green infrastructure investment aiding the maximisation of biodiversity conservation, with relevance for targets 2 and 3 of the 2030 Biodiversity Strategy.
4. provide novel information on pesticide use and transfer across aquatic-terrestrial boundaries, with implications for the Zero Pollution Action Plan.
5. disseminate all policy-relevant results in specific forums and platforms dedicated to the science-policy interface. This will include openly sharing information in the EKLIPSE community via the KNOCK forum (Knowledge Network and Open Community) and the OPPLA open platform, the EU repository for nature-based solutions.

Study areas

RIPARIANET will combine remote earth observations and field experiments to develop science-based guidance and reproducible approaches for biodiversity conservation of riparian networks enhancing ecological connectivity across the aquatic and terrestrial realms. The study areas (SA) will cover six river basins in five countries, reflecting different European biogeographic zones: Boreal, Continental, Alpine, Mediterranean and Atlantic. Between 10 and 20 study reaches will be surveyed in each basin (Fig. 3).

The Swedish SA is the Sävar River Basin, dominated by boreal forest, including several mires and lakes, originating in Lossmen Lake and ending in the Bothnian Sea. The lower part of the river is a Nature 2000 reserve, with unusual broadleaf swamp forests of high biological values.The German SAs is the Queich River Basin. It originates from a forested area (UNESCO Biosphere Reserve Palatinate Forest) and flows into the river Rhine. The middle and downstream reaches run through vineyards, urban areas and intensively-used agricultural land, yet some stretches are surrounded by very extensively-used pasture.

The Italian SAs are the Noce Stream Basin in the Alpine Region and the River Tiber Basin in the Mediterranean Region. The Noce Stream originates in the Stelvio National Park and flows into the Adige River. The headwaters are mainly fed by glacial and snow melt and upper course of the Noce Stream is a designated Natura 2000 Reserve Network, an "ecological corridor" of protected areas, including three Special Areas of Conservation (SACs). However, two hydropower plants strongly alter the hydrological regime of the lower reaches. The Tiber River Basin covers a vast heterogeneous landscape across four Italian regions with climate ranging from continental to Mediterranean. Numerous protected areas from the Natura 2000 network are present throughout the network, such as the Farfa River and its confluence with the Tiber (Tevere-Farfa Reserve). However, growing urbanisation (including the City of Rome) exerts substantial pressure on both aquatic and riparian integrity.

The Spanish SA comprises the Pas River Basin in the Cantabrian Cordillera. Heathland communities and extensive pasture dominate the Pas territory. Natural vegetation in the higher parts has been predated centuries ago and was converted to pasture. In the lowlands, urban sprawling and eucalyptus plantations are the main drivers of land-use and land-cover change. Despite this, the riparian vegetation of the Pas River still has a reasonable status of conservation in many parts of the catchment and the Pas main axis is part of the Natura 2000.

The Portuguese SA is the Cávado River Basin, crossing the Cantabrian Atlantic Subprovince biogeographic region. The higher part of the Cávado presents two areas with relevant conservation interest: the Peneda-Gerês National Park (Natura 2000) and the Barroso District at Montalegre (a Globally Important Agricultural Heritage System [UNESCO]). A vast amount of biological and environmental data (e.g. water quality, micropollutants, streamflow series, invertebrates, fish, birds, macrophytes), as well as established links with local stakeholders are already available for each basin, derived from both statutory monitoring and specific research projects from the Consortium. These projects include Climalert, Streameco and River2Ocean [PT], S-Hydro and REPORT [IT], Alice and LIFE-DIVAQUA [ES], SystemLink [DE].

Budget

The overall budget of the project is about 1.1 million Euros.

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Funding program

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Conflicts of interest

The authors have declared that no competing interests exist.

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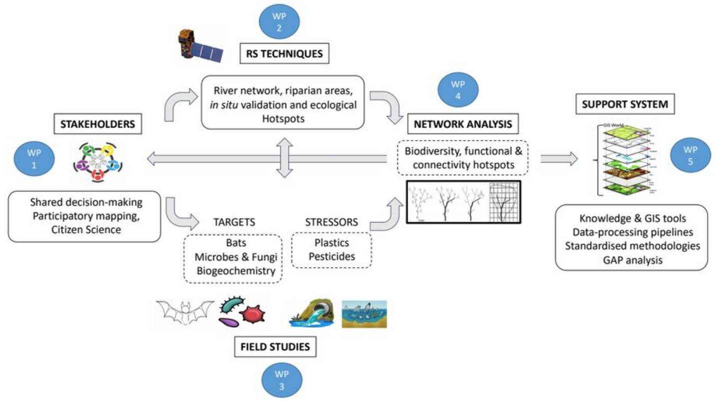

Figure 1.

Operational flow diagram of the key approaches, targets, stressors and output associated with the RIPARIANET project.

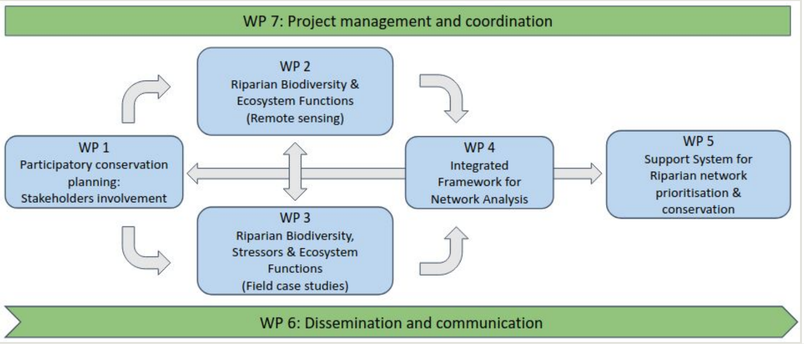

Figure 2.

Work Packages interactions in RIPARIANET.

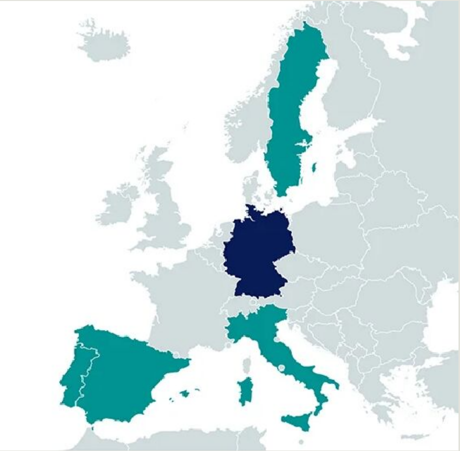

Figure 3.

Map of the countries involved in RIPARIANET.