Science of the Total Environment 652 (2019) 1396–1408

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

# Exploring variability in environmental impact risk from human activities across aquatic ecosystems

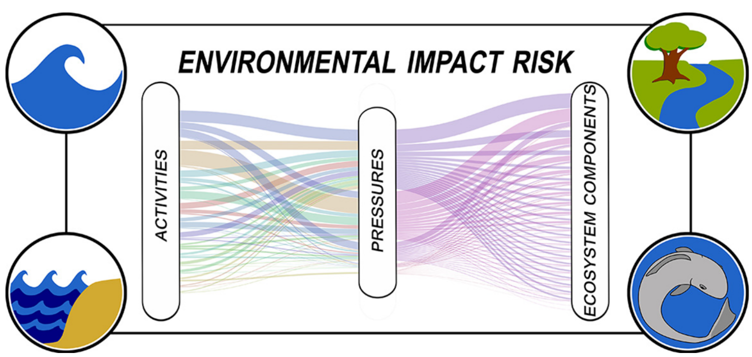
Florian Borgwardt [a,*], Leonie Robinson [b], Daniel Trauner [a], Heliana Teixeira [c], Antonio J.A. Nogueira [c], Ana I. Lillebø [c], Gerjan Piet [d], Mathias Kuemmerlen [e], Tim O'Higgins [f], Hugh McDonald [g], Juan Arevalo-Torres [h], Ana Luisa Barbosa [h], Alejandro Iglesias-Campos [h], Thomas Hein [a], Fiona Culhane [b]

[a] *University of Natural Resources and Life Sciences, Vienna, Institute of Hydrobiology and Aquatic Ecosystem Management, Gregor Mendel Strasse 33, 1180 Vienna, Austria*
[b] *University of Liverpool, Department of Earth, Ocean and Ecological Sciences, Nicholson Building, Liverpool L69 3GP, UK*
[c] *Department of Biology & CESAM, University of Aveiro, Campus Universitário de Santiago, 3810-193 Aveiro, Portugal*
[d] *Wageningen Marine Research, Haringkade 1, 1976 CP IJmuiden, the Netherlands*
[e] *Eawag, Department Systems Analysis, Integrated Assessment and Modelling, Ueberlandstrasse 133, CH-8600 Duebendorf, Switzerland*
[f] *Environmental Research Institute, University College Cork, Cork, Ireland*
[g] *Ecologic Institute, Pfalzburger Strasse 43/44, 10717 Berlin, Germany*
[h] *Intergovernmental Oceanographic Commission of UNESCO, Marine Policy and Regional Coordination Section, 7 Place de Fontenoy, F-75352 Paris, France*

## HIGHLIGHTS

- Application of a risk assessment across different aquatic ecosystem types.
- Activities related to energy production introduce high risk to aquatic ecosystems.
- Physical and chemical pressures introduce the greatest impact risk to aquatic ecosystems.
- Ecosystem components acting as ecotones are at high impact risk.
- Importance to consider spatial separation of activity location and pressure effect

## GRAPHICAL ABSTRACT




## ARTICLE INFO

*Article history:*
Received 2 August 2018
Received in revised form 24 October 2018
Accepted 25 October 2018
Available online 26 October 2018

Editor: Damia Barcelo

*Keywords:*
Aquatic ecosystems
Freshwater
Marine
Coastal
Biodiversity
Drivers

## ABSTRACT

Aquatic ecosystems are under severe pressure. Human activities introduce an array of pressures that impact ecosystems and their components. In this study we focus on the aquatic domains of fresh, coastal and marine waters, including rivers, lakes and riparian habitats to transitional, coastal as well as shelf and oceanic habitats. In an environmental risk assessment approach, we identified impact chains that link 45 human activities through 31 pressures to 82 ecosystem components. In this linkage framework >22,000 activity-pressure-ecosystem component interactions were found across seven European case studies. We identified the environmental impact risk posed by each impact chain by first categorically weighting the interactions according to five criteria: spatial extent, dispersal potential, frequency of interaction, persistence of pressure and severity of the interaction, where extent, dispersal, frequency and persistence account for the exposure to risk (spatial and temporal), and the severity accounts for the consequence of the risk. After assigning a numerical score to each risk criterion, we came up with an overall environmental impact risk score for each impact chain. This risk score was analysed in terms of (1) the activities and pressures that introduce the greatest risk to European aquatic domains, and (2) the aquatic ecosystem components and realms that are at greatest risk from human activities. Activities related to energy

* Corresponding author.
*E-mail address:* florian.borgwardt@boku.ac.at (F. Borgwardt).

https://doi.org/10.1016/j.scitotenv.2018.10.339
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Pressures
Stressors
Biota

production were relevant across the aquatic domains. Fishing was highly relevant in marine and environmental engineering in fresh waters. Chemical and physical pressures introduced the greatest risk to the aquatic realms. Ecosystem components that can be seen as ecotones between different ecosystems had high impact risk. We show how this information can be used in informing management on trade-offs in freshwater, coastal and marine resource use and aid decision-making.

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## 1. Introduction

Aquatic environments including freshwater, transitional and marine ecosystems are subject to threats from multiple human activities as people use these systems for food and raw material provision, transport, waste treatment and recreation among others (Halpern et al., 2015). This continuous human activity places pressure on aquatic ecosystems resulting in an ongoing, dramatic loss in their biodiversity, more so than in terrestrial ecosystems (Ban et al., 2010; Dudgeon et al., 2006; Sala, 2000). An integrated ecosystem based management (EBM) approach, that allows a better understanding of the trade-offs between ecosystem integrity, biodiversity conservation, and human activities is needed to halt biodiversity loss (EC, 2011b, Piet et al. this issue).

In EBM approaches, interactions between human activities and pressures need to be identified and prioritized for a fully integrated management (Long et al., 2015). If the goal is to identify potential improvements at the scale of whole ecosystems, knowledge of the whole suite of pressures is required, thus considering the full array of human activities across all types of aquatic ecosystems. Environmental (or ecological) risk assessments (ERAs) play a crucial role in operationalizing EBM approaches (McLeod and Leslie, 2009). For the establishment of a holistic understanding of the linkages within social-ecological systems, risk assessments are highly valuable as they relate ecological elements of interest, such as species or habitats, to probable effects of pressures. In further steps, they are critical to identify indicators, quantify reference conditions, and evaluate management alternatives (Piet et al., 2015, 2017).

Environmental risk assessments have a long history (e.g., Mace and Lande, 1991) starting from assessments of single pressure effects on species or habitats, such as the effects of toxic substances. The Driver–Pressure–State–Impact–Response (DPSIR) framework (EEA, 1999), which considers single chains of causal links, has been commonly used in environmental risk assessment. Recent developments have aimed to expand this approach from a single chain to multiple chains (Dolbeth et al., 2016; Patrício et al., 2016) while also explicitly considering human activities to represent human needs and their drivers, as well as introducing human welfare into the DPSIR concept (Elliott et al., 2017). However, the representation of drivers through human activities and the complex interplay of multiple activities and their pressures is not sufficiently addressed yet. Moreover, unmanaged activities and pressures may be unseen, although they may have a relevant impact on the ecosystem (Elliott, 2011; Piet et al., 2017). Hence, an overall assessment is needed where risks to the ecosystem are linked to elements of the socio-economic system such as human activities and pressures (Tamis et al., 2016). Although, he step from single chains to an integrated network of activities, pressures and ecosystem components is conceptually a small one (Knights et al., 2013, 2015) the practical assessment of risks represents a complex challenge. In a first step, several individual chains need to be identified and can be then combined into an overall measure of how these chains may affect the ecosystem. Such approaches have been developed and applied in marine systems where the assessments have broadened their view including different taxa groups as well as several pressures and economic sectors (Halpern et al., 2015; Holsman et al., 2017; Knights et al., 2013).

Despite the connections between marine and freshwater ecosystems, such as through water flow from rivers into seas, and the migration of species from seas to rivers, the different systems are largely assessed in isolation of each other, leading to some kind of functional silos (Ensor, 1988). Furthermore, in Europe, the key environmental policies governing marine and freshwater systems are separate. The Water Framework Directive (WFD) (EC, 2000), targeting fresh, transitional and coastal waters, and the Marine Strategy Framework Directive (MSFD) (EC, 2008) both demand a good (ecological or environmental) status of the aquatic ecosystems. However, the approaches to reach the targets differ to some extent. The MSFD aims to manage pressures on the marine environments through the activities that introduce them. The WFD directly identifies and prioritises the main pressures to develop mitigation and restoration measures acting on taxa and habitats. We argue that an approach, which could harmonise management of marine and freshwater ecosystems, would fit with EBM, by recognising the social and ecological connections between these systems. Thus, in this study, we expand a risk assessment framework, such as that applied by Knights et al. (2015) to marine ecosystems, to incorporate freshwater and transitional ecosystems based on seven case studies across Europe.

The approach used here builds on a linkage framework that consists of a series of interconnected matrices that characterise the complex relationships between human activities driven by the socio-economic system and ecological components (Elliott, 2002; Holman et al., 2005; La Jeunesse et al., 2003), following the approach of Robinson et al. (2013). We address two research questions: (i) what are the human activities and pressures that introduce the most risk within aquatic realms and (ii) how do the levels of risk from human activities and pressures vary across (or differ between) aquatic realms? We explore how this approach can contribute to help achieve integrated EBM across aquatic ecosystems.

## 2. Methods

In order to address the research questions of this study, we established a typology of human activities, a typology of pressures those activities introduce to aquatic ecosystems and a typology of aquatic ecosystems impacted by those pressures, relevant for seven European case studies (CSs). We chose the CSs to cover different ecosystem types located in fresh, coastal and marine waters as well as the transitions in between. On the other hand, the CSs were chosen to cover different environmental as well as social conditions. As indicated in Fig. 1, the CSs cover a broad geographical range with diverse climatical and economic conditions.

### 2.1. Typologies of activities and pressures in fresh and marine waters

Human activities are the particular economic activities devoted to the co-production and conveyance to the social system of the goods and services provided by natural capital in combination with human work and capital (EC, 2006). A human activity may be the source of multiple pressures and any single pressure may be caused by more than one activity (see Fig. 1, Knights et al., 2013). We adapted the typologies of activities and pressures from previous classifications from the EU Habitats Directive, EU WFD, and EU MSFD (EC, 1992, 2000, 2008), as well as the statistical classification of economic activities (EC, 2006) and previous typologies applied to marine systems (White et al., 2013; Smith et al., 2016). More details on the typologies used can be found in the

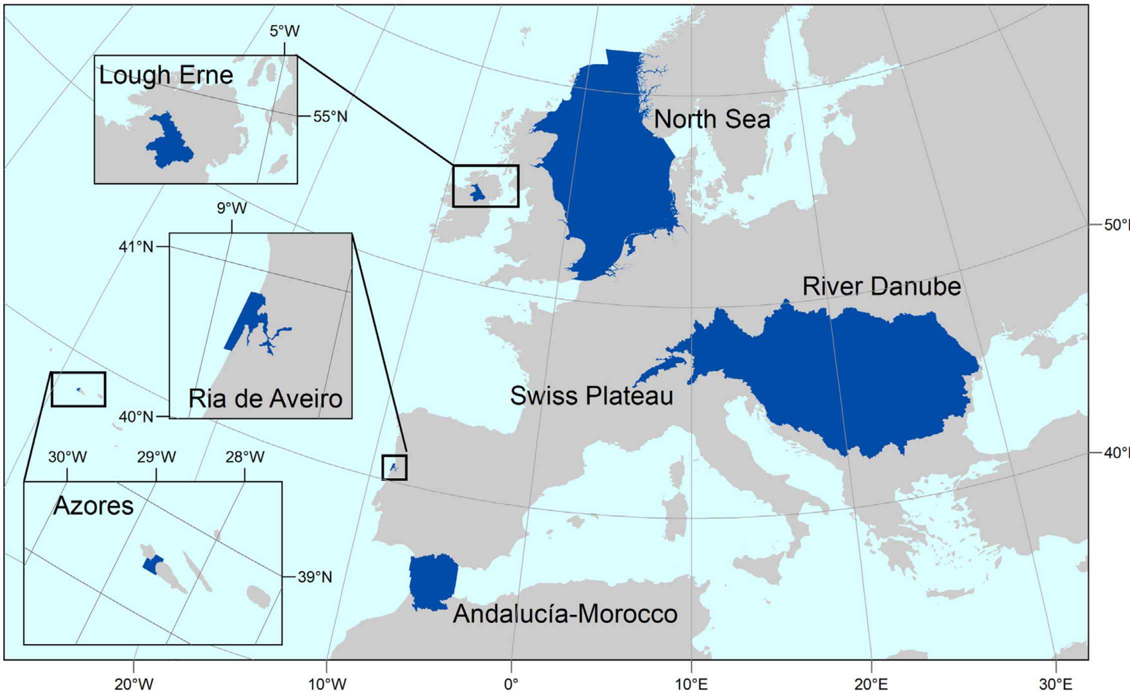


**Fig. 1.** Map showing the seven case studies and their spatial extent.

Supplementary material (Supplemental Tables 1, 2, and 3 as well as Appendix 1).

Activities were identified by case study experts as any human activity introducing an ongoing pressure to the aquatic ecosystem in their CS area. A total of 45 activities across all CSs were identified, and these were structured under primary activity types according to the European Commission (EC, 2006). We only included activities that we considered manageable in the CS areas, therefore, we did not include pressures coming from climate change and other sources external to the CSs.

We considered pressures as 'the mechanism through which an activity has an effect on any ecosystem component' (Knights et al., 2013). In total, 31 pressures in five categories were identified within the broad: physical (e.g., Abrasion), chemical (e.g., Introduction of Synthetic Compounds), biological (e.g., Introduction of Microbial Pathogens) and energy (e.g. Thermal Changes) pressure types.

### *2.2. Typology of aquatic ecosystems based on components, realms and domains*

The typology of aquatic ecosystems implemented here, covers three hierarchical levels going from specific habitats to broad types of water categories. The starting point of the typology was the habitats defined by the EUNIS habitat classification, as provided by the European Environment Agency (Davies et al., 2004). EUNIS represents a pan-European, hierarchical system that covers all types of habitats. We included fully aquatic habitats and those directly supporting aquatic biodiversity, i.e. aquatic, semi-aquatic and riparian habitats.

The ecosystem components were then aggregated into realms that represent broad ecosystem types within the categories of fresh, coastal and marine waters (e.g. rivers, lakes, wetlands and riparian habitats for freshwater ecosystems). Finally, these realms build together the aquatic domains of fresh, coastal and marine waters (FW, CW, and MW respectively, see Supplemental Table 3). Additionally, we defined five mobile biotic groups: fish & cephalopods, birds, amphibians, reptiles, mammals, and adult insects. These biotic groups were not assigned to specific habitats within the realms as they are mobile and can move between habitats. Sessile or sedentary biota (i.e. those strongly associated to benthic substrates and the small passive planktonic taxa) were considered to be represented in their habitats.

The presence/absence of habitats within the CSs was verified with the help of maps through a GIS analysis, the data base on the EUNIS homepage (eunis.eea.europa.eu/habitats.jsp), as well as expert knowledge (see Teixeira et al., this issue). Habitats were identified to the most detailed EUNIS level possible, up to EUNIS level 3. Depending on the available information, the identified EUNIS level varied among

**Table 1**
Characterisation of the seven case studies (CSs) by area, number of identified primary activities, pressures, their focus domain, the number of covered aquatic domains, realms and ecosystem components (ECs) as well as the number of impact chains within the CS. Domains are: MW = Marine Waters, CW = Coastal Waters (including Inlets and transitional), FW = Freshwater.

| Case study | CS area ($km^2$) | Number primary activities | Number pressures | Focus domain | Number domains | Number realms | Number ECs | Number impact chains |
|---|---|---|---|---|---|---|---|---|
| North Sea | 547,224 | 36 | 31 | MW | 3 | 9 | 14 | 7771 |
| Andalucía-Morocco | 47,937 | 31 | 31 | FW/CW/MW | 4 | 17 | 40 | 2759 |
| Danube | 801,463 | 31 | 30 | FW | 2 | 13 | 31 | 5323 |
| Lough Ern | 48 | 27 | 28 | FW | 2 | 10 | 13 | 2394 |
| Ria de Aveiro | 512 | 20 | 24 | CW | 4 | 16 | 35 | 647 |
| Swiss Plateau | 11,168 | 23 | 30 | FW | 2 | 8 | 16 | 2770 |
| Azores | 237 | 21 | 27 | CW/MW | 3 | 6 | 11 | 1524 |

case studies between EUNIS2 and EUNIS3. From here on, we refer to the five biotic groups and the EUNIS habitats as ecosystem components (ECs).

The CSs included here covered the North Sea, Andalucía-Morocco Biosphere reserve, the Danube Basin, Lough Erne, the Ria de Aveiro Natura 2000 (see details in Lillebø et al., 2019; this issue) sites from catchment to coast, the Swiss Plateau (see details in Kuemmerlen et al., 2019) and the Azores Pico-Faial channel (Fig. 1). These CSs varied in their size from small (e.g. Azores, around 240 $km^2$) to very large (e.g. Danube Basin, around 800,000 $km^2$) and in their focus of the aquatic domain and realms, e.g. North Sea CS focused on the ecosystem components in the marine domain and Swiss Plateau CS focused on freshwater realms (Table 1).

### 2.3. Identifying and weighting impact chains

We identified the specific pathways of impact from activity to pressure and from pressure to ecosystem component. The identified activity-pressure-EC chains provided a comprehensive list of impact chains for each CS (also see Knights et al., 2013). Each individual impact chain was then weighted based on five criteria: (i) extent, (ii) dispersal, (iii) frequency, (iv) persistence, and (v) severity (Table 22). The extent, or overlap of each activity with each EC, was evaluated by considering the spatial distribution of human activities and ECs in the CS area, and how much spatial overlap in these there is (e.g. Forestry activities with Riparian habitats). The area of overlap is relative to the area occupied by the EC in question within the CS area. The actual location of pressures and their impact pathways was considered when assigning spatial extent (e.g. accounting for the fact that not all pressures are introduced across the whole operating area of an activity; for example, abrasion is only introduced where fishing vessels are trawling or anchoring, while noise is introduced while also steaming). Dispersal evaluated the potential of an activity-pressure impact to spread and increase its spatial overlap with an EC beyond that of the area of extent where the pressure and EC overlap initially. Frequency of interactions described the most likely number of times the activity interacts with an average square kilometer of an EC in an average year, where they overlap in space. Moreover, it is important to consider the length of time it would actually take for the pressure associated with a particular activity to disappear after cessation of any further activities causing the particular pressure. This temporal component was described by persistence. For example, while habitat loss is persistent, organic enrichment is not. Finally, severity described the generic severity of an interaction in terms of its effects on the EC. The type of response of the EC to the pressure type was categorised as either ‘Acute’, ‘Chronic’ or ‘Low’. More details on the five criteria and the classifications are given in Table 2. The weighting of each impact chain was carried out by CS experts and coordinated by a core expert team that ensured consistency in the approach across CSs (guidance information see Appendix 2). Categorical weights were converted to numerical scores based on the justifications in Table 2.

## 3. Calculating individual environmental impact risk scores

We understand impact risk as a measure of the likelihood of a detrimental ecological impact that occurs following an activity–pressure introduction (Sharp et al., 2014). We follow a standard approach to environmental risk assessment that considers impact risk as being

**Table 2**
Impact risk criteria with their categories (after Robinson et al., 2013) and assigned numerical scores (adapted from Knights et al., 2015) used to weight each impact chain.

| Description | | Standardized score |
|---|---|---|
| Spatial extent | Spatial overlap of each activity-pressure combination with an ecosystem component | |
| Exogenous | The activity occurs outside of the area occupied by the ecosystem component, but one or more of its pressures would reach the ecosystem component through dispersal | 0.01 |
| Site | The activity overlaps with the ecosystem component by **up to 5%** of the area occupied by the EC in the case study area | 0.03 |
| Local | The activity overlaps with the ecosystem component by **between 5 and 50%** of the area occupied by the EC in the case study area | 0.37 |
| Widespread patchy | The activity overlaps with the ecosystem component by **between 50 and 100%** of the area occupied by the EC in the case study area, but the distribution within that area is patchy | 0.67 |
| Widespread even | The activity overlaps with the ecosystem component by **between 50 and 100%** of the area occupied by the EC in the case study area, and is evenly distributed across that area | 1 |
| Dispersal | Effect of the dispersal of the pressure on realised area of spatial overlap | |
| None | The pressure does not disperse in the environment | 0.01 |
| Moderate | The pressure disperses, but stays within the local environment | 0.1 |
| High | The pressure disperses widely and can disperse beyond the local environment | 1 |
| Frequency | Temporal overlap of each activity-pressure combination with an ecosystem component | |
| Rare | Occurs approximately **1–2 times** in a 5 year period but may (or may not) last for several months when it occurs | 0.01 |
| Occasional | Can occur in most years over a 5 year period, but **not more that several times a year** | 0.11 |
| Frequent | (1) occurs in **most years** over a 5 year period, and **more than several times** in each year, or (2) can occur in **1–2 years** in a 5 year period but also in **most months** of those years | 0.33 |
| Very frequent | Occurs in **most months** of **every** year, but is not constant where it occurs | 0.72 |
| Continuous | **Constant** in **most or all** months of a 5 year period | 1 |
| Persistence | Length of time that is needed that a pressure disappears after activity stops | |
| Low | 0 to <2 yr | 0.01 |
| Moderate | 2 to <10 yr | 0.06 |
| High | 10 to <100 yr | 0.55 |
| Persistent | The pressure never leaves the system or > 100 yr | 1 |
| Severity | Likely sensitivity of an ecosystem component to a pressure where there is an interaction | |
| Low | An interaction that, irrespective of the frequency and magnitude of the event(s), never causes a noticeable effect for the ecosystem component of interest in the area of interaction | 0.01 |
| Chronic | An impact that will eventually have severe consequences at the spatial scale of the interaction, if it occurs often enough and/or at high enough levels | 0.1 |
| Acute | A severe impact over a short duration | 1 |

composed of exposure to activity-pressures, and the consequence of that exposure (e.g. Arkema et al., 2014; Knights et al., 2015; Samhouri and Levin, 2012).

We consider the total exposure to be the combined effect of spatial (extent and dispersal) and temporal (frequency and persistence) exposure, thus based on four criteria, which are not independent of each other. Exposure was taken as the average of spatial and temporal exposure (Eq. 1). Severity contributes to the consequence of the activity-pressure-ecosystem component combination and this was the only criterion we used for consequence.

Finally, we calculated impact risk (IR) for each impact chain as a function of the exposure of the EC to the activity-pressure and the consequence for the EC of the activity-pressure, where we consider exposure and consequence to be independent of each other in contributing to risk (Eq. 2). IR represents the distance from the origin (i.e. Euclidean distance), assuming that an increase in exposure and an increase in severity leads to an increase in IR. We used Euclidean distance (as opposed to finding the product) because this gives a more precautionary score (higher risk) (Sharp et al., 2014). The final IR score was scaled to be between 0 and 1.

$$Exposure\ (E) = \frac{E_{Extent} + E_{Dispersal} + E_{Frequency} + E_{Persistence}}{n_E} \quad (1)$$

where…

$E_{Extent}$ is the Exposure criterion score given based on the extent of an activity pressure combination.

$E_{Dispersal}$ is the Exposure criterion score given based on the dispersal potential of an activity pressure combination.

$E_{Frequency}$ is the Exposure criterion score given based on the frequency of an activity pressure combination.

$E_{Persistence}$ is the Exposure criterion score given based on the persistence of an activity pressure combination.

$n_E$ is the number of Exposure criteria used

$$Impact\ Risk_a\ (IR) = \sqrt{(E-1)^2 + (C-1)^2} \quad (2)$$

where…

$E$ is the exposure (see Eq. 1).

$C$ is the Consequence criterion score given based on the severity of an activity pressure combination.

**Table 3**
Number of impact chains identifies for each realm, the number of contained ecosystem components (ECs) and the number of impact chains per ecosystem component.

| Domain | Realm | Number of impact chains | Number of ECs | Number of impact chains per EC |
|---|---|---|---|---|
| FW | Lakes | 1057 | 4 | 264 |
| | Riparian | 2780 | 17 | 164 |
| | Rivers | 1286 | 3 | 429 |
| | Wetlands | 2060 | 9 | 229 |
| CW | Coastal | 3414 | 10 | 341 |
| | Coastal Terr | 815 | 9 | 91 |
| | Inlets Transitional | 2865 | 17 | 169 |
| MW | Oceanic | 519 | 2 | 260 |
| | Shelf | 996 | 5 | 199 |
| Biota | Amphibian | 793 | 1 | 793 |
| | Birds | 1105 | 1 | 1105 |
| | Fish & Cephalopods | 1689 | 1 | 1689 |
| | Insects (adults) | 739 | 1 | 739 |
| | Mammals | 1281 | 1 | 1281 |
| | Reptiles | 917 | 1 | 917 |
| Total | | 22,316 | 82 | 272 |

## 4. Statistical analysis

The linkage framework and the resulting IR were investigated in more detail in three ways. The IR scores were aggregated for each EC in the CSs to show mean and summed environmental IR per human activity, per pressure and per aquatic realm. We used the mean of IR to represent the impact potential associated with the IR of an activity or a pressure (mean) as the CSs cover different real-world situations across Europe. In turn, the sum of IR is supposed to mirror the actual situation in the CSs in terms of how much IR is introduced by an activity or a pressure. Moreover, we calculated the modularity between pressures and realms based on the IR sum to identify aquatic realms that are prone to IR from certain pressures. Modularity is a measure of the structure of networks and measures the strength of divisions into modules similar to clusters by identifying sub-sets of nodes in the network with greater likelihood to interact with each other than with other nodes (Beckett, 2016). We used Newman's modularity measure that maximises weighted bipartite modularity in the 'LDTR_LPA_wb_plus' function (Beckett, 2016) in the R package 'bipartite' (Dorman et al., 2017).

Secondly, we calculated the connectance of the impact chains (Gardner and Ashby, 1970). This characteristic describes the connectivity of elements by the fraction of impact chains across all impact chains for a given element. Connectance does not rely on the IR but on the number of connections an impact chain has, as identified through the linkage framework analysis. Connectance helps to identify elements that are well connected in the whole system. Greater connectance is found for ECs with comparatively more links to human activities and pressures and therefore, may be of interest in the context of EBM. Here, we show connectance for the different aquatic realms summarising their ECs, as they are the aim of management.

Thirdly, we analysed the relationship between IR, based on weighted impact chains, and connectance, based on unweighted impact chains, to look if these two elements are linked to each other. This would indicate that activities and/or pressures that are well connected in the system also introduce more IR. We firstly assessed whether the connectance and IR represent populations having the same distribution by applying a Wilcoxon signed rank test. To describe the relationship between connectance and IR we calculated Pearson's correlation as well as a linear regression to compare the gradients in the relationships across the realms.

Analysis and plots were done in the statistical software R v3.5.1 (R Core Team, 2018) using packages ggplot (Wickham, 2016), MASS (Venables and Ripley, 2002) and bipartite (Dorman et al., 2017).

## 5. Results

In total, we evaluated 22,316 impact chains connecting 45 primary activities with 31 pressures and 82 ECs in 15 realms of 4 aquatic domains. The highest number of impact chains was observed in freshwater (FW) (n = 7183), followed by coastal water (CW) (n = 7094), mobile biota (n = 6524) and marine water (MW) (n = 1515) (Table 3). Proportionally, mobile biota showed a higher amount of impact chains than the ECs related to habitats. Within the latter, rivers and coastal ECs had the highest portion of impact chains.

The IR values related to human activities showed a diverse picture (Fig. 2). Activities related to environmental engineering (such as alteration of water levels, flood and coastal protection, species control, stocking for conservation, transversal instream structures, and waterway construction) only played a role in FW and for mobile biota. Renewable energy represented an activity type where the primary activities were either affecting FW and Biota or CW, MW and Biota. In more detail, hydropower was only relevant for FW and Biota but wind farms showed IR in CW, MW and for Biota. Water supply showed a high range for mean as well as summed IR in FW. In turn, artificial reefs, beach replenishment, fishing by benthic trawling, military, tidal sluices and barrages,

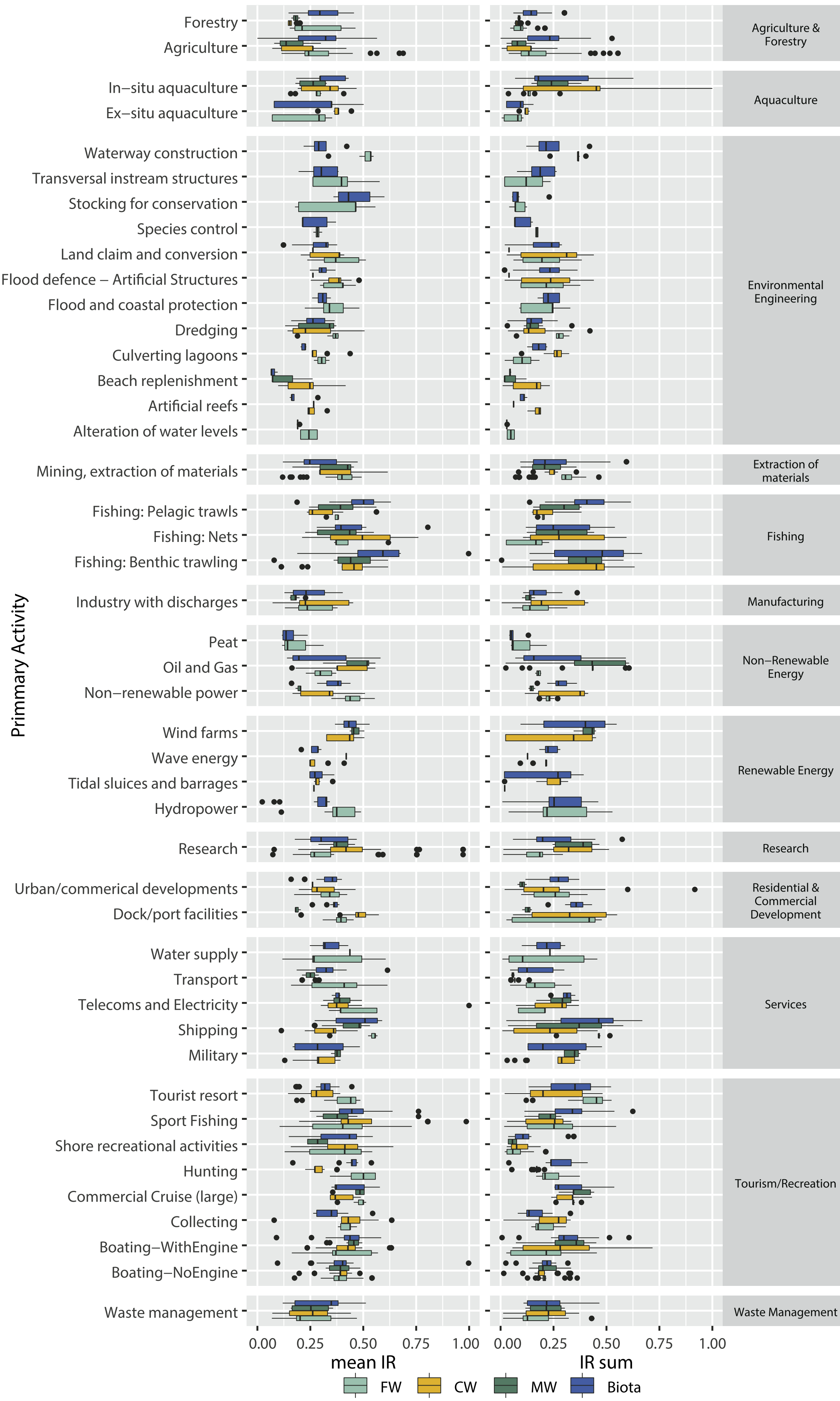


**Fig. 2.** Box and whiskers plots of mean (left panel) and summed (right panel) environmental impact risk of human activities across the aquatic domains; each value represents an ecosystem component (N = 2774).

wave energy, and wind farms were only relevant in CW, MW as well as for Biota (Fig. 2).

Within environmental engineering, land claim and conversion as well as flood defence based on artificial structures showed high IR (mean and sum). The activity type tourism showed many single primary activities with a large range of IR scores. Especially boating with engine and tourist resorts gained high IR sums. Sport fishing showed high mean IR. Activities related to fishing showed high scores for both, mean and summed IR, and were especially relevant to CW, MW and Biota. However, fishing with nets also comprised notable IR sum in FW. Beside the fishing activities, renewable (wind farms) and non-renewable (oil and gas) were highly relevant in the marine domain.

Although the majority of IR values for agriculture had rather low mean IR there were some impact chains with considerable IR scores. In some cases, the summed IR of agriculture was very high in FW and biota. Forestry showed much lower IR scores. For Biota, fishing activities as well as wind farms comprised high mean and summed values. Notably, very high summed IR occurred for residential and commercial development activities in CW but also in FW. Waste management covered similar ranges or scores for mean and summed IR as well as in the different realms. Interestingly, research activities gained very high mean IR and still high summed IR scores, especially in CW and MW.

The mean IR of pressures could be described by three groups of IR scores (Fig. 3 left): The first group is made up by the pressures extraction of flora and/or fauna, total habitat loss, extraction of non-living resources, and death or injury by collision. Secondly, some biological disturbance pressures (translocations, introduction of genetically modified species, and introduction of non-indigenous species) as well as chemical change pressures (litter, introduction of synthetic compounds/radionuclides/non-synthetic compounds) grouped

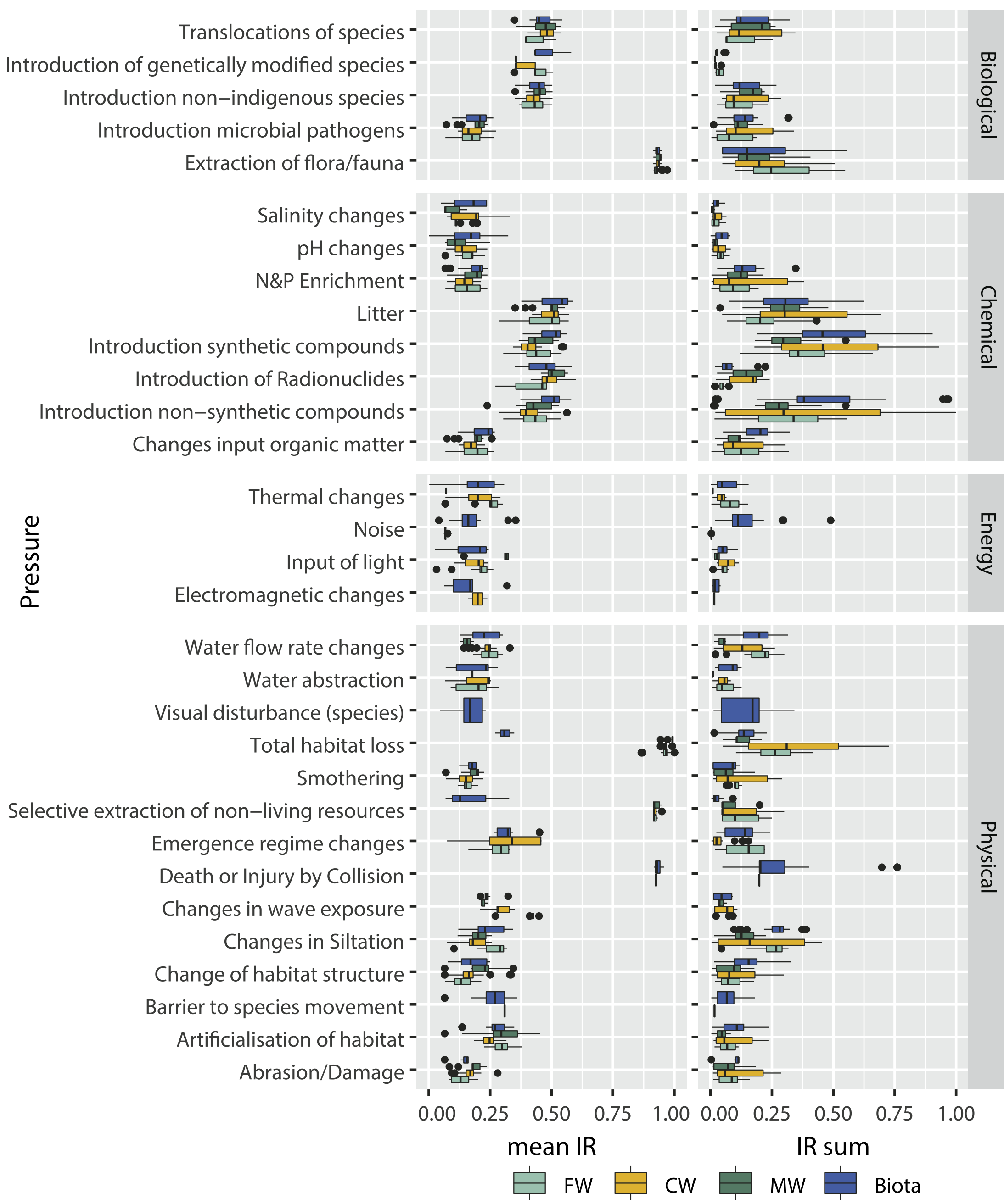


**Fig. 3.** Box and whiskers plots of mean (left panel) and summed (right panel) environmental impact risk of single pressures across the aquatic domains; each value represents an ecosystem component (N = 2737).

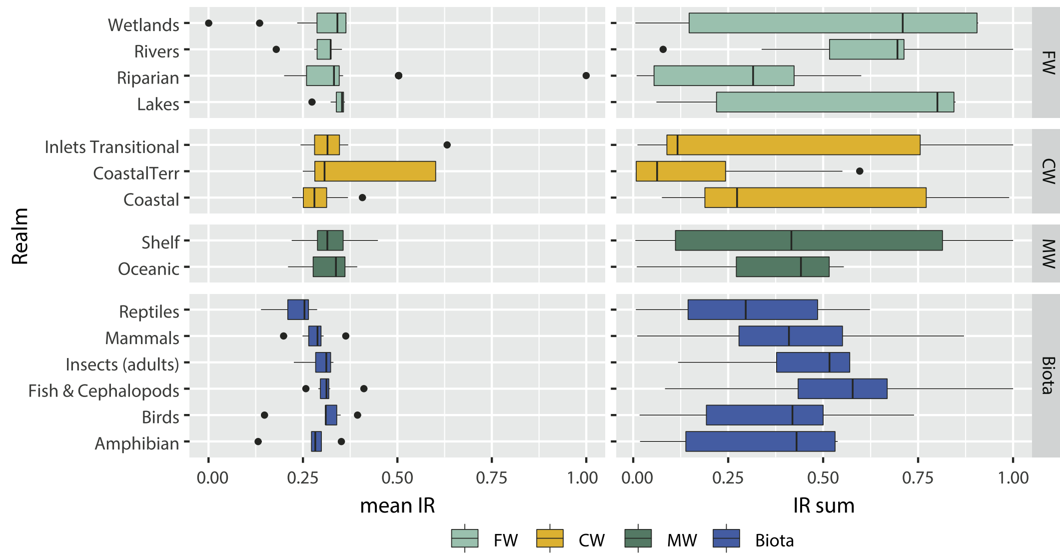


**Fig. 4.** Mean (left) and summed (right) environmental impact risk of ecosystem components across aquatic realms (N = 163).

together. Lastly, a third group of pressures with lower value ranges of mean IR was found. Generally, the pressures showed similar ranges of mean IR across the different aquatic domains.

Summed IR generally covered larger value ranges for the different pressures than mean IR (Fig. 3). Especially chemical pressures reached high summed IR with introduction of non-synthetic compounds having highest IR for CW and biota. However, the chemical pressures introduction of synthetic compounds and litter also reached high values. N&P enrichment that showed a rather small mean IR reached relatively high summed IR relevant to CW and biota. Among physical pressures, total habitat loss for CW and death or injury by collision for biota reached highest IR sum. In FW, the pressures total habitat loss, water flow rate changes and changes in siltation showed high IR sums. Highest IR sums for biota were associated with pressures death or injury by collision, noise and visual disturbance. Pressures related to energy were among those with rather low IR with exception of noise relevant to biota.

Mean IR of ECs in the aquatic realms was similar across the domains. An EC of the Riparian realm reached the highest mean IR followed by Inlets Transitional and Coastal Terrestrial. Some ECs in the Riparian realm as well as in Inlets Transitional and Coastal Terrestrial realms comprised high IR whereas some ECs of Wetlands comprised low values (Fig. 4). In contrast, the summed IR showed much larger ranges especially for Wetlands, Riparian and Lakes as well as for Inlets Transitional and Coastal realms. Coastal Terrestrial ECs that comprised high mean IR values showed low values for summed IR. Among the biotic groups, Fish & Cephalopods had the highest sum of IR followed by mammals.

The connectance of ECs highlighted interfaces (i.e. ecotones) of different realms and domains as highly connected ecosystem parts (Fig. 5). Firstly, the realms located between FW and MW, namely the ECs of the Coastal and Inlets Transitional realms, also representing ecotones to terrestrial ecosystems, showed the overall highest connectance. Within the FW domain, Riparian and Wetlands that also represent the transition to terrestrial habitats showed higher connectance than Rivers and Lakes. Among biota, Fish & Cephalopods had highest connectance. The marine ECs showed relatively low connectance.

Modularity of pressures and realms gave three modules (Fig. 6). One module summarised the mobile biota. The second module comprised Coastal, Inlets Transitional, Oceanic and Shelf, and the third module covered Coastal Terrestrial, Lakes, Riparian, Rivers and Wetlands. The first module was mostly related to biological disturbance pressures such as collision, visual disturbance. Additionally, the chemical pressures introduction of synthetic and non-synthetic compounds, the physical pressure barrier to movement, and the energy pressures noise and electromagnetic change were assigned to this module. The second, mostly marine module was characterised by physical (abrasion, smothering, changes in wave exposure and siltation) and chemical pressures (litter, N&P enrichment, pH and salinity changes, introduction of radionuclides) supplemented with biological disturbance pressures (non-native species, translocation of species and introduction of pathogens). The third, mostly FW, module was dominated by physical pressures, namely artificialisation of habitat, change of habitat structure, emergence regime changes, extraction of non-living resources, total habitat loss, water abstraction and water flow rate changes.

There was a positive relationship between connectance and IR of primary activities and pressures in all aquatic domains (Fig. 7). For primary activities, the correlation between connectance and IR was higher than for the pressures (Table 4). Mobile biota showed the highest values. The Wilcoxon signed rank test was significant in all cases and confirmed that the two values represented non-identical variables in all aquatic

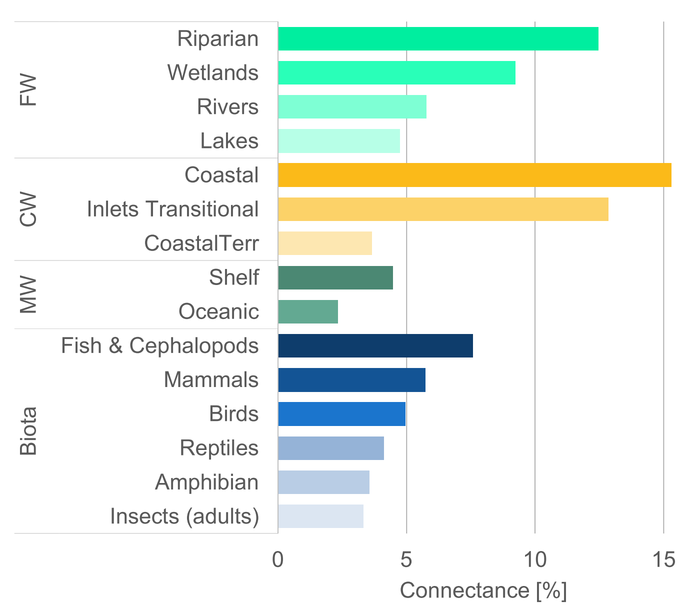


**Fig. 5.** Connectance of the aquatic realms within the whole linkage framework; FW = fresh waters, CW = coastal waters, MW = marine waters.

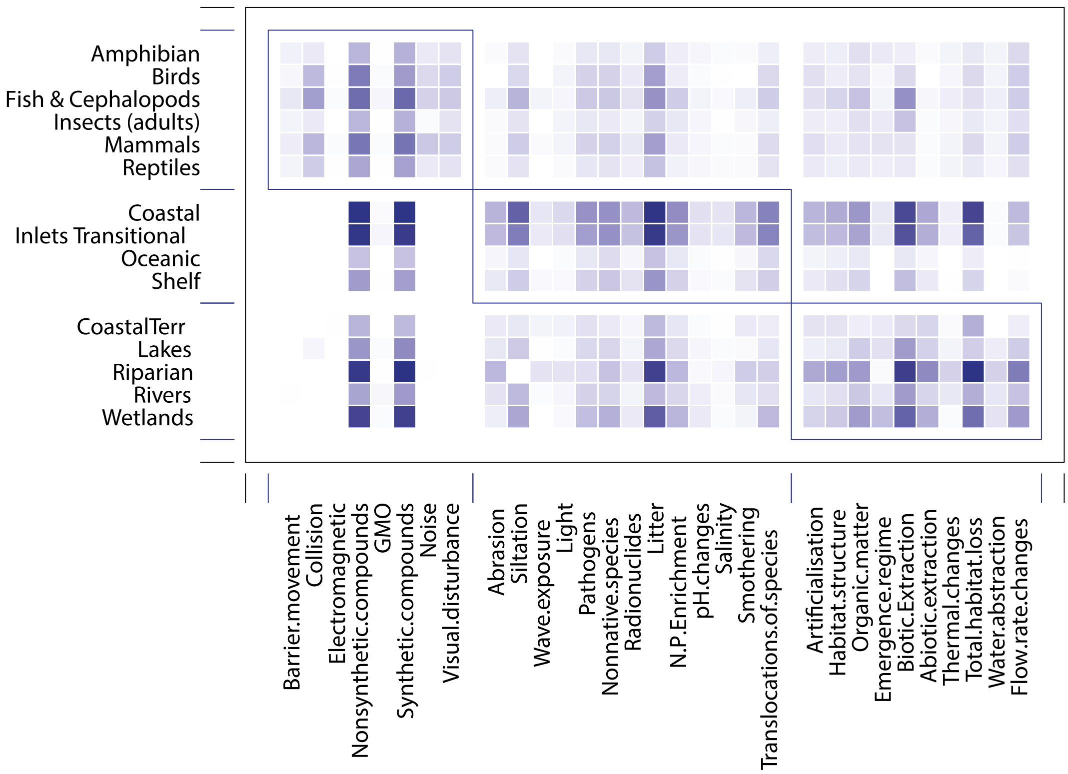


**Fig. 6.** Modularity of pressures and realms indicating the main modules identified.

domains. The regression coefficient was positive in all cases, with similar coefficients in CW and MW. According to adjusted $r^2$, connectance explained a noteworthy amount of variance of IR (up to $r^2 = 0.82$ for mobile biota). The portion of explained variance was smaller for pressures than for activities (Table 4).

## 6. Discussion

Linkage frameworks have already proven their applicability in the context of environmental risk assessment (e.g. Knights et al., 2015), as well as to support ecosystem based management (e.g. Piet et al., 2015,

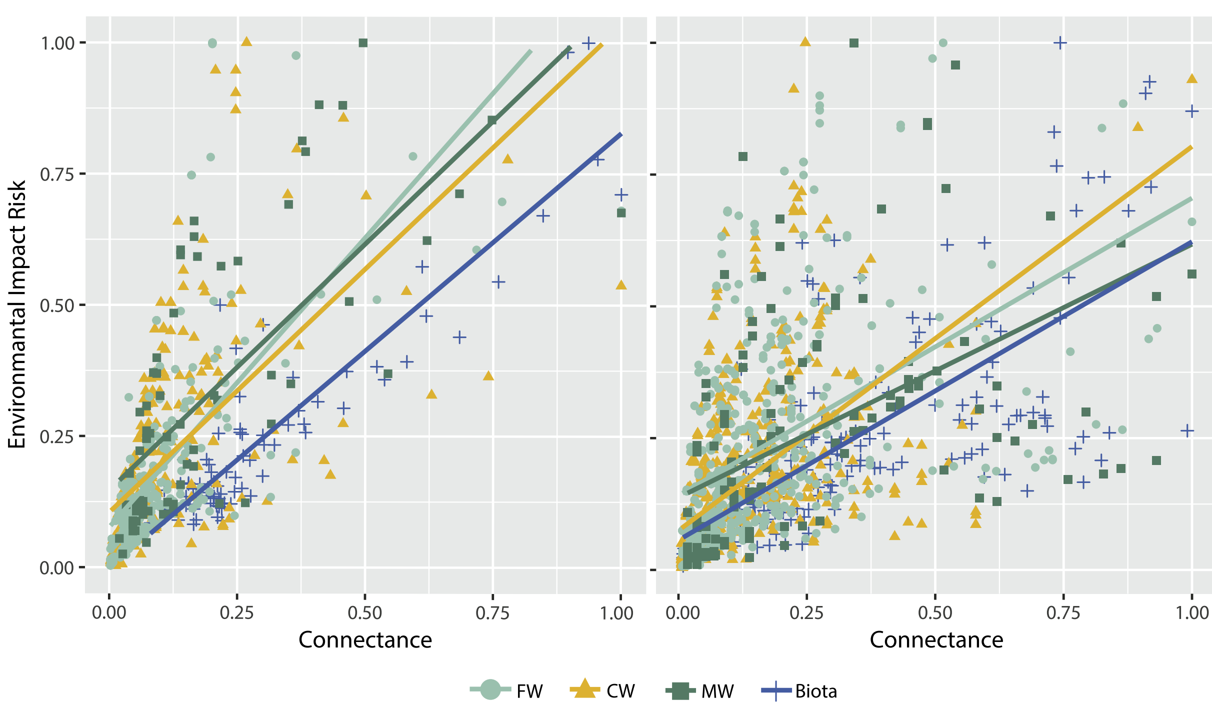


**Fig. 7.** Scatterplot of connectance vs. environmental impact risk of human activities (left) and pressures (right) in the aquatic realms with linear trend lines; further statistics can be found in Table 4 Characteristics of correlation, regression as well as Wilcoxon signed rank test to analyse the relationship between connectance and environmental impact risk sum of activities and pressures as shown in Fig. 7; each symbol represents an activity/pressure in a realm; FW = fresh water, CW = coastal water, MW = marine water.

**Table 4**
Characteristics of correlation, regression as well as Wilcoxon signed rank test to analyse the relationship between connectance and environmental impact risk sum of activities and pressures as shown in Fig. 7; FW = fresh water, CW = coastal water, MW = marine water; Reg Coeff = regression coefficient.

| Domain | Primary activities | | | | | Pressures | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | p Wilcoxon test | Pearon's r | Reg Coeff | Adj $r^2$ | p Regression | p Wilcoxon test | Pearon's r | Reg Coeff | Adj $r^2$ | p Regression |
| FW | <0.001 | 0.66 | 1.11 | 0.43 | <0.001 | <0.001 | 0.45 | 0.56 | 0.20 | <0.001 |
| CW | <0.001 | 0.61 | 0.93 | 0.37 | <0.001 | <0.001 | 0.57 | 0.73 | 0.32 | <0.001 |
| MW | <0.001 | 0.71 | 0.94 | 0.50 | <0.001 | <0.001 | 0.53 | 0.48 | 0.27 | <0.001 |
| Biota | <0.001 | 0.91 | 0.83 | 0.82 | <0.001 | <0.001 | 0.71 | 0.57 | 0.51 | <0.001 |

2017). Here, we applied this approach for the first time to all types of aquatic ecosystems that are relevant for aquatic biodiversity. Our approach is based on an extensive description of links between human activities and aquatic ecosystem components including freshwater, marine and transitional components. Such holistic approaches are relevant to several environmental policies aiming at the improvement of aquatic ecosystems such as the EU Biodiversity Strategy, the EU Marine Strategy Framework Directive, and the EU Water Framework Directive, as they support the decision-making needs of environmental managers based on a flexible, problem-solving solution linking human activities and ecosystem components (ECs) (Piet et al., 2017). To manage the impacts of pressures on aquatic ecosystems, it is ultimately necessary to understand the pathways through which human activities affect ECs. If management should mitigate impacts of pressures that are mediated by activities, the clear identification of links between activities, pressures and the affected ECs is essential.

We aimed to address two research questions through the application of this approach. Firstly, what are the human activities and pressures that introduce the most risk within aquatic realms? Secondly, what are the realms that have highest levels of risk from human activities and pressures, and how does this vary across domains? We found energy activities to be highly relevant to the IR across aquatic realms: renewable (hydropower, wind farms) but also non-renewable (oil & gas, and others). Running water systems have been used to generate hydropower over the last centuries, with ever increasing demands, e.g. in South-Eastern Europe. This has resulted in heavy modification of freshwater ecosystems across Europe (Schinegger et al., 2012, 2016), for example the upper part of the Danube River as well as most tributaries in the upstream basin are heavily used for hydropower generation (ICPDR, 2013). In marine ecosystems, the oil and gas sector is economically one of the most important in regions such as the North Sea. Common to both, FW and MW domains, and independent of renewable vs. non-renewable, the energy-related activity is often removed from the location of energy needs. Strategical planning of energy production is therefore needed to sustain the ecosystems where it is produced (Seliger et al., 2016).

However, while some activities were common across domains, the greatest risk to each individual domain was found to come from activities that were specific to those domains. In line with Piet et al. (2015), our results underlined the role of fishing activities in impacting all ecosystem components of marine waters (including coastal), highlighting that fishing is the most widespread and exploitive human activity in the marine environment with detrimental effects on the ecosystem (Knights et al., 2015).

High impact risk in FW systems was linked to environmental engineering activities. The importance of these activities clearly underlines how human society may actively transform ecosystems in the long term. Freshwater ecosystems and especially rivers and associated wetlands and riparian areas have a long history of humans using and adapting these systems to their needs (Hein et al., 2018; Hohensinner et al., 2011). This is also expressed by the IR introduced by land claim and conversion activities, as well as by extraction of non-living resources. In many parts of Europe, rivers and wetlands are now integral parts of the man-made landscape, reflecting the need of the society for their associated goods and services (e.g. Lillebø et al., 2019; this issue).

The results clearly highlight the role of chemical and physical pressures for aquatic ECs. Interestingly, the summed IR of chemical pressures covered a large range. This may be related to policies that manage the emission of different substances into water. Water quality control has a long tradition but the implementation of waste water treatment differs hugely across Europe; e.g. it fulfils high standards in the upper Danube Basin, whereas the sewage management in the lower Danube Basin is still under development. The risk found to be associated with synthetic and non-synthetic compounds was often related to agriculture activities (Matthaei et al., 2010). Moreover, pressures with immediate and severe consequences to the ECs, and especially mobile biota, were associated with high IR. For example, total habitat loss that was related to activities of flood defence, land claim and conversion, as well as the pressures extraction of inorganic material, death by collision or selective extraction of flora/fauna that was related to angling, fishing and boating.

Modularity analysis highlighted two pressures, litter and N&P enrichment, mainly associated to marine and coastal ECs, but which are also relevant for freshwater ECs. This fact emphasises the need for a more integrated management, as large volumes of litter and nutrients are transported by the flow of water from rivers to seas.

Our results indicated that each aquatic domain is subject to a substantial amount of IR due to several activities and pressures. Thus, ECs in every aquatic ecosystem are under high environmental IR. This IR varies according to the method of aggregation of the risk score (see Piet et al., 2017). Overall, the different types of pressures (physical, chemical, biological) introduce similar mean IR in the different realms. However, summed IR indicates larger differences. The IR introduced by pressures is strongly related to the presence of the underlying activities.

Furthermore, the results indicated that transitional zones of aquatic ecosystems such as wetlands and riparian areas of freshwater but also coastal waters showed the highest mean IR. Moreover, connectance supported this finding. These transitional zones are intensively used areas where agriculture, residential development and tourism introduce environmental IR. For example, several large cities are located directly next to large rivers with detrimental consequences for the floodplains. Similarly, European coastlines represent highly populated areas (EC, 2011a). Our analyses also underlined that high IR is introduced to riverine ecosystems indicated by the highest IR sum within the freshwater domain. Rivers are strongly dependent on the surrounding landscape (Allan, 2004; Poff, 1997). The relationship of IR and connectance shows that well connected activities and pressures introduce the highest risk to the ecosystems irrespective of the realm. Here, our linkage framework approach can help to identify these highly connected activities and pressures as a starting point for quantitative assessments.

Although, connectance does not provide an assessment or quantification of the risk score or impact intensity, it is valuable for management purposes, as well as the development of scenarios. Human activities related to tourism and recreation emerged as the most connected followed by environmental engineering in fresh and coastal waters, as well as for mobile biota. In marine waters, human activities related to services and fishing were the most connected followed by the tourism activities.

Human activities represent a classification that is clearly definable with respect to management measures (Knights et al., 2013). The approach can easily be adapted and limited to selected aspects within the whole framework, e.g. looking at specific ECs and the pressures occurring therein or, vice versa, looking at a specific activity and the pressures that are related to it.

Accordingly, management scenarios can be developed and tested based on this linkage framework that covers different aquatic ecosystem types. In a first step, simple reduction of highly connected activities can be investigated. Piet et al. (2015) demonstrated a simple approach to how management measures can be identified based on a linkage framework approach. Such an evaluation can be based on both a qualitative and quantitative perspective of the relative performance of the measures. Although IR (and the criteria it is based upon) mirrors the socio-economic system, the way IR is assessed and calculated prevents a simple linear relationship with the real effects of activities and pressures.

In real-world scenarios, the socio-economic needs and limitations should be taken into account. Moreover, the regulatory, economic and social background of management measures has an effect on the characteristics of the linkage framework and thus may change completely the nature or existence of impact chains. Finally the number of threats and constraints on resources can restrict potential management measures to a limited number of options and often not necessarily to those providing the greatest benefit to the ecological integrity of the ecosystems.

We considered >22,000 impact chains forming a complex network of linkages. The complexity of the full network was summarised to produce aggregated results for human activities, pressures, and realms within the aquatic domains. Piet et al. (2017) highlighted that an IR score based on weightings, as applied in our approach, improves the performance of ERA. In agreement with the findings of the aforementioned study, our aggregation into mean and sum values did not prioritise the same activities and pressures. Piet et al. (2017) explain that this is simply reflecting the fact that summed IR is more sensitive to the number of impact chains which is reflected in the differences between mean and summed impact risk observed here. Although some of the difference here may be due to artificial differences in the numbers of chains related to a particular activity (e.g. because some activities are described in more detail than others) much of the difference reflects the fact that some activities simply introduce more pressures and interact through those pressures with more ecosystem components.

The number of impact chains and therefore connectance of activities and/or pressures is an important descriptor of the relationship of the social to the ecological system. Highly connected elements have intrinsically a higher ability to affect an ecosystem, so summed impact risk is an important outcome to consider in addition to connectance. Although we built an ERA as comprehensive as possible for aquatic ecosystems across Europe, including five different aspects to weight the impact chains, there are at least two further aspects that may be added to our approach in a further step: (i) intensity of pressures, and (ii) resilience of the ECs. Although we accounted for the frequency of a given activity-pressure impact chain, we did not account for the intensity of pressures or how the ecosystem component reacts to this intensity. Although it may be desirable to include pressure intensity, this is not a simple issue. The response of ecosystem components to pressure effects is not always linear and is often context dependent (Stendera et al., 2012). This is also somehow supported by our results by the sometimes broad ranges of IR values, which are coming from the diverse realities and contexts covered by our CSs. In some cases it might be even not clear if the effect is positive or negative. Moreover, this also does not consider the interaction of multiple pressures (Nõges et al., 2016). Assessments of cumulative impacts still rely on assumptions of linear and additive responses of natural systems to impacts. However, aquatic ecosystems may exhibit threshold responses to intense and cumulative impact, creating nonlinear relationships of cumulative impact to the ecosystem components. According to recent syntheses, the nonlinear responses of ecosystems to impacts are hardly predictable (Hunsicker et al., 2016). Sufficient information is lacking to allow adequate incorporation of nonlinear relationships into impact risk assessment at this time (Halpern et al., 2015). However, the risk assessment can be accommodated once the information is available. Accordingly, using the outcomes of our risk assessment should explicitly consider these methodological choices to adequately inform managers and stakeholders, and to allow them to appreciate these choices in their decisions (Piet et al., 2017).

In a further step, it would be of interest to consider the duration of the impact after the activity or the pressure has been eliminated, i.e. recovery of the EC or resilience (Knights et al., 2015). For example, abrasion from trawling (fishing) occurs during fishing operations. If trawling was restricted in a particular area, the pressure would immediately stop. In the weighting of persistence, this would be defined as 'low', but recovery of the habitat may then take more than two years. This would be picked up under resilience, which we did not assess here. In contrast, heavy metal contamination in soft sediments can persist for many years due to low turn-over and poor biodegradation (Jaglal, 2017), and thus the persistence of the pressure would be classified as 'high', whereas recovery potential of the habitat may actually be quite high if the contamination eventually leaves the system.

The nomenclatures and understanding of relevant drivers, human activities and pressures is driven by different research disciplines as well as policies. The relevance of human activities for environmental management is well integrated in marine assessments (Knights et al., 2013; Piet et al., 2015; Tamis et al., 2016) but is relatively new to the management of freshwater ecosystems (Elliott et al., 2017). Our approach represents a first, highly valuable step to overcome these silos (Ensor, 1988) related to isolated policies and different research disciplines. From a management perspective, it may be useful to have harmonious typologies, while it may not be so important for the implementation of the EU MSFD and EU WFD itself. However, recent developments have shown that the DPSIR cycle lacks a concrete, accessible unit at the beginning (Elliott et al., 2017). Therefore, the approach presented here, can provide benefits to supplement the pressure-oriented approach of the WFD and to establish an activity-oriented management perspective. As highlighted by the recent report on the status of European waters (EEA, 2018), merely mitigating pressures may not suffice to sustainably improve ecosystems in highly cultivated landscapes impaired by a multitude of anthropogenic activities. In turn, the EU Biodiversity Strategy as well as the EU Habitat Directive do not distinguish between aquatic ecosystem types, thus urgently demanding a common understanding of how social demands are linked to the impacts on ECs.

The linkage framework across the ecosystem categories describes a complex interplay of social and ecological systems. However, the IR scores as presented here imply two major issues that must be considered for the interpretation and further use of the results: (i) how IR is calculated (i.e. how the weighting criteria are combined to gather the final IR score), and (ii) aggregation of IR scores independent of the underlying typology of activities and pressures. The calculation and aggregation of IR scores represents a critical step in the ERA (Piet et al., 2017). The euclidean distance resulted in higher relative scores for the same impact chains compared to multiplying exposure and consequence, which would represent a less precautionary approach, with a greater number of lower scores for the impact chains with 'moderate' risk. Furthermore, the aggregation of IR scores, especially summing IR scores, is strongly dependent on the number of underlying impact chains. Accordingly, a subset of relevant linkages will change the aggregated IR scores. However, both, a comprehensive as well as a subset, do not necessarily contradict each other. The comprehensive linkage framework is important to identify the most important activities and pressures.

Hence, subsetting represents a further step. In a decision making process and in discussions with stakeholders such a subset of the most relevant impact chains can help to receive a balanced distribution of impact chains per activity and/or pressure type (facilitating aggregation) and helps to keep the focus of the discussion on certain aspects (see Piet et al. in this issue).

The extension of the linkage framework approach across different aquatic ecosystem types supports truly integrated management of aquatic ecosystems, one that succeeds in halting biodiversity loss in all aquatic ecosystems. By applying an approach developed for marine systems to ECs relevant to all aquatic ecosystems, we aim to support a common understanding on how to counteract fragmented views due to fragmented policies and/or fragmented research disciplines. Only with a consistent terminology, a common understanding and a better focus of research and management it will be possible in the future to halt the biodiversity loss of aquatic ecosystems.

## Acknowledgment

This work was funded by the projects AQUACROSS (Knowledge, Assessment, and Management for AQUAtic Biodiversity and Ecosystem Services aCROSS EU policies, Contract 642317; http://aquacross.eu). Thanks are also due, for the financial support to CESAM (UID/AMB/50017 - POCI-01-0145-FEDER-007638), to FCT/MEC through national funds (PIDDAC), and the co-funding by the FEDER, within the PT2020 Partnership Agreement and Compete 2020. Finally, we thank two reviewers for their valuable comments on an earlier version of the manuscript.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2018.10.339.

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