

Assessment of drivers and pressures in the case studies

Synthesis report

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List of abbreviations

AF	Assessment Framework
CS	Case Study
D-P-S	Driver-Pressure-State
EBM	Ecosystem based management
EEA	European Environment Agency
ESS	Ecosystem service
EUNIS	European nature information system web site, *EUNIS* database
FCM	Fuzzy Cognitive Mapping
GIS	Geographical Information System
HP	Hydropower
HPPs	Hydropower Plants
IBRM	Intercontinental Biosphere Reserve of the Mediterranean
MSFD	Marine Strategy Framework Directive
SEE	Southeast Europe
TEN-T	Trans-European Transport Network
WFD	Water Framework Directive
WP	Work Package
WWF	World Wildlife Fund

About AQUACROSS

Knowledge, Assessment, and Management for AQUAtic Biodiversity and Ecosystem Services aCROSS EU policies (AQUACROSS) aims to support EU efforts to protect aquatic biodiversity and ensure the provision of aquatic ecosystem services. Funded by Europe's Horizon 2020 research programme, AQUACROSS seeks to advance knowledge and application of ecosystem-based management (EBM) for aquatic ecosystems to support the timely achievement of the EU 2020 Biodiversity Strategy targets.

Aquatic ecosystems are rich in biodiversity and home to a diverse array of species and habitats, providing numerous economic and societal benefits to Europe. Many of these valuable ecosystems are at risk of being irreversibly damaged by human activities and pressures, including pollution, contamination, invasive species, overfishing and climate change. These pressures threaten the sustainability of these ecosystems, their provision of ecosystem services and ultimately human well-being.

AQUACROSS responds to pressing societal and economic needs, tackling policy challenges from an integrated perspective and adding value to the use of available knowledge. Through advancing science and knowledge; connecting science, policy and business; and supporting the achievement of EU and international biodiversity targets, AQUACROSS aims to improve ecosystem-based management of aquatic ecosystems across Europe.

The project consortium is made up of sixteen partners from across Europe and led by Ecologic Institute in Berlin, Germany.

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1 Background and Objectives

The AQUACROSS project seeks to improve the management of aquatic ecosystems, thereby supporting the achievement of the EU 2020 Biodiversity Strategy targets and the Strategic Plan for Biodiversity 2011-2020. The AQUACROSS assessment framework (AF) considers two perspectives to analyse the interrelated sets of linkages between the ecological and the socio-economic parts of the social-ecological system: the supply-side and the demand-side perspective. The latter conceptualises how human activities result in demands of ecosystem services and abiotic outputs that may trigger detrimental changes to aquatic ecosystems through the pressures they exert over their components. This assessment level is essential to understand how human activities and pressures affect ecosystems and biodiversity, and thus the capacity of aquatic ecosystems to continue providing the services society depends on.

Deliverable D4.1 previously has established the conceptual basis for the analysis of drivers and pressures on aquatic ecosystems by providing guidance for indicators and methods that could be applied to assess drivers and pressures within the AQUCROSS case studies (CSs). Accordingly, this report presents methods and evidence on how we can assess the demand-side (Driver-Pressure-State (D-P-S) part) of complex social-ecological systems. In more detail, Deliverable 4.2 (D4.2) addresses the application of D-P-S indicators and methods in the CSs to analyse the connections within the demand-side.

This deliverable addresses the following objectives:

- Assessment of individual and combined direct, indirect and emerging drivers of change, which, through introducing pressures, can cause change in the status and trends of aquatic ecosystems, at different temporal and spatial scales within the CSs.
- Testing the AF by analysing the interactions and relationships between drivers and pressures.
- Analysis of indicators and approaches to assess the key pressures in each CS.

The demand-side analyses are conducted at two levels:

- The **linkage framework analyses** covering all aquatic realms in one approach, evaluating drivers through their manifestation as human activities that introduce pressures on ecosystem components.
- **Specific exploratory analyses** of the CSs that take the CS-specific conditions into account and allow for detailed quantitative (and qualitative) analyses and descriptions of the social-ecological system.

Both, the linkage framework and the specific exploratory analyses contribute to developing a common understanding of drivers and pressures across aquatic realms, thus supporting a better implementation of ecosystem-based management (EBM) approaches.

The two levels of the demand-side analyses provide the basic structure of this deliverable. Chapter 2 is dedicated to the linkage framework approach. After a short description of the approach, we present results on connectance and weighting of the so-called impact chains. Chapter 3 then addresses the specific D-P-S analyses performed within the CSs. Selected CSs are presented in boxes as examples to introduce the analyses and application of the AQUACROSS AF for different D-P-S elements. Furthermore, a number of methodical approaches used in AQUACROSS are presented. Both sections conclude their findings and formulate recommendations at the end.

Please note that this deliverable only includes selected summaries and conclusions from the case studies, while full details are provided in the respective case study reports available at the AQUACROSS website.

2 Assessing drivers and pressures through a linkage framework approach

2.1 The linkage framework

Linkage-based frameworks are used to characterise complex human and ecological relations (Elliott 2002; La Jeunesse *et al.* 2003; Holman *et al.* 2005; Knights *et al* 2013). The AQUACROSS linkage framework takes a Driver-Pressure-State (D-P-S) approach (EEA 1999), with the framework consisting of interconnected matrices, linking the social demand-side, represented by types of human activities, via pressures and their interactions with ecosystem components (addressed in WP4), to the supply-side, represented by ecosystem services (addressed in WP5). Thus, this describes aspects of the full social-ecological system. The WP4-relevant part of the linkage framework consists of three elements:

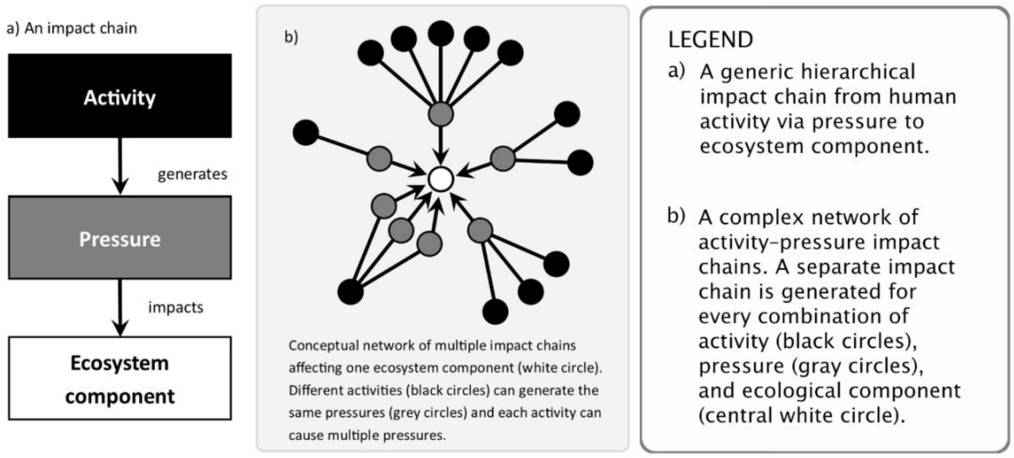
- Human activities
- Pressures
- Ecosystem Components

To apply the linkage framework approach across all aquatic realms, a common typology of human activities, pressures and ecosystem components had to be established. The definitions of human activities that represent the manifestation of drivers in the social-ecological system, is mainly based on the statistical classification of economic activities (EC 2006) supplemented with activity types relevant to aquatic ecosystems from previous typologies (White *et al.* 2013; Smith *et al.* 2016). The pressures are based on classifications from the EU Habitats Directive (HD, EC 1992), the EU Water Framework Directive (WFD, EC 2000), and the EU Marine Strategy Framework Directive (MSFD, EC 2008). For further information see D4.1, where the linkage framework and the established typology of human activities and pressures are described in detail. The 'state' level is described through ecosystem components that are based on definition of the EUNIS habitats (Davies *et al.* 2004) supplemented by mobile biota groups (amphibians, birds, fish & cephalopods, adult insects, mammals, and reptiles) that are not restricted to single habitats.

The EUNIS habitat classification is a comprehensive pan-European system to facilitate a harmonised description for habitat identification. It is hierarchically structured covering different levels of detail from EUNIS1 (broad categories) to EUNIS3 (more specific categories). The classification covers habitats from natural to artificial, as well as from terrestrial to freshwater and marine. In the linkage framework analyses, we only considered habitats that are relevant for aquatic biodiversity and ecosystem services (see also D5.1 and D5.2). In D4.2 we show results based on the level EUNIS2, as this resolution is available for all CSs.

The established typology was used to identify the human activities, the pressures they cause, and the ecosystem components they interact with, within the AQUACROSS CSs. This process was conducted based on information from literature and expert judgement. Accordingly, a network of impact chains was created, where one activity can cause many pressures; different activities can cause the same pressures; and where the pressures can affect the same or different ecosystem components. Thus, the linkage framework provides a complex and detailed picture of how human activities are related to ecosystems (Figure 1, Knights *et al.* 2013).

Figure 1 Impact chains adapted from Knights et al. 2013.



2.2 Methods: Introducing the linkage framework

Within D4.2, we present two approaches to further analyse the linkage framework. Firstly, we present connectance, simply based on the number of linkages or impact chains in the network; and secondly, we consider weighting impact chains. Connectance describes the percentage of the number of linkages per category in relation to the total number of linkages (Gardner and Ashby 1970). The higher the value, the better the connectance of the category throughout the linkage framework. It is calculated for the different linkage framework elements on the level of primary activity types, pressures types and the ecosystem components.

Secondly, results of the weighting of impact chains are shown. Piet *et al.* (2017) underlined the need to weight impact chains to increase the explanatory power of the identified linkages between human activities, pressures and ecosystem components. The weighting of the single impact chains according to different criteria enables a differentiation of more and less important ones, thus highly relevant for management prioritisation. The impact chains were weighted in five categories consisting of two spatial categories, two temporal, and one based on severity:

- Spatial extent (spatial): Describing the extent of spatial overlap of each activity and pressure with each ecosystem component.
- Dispersal (spatial): Level of dispersion outside the original activity area.
- Frequency of interactions (temporal): Most likely number of times activity interacts with an ecosystem component in an average year.
- Persistence (temporal): Time the pressure is affecting the system after cessation of the activity.
- Severity of interactions: Level of severity of the activity-pressure on an ecosystem component.

Details of the weighting categories are listed in Table 1. More information on the methodology of the linkage framework is provided in Borgwardt et al. (2019) (see Annex C).

Here, we selected impact chains for further consideration according to the most connected activities, as identified by connectance. From these selected impact chains, we show their contribution to each weighing category. All other weighted impact chains can be found in Annex A, Table 15 to Table 19. In the selection process, we took the top five activities, which showed the most links in each CS. Accordingly, we assigned a value from 1 to 5 to each activity. A weight of 5 for the most linked activity to a weight of 1 for the fifth most linked activity of the CS. In this way an equal number of impact chains was considered for each CS. Subsequently, the values of the activities were added up across CSs and the seven activities with the highest sums were selected to be presented in this chapter.

Table 1: Weighting levels of the five categories used to weight the activity-pressure impact chains

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
Site	The activity overlaps with the ecosystem component by **up to 5%** of the area occupied by the EC in the case study area
Local	The activity overlaps with the ecosystem component by **between 5- 50%** of the area occupied by the EC in the case study area
Widespread Patchy	The activity overlaps with the ecosystem component by **between 50 – 100%** of the area occupied by the EC in the case study area, but the distribution within that area is patchy.
Widespread Even	The activity overlaps with the ecosystem component by **between 50 – 100%** of the area occupied by the EC in the case study area, and is evenly distributed across that area
Dispersal	Size of spatial effect of the activity-pressure
None	the pressure does not disperse in the environment
Moderate	the pressure disperses, but stays within the local environment
High	the pressure disperses widely and can disperse beyond the local environment
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
Occasional	*can* occur in most years over a 5 year period, but **not more that several times a year**
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
Very Frequent	occurs in **most months** of **every** year, but is not constant where it occurs
Continuous	**constant** in **most or all** months of a 5 year period
Persistence	Length of time that is needed that a pressure disappears after activity stops
Low	0 to <2 yr
Moderate	2 to <10 yr
High	10 to <100 yr
Persistent	the pressure never leaves the system or >100 yr
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
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
Acute	a severe impact over a short duration

2.3 Results – Connectance

Over all CSs, we identified 12 broad primary activities with 49 more specified activities. In four pressure categories (chemical, physical, biological, and energy pressures) a total of 31 single pressures were found to affect 7 domains (i.e. Marine Waters, Coastal Waters, Freshwaters and Mobile biota), 18 realms (including 6 mobile biota groups), and 45 ecosystem components (39 EUNIS2 habitats plus 6 mobile biota groups). In total, the linkage framework consists of 68,338 impact chains from a human activity through a pressure to an ecosystem component (Table 2).

Table 2: Number of impact chains per case study

Case Study	Nr. of impact chains
CS1	43,635
CS2	7,249
CS3	6,425
CS4	3,111
CS5	669
CS7	3,444
CS8	3,802

2.3.1 Connectance of Primary activities

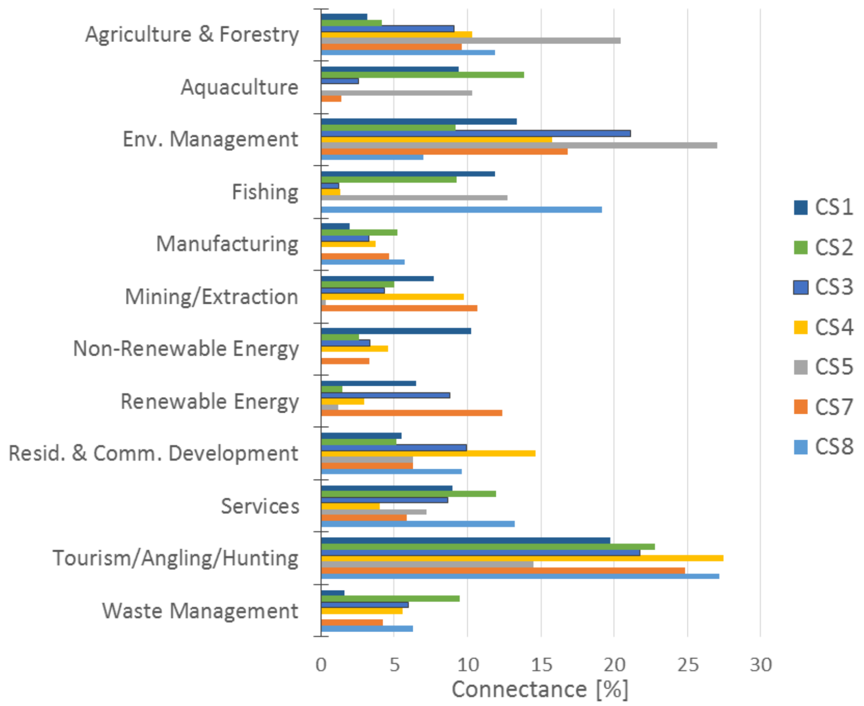
As this section focuses on all CSs, we use the higher aggregation level of broad primary activities to give an overview across the realms. Analyses of the finer sub-categories of aggregated activities in each CS are shown in Annex A, Figure 19 to Figure 24.

The connectance of primary activities from all CSs is shown in Figure 2. A detailed description of the considered activities can be found in D4.1. Overall, the activity types ‘Tourism/ Angling/Hunting’, ‘Environmental Management’, ‘Fishing’, ‘Services’, and ‘Agriculture & Forestry’ were very influential across the CSs. The activity ‘Tourism/Angling/Hunting’ had the highest connectance. On the one hand, this is due to the fact that these human activities are extensively present, but also because many single activities have been summarised in this category, resulting in a high number of linkages. Even though this activity is highly connected, when compared to others, the influence of the pressures introduced by this activity can be removed from the system relatively fast, thus having a high management potential (also see Table 4).

‘Environmental Management’ also had a high connectance. However, the freshwater and coastal CSs (CS3 Danube River, CS4 Lough Erne, CS5 Vouga River, CS7 Swiss Plateau) indicated a higher level of connectance than mainly marine CSs (CS1 North Sea, CS8 Azores) with the exception of CS2 Andalusia & Morocco, a case study that covers marine as well fresh water habitats. Even though this CS includes freshwater habitats, it seems to be less affected by ‘Environmental

Management'. This connectance pattern of 'Environmental Management' between freshwater and marine waters, is understandable if the many regulatory and flood protection measures implemented in freshwater ecosystems are taken into account.

Figure 2: Connectance of primary activities in the AQUACROSS case studies (CS).



The activity categories 'Services' and 'Residential & Commercial Development' were both present in and relevant to all CSs. In contrast to 'Environmental Management', there were no clear visible trends between realms.

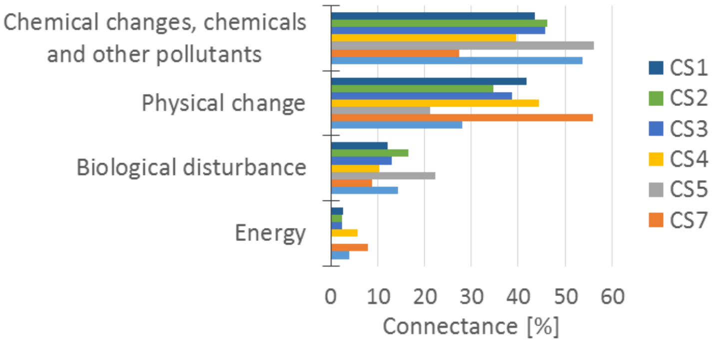
'Agriculture & Forestry' had a low connectance in CS1 North Sea and CS2 Andalusia & Morocco. The freshwater (plus coastal) case studies CS3-7 had a higher connectance for 'Agriculture & Forestry', with the highest in CS5 Vouga River. Interestingly, CS8 Azores has the second highest connectance for this activity. In turn, 'Aquaculture' and 'Fishing' showed higher levels of connectance for CSs including marine and coastal habitats (CS1, CS2, CS8) compared to freshwater (CS3-7).

Another difference that becomes visible between realms, that summarises the ecosystem components, is one concerning the energy-related activities. CS1 North Sea has a high number of pressures being induced by 'Non-Renewable Energy' compared to other CS. This is because of the presence of fossil fuel related activities in this area. In contrast, hydropower related activities are responsible for a high connectance in the primary activity 'Renewable Energy' in CS3 Danube River and CS7 Swiss Alps. CS1 North Sea had a relative high connectance in 'Renewable Energy' as well due to the presence of wind, tidal, and wave energy power plants.

2.3.2 Connectance of Pressures

An overview of pressure categories for all CSs can be seen in Figure 3. A detailed analysis on the level of single pressures in each CS can be found in Annex A, Figures 25 to Figure 31.

Figure 3: Connectance per pressure category in the AQUACROSS cases studies (CS)



Chemical pollution & other pollutants showed the overall highest connectance across CSs. Physical change pressures had the highest connectance in CS4 and CS7, followed by CS1. Biological disturbance and energy pressures showed much lower connectance. Concerning chemical pollution CS5 Vouga River and CS8 Azores had the highest values, while CS7 Swiss Plateau had the lowest.

2.3.3 Connectance of Ecosystem components

The connectance results for ecosystem components are shown for EUNIS2 habitats in Figure 4 and for mobile biota in Figure 5. Results on a more detailed level of the EUNIS classification in each CS are found in Annex A Figure 32 to Figure 38.

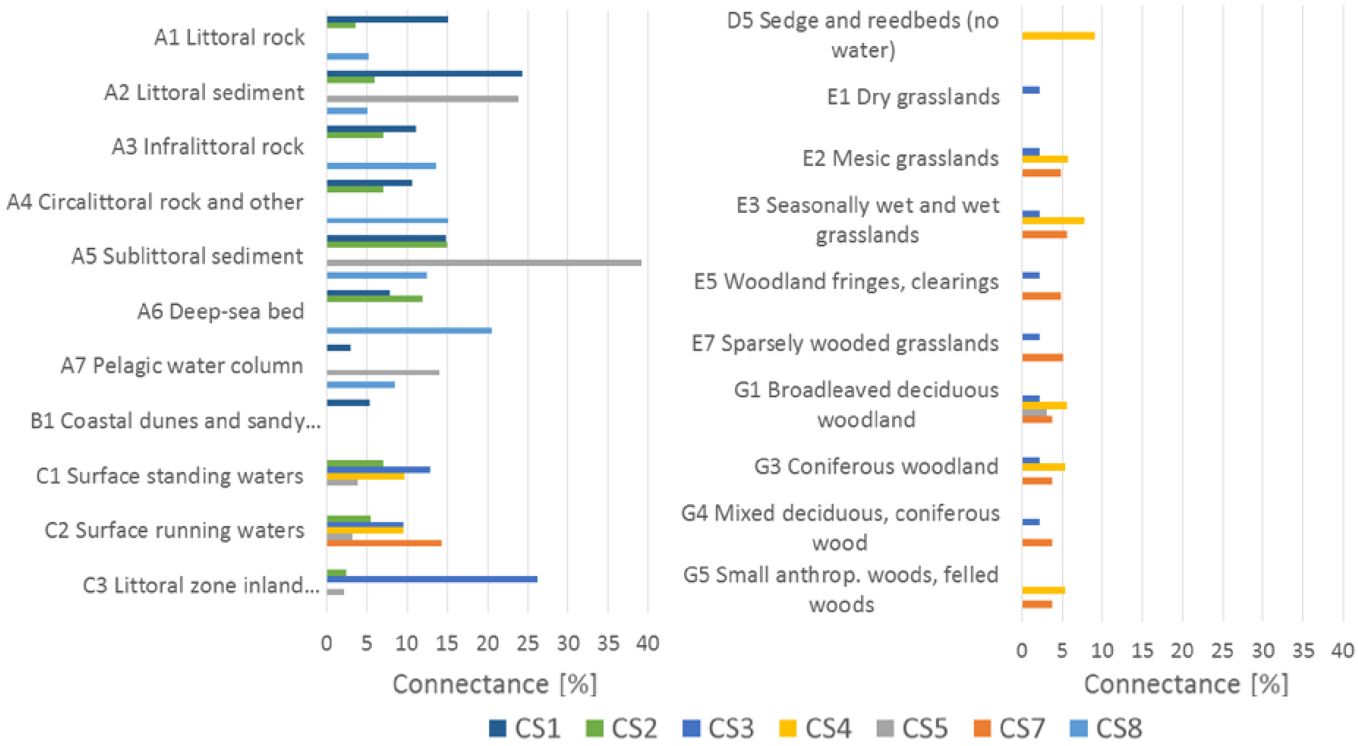
Over all AQUACROSS CSs, CS2 Andalusia & Morocco showed highest diversity of ecosystem components with 40 out of 45 EUNIS2 habitats and mobile biota (Table 3). The lowest number of ecosystem components was found in Azores.

Results indicated a clear separation in marine and freshwater case studies (Figure 4). Case studies including marine and coastal habitats had high connectance for their habitats (CS1 North Sea, CS2 Andalusia & Morocco, CS5 Vouga River, CS8 Azores) in relation to the numbers of activities and pressures interacting with them. Freshwater case studies CS3 Danube River, CS4 Lough Erne, and CS7 Swiss Plateau showed a more even distribution of connectance that was much lower across their habitats.

Table 3: Number of ecosystem components (and mobile biotic groups) in the AQUACROSS case studies (CS)

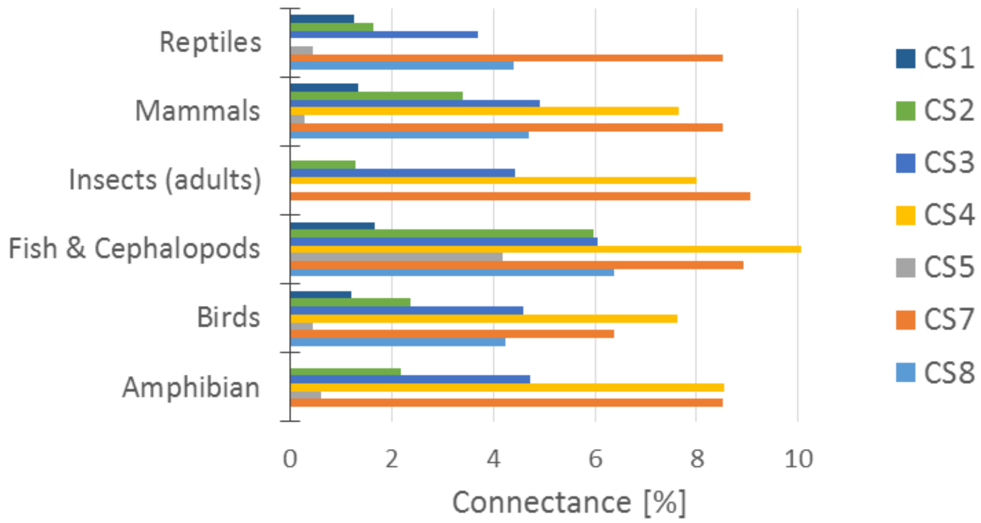
Case Study	Number of ecosystem components
All CS	45
CS1	14
CS2	40
CS3	22
CS4	13
CS5	18
CS7	15
CS8	11

Figure 4: Connectance of ecosystem components (EUNIS2 level) in the AQUACROSS cases studies (CS), Habitats with a connectance of 2% or higher are shown.



The mobile biota group with the highest connectance was clearly 'Fish & Cephalopods', but as most CSs include freshwater, fish had higher relevance than cephalopods. CS4 Lough Erne and CS7 showed the highest connectance for their relevant mobile biota across the groups, while CS5 Vouga River showed the lowest (Figure 5).

Figure 5: Connectance of mobile biota groups in the AQUACROSS cases studies (CS)



2.4 Results– Weighting impact chains

In the following section, we highlight results that show the proportion of the different weighting categories within certain primary activities. In this way, all single impact chains (including the pressures) are summarised in a way that is relevant to management as the activities introduce the pressures. If an activity is managed, the resulting pressures and therefore the effects on the ecosystem will change. However, this approach can also be used to explore management that directly targets pressures (e.g. input of nutrients) or ecosystem components (e.g. restoration of habitats), although this is not shown here.

2.4.1 Proportions of different weighting classes

The following chapter summarises the relative portions of assigned weightings for the different weighting categories within the primary activities 'Tourism, Angling & Hunting', 'Environmental Management', 'Agriculture & Forestry', 'Fishing', and 'Residential & Commercial Development'.

Spatial extent of 'Tourism, Angling & Hunting' activities was mostly found to have a local extent (5-50% of the study area) in CSs (Table 4). In CS1 and CS5, most impact chains were weighted as widespread patchy, i.e. locally occurring but distributed widely across the CS area. CS8 identified most impact chains of this activity as exogenous. The weighting of frequency varied between occasional (occurs in most years of a five year period), frequent (occurs in every year of a five year period), and very frequent (occurs in most months of a year). Severity was mostly chronic across all CSs, which means the introduced pressure can build up over time (or with intensity) to become severe for the ecosystem component. However, the persistence of the impact chains is mostly low (0 to 2 years), which means most of the pressures will leave the system once the related activities are stopped. Accordingly, management measures decreasing the amount or fully stopping tourism activities, could allow the ecosystem components to start recovery. Here, the exception is CS5 with a high persistence (>100 years dispersal weightings varied between moderate (disperses in local environment) to high (disperses beyond local environment).

Table 4: Proportion of the different weighting categories for the primary activity "Tourism, Angling and Hunting" in the AQUACROSS cases studies (CS)

	EXTENT					FREQUENCY					SEVERITY			PERSISTENCE				DISPERSAL		
	EXOGENOUS	SITE	LOCAL	WIDESPREAD PATCHY	WIDESPREAD EVEN	RARE	OCCASIONAL	FREQUENT	VERY FREQUENT	CONTINOUS	LOW	CHRONIC	ACUTE	LOW	MODERATE	HIGH	PERSISTENT	NONE	MODERATE	HIGH
Total	**11%**	**6%**	**42%**	**37%**	**3%**	**14%**	**24%**	**36%**	**23%**	**3%**	**5%**	**88%**	**7%**	**54%**	**18%**	**25%**	**4%**	**25%**	**40%**	**34%**
CS1	10%	0%	36%	53%	0%	10%	29%	44%	16%	0%	2%	90%	8%	56%	21%	19%	3%	28%	42%	30%
CS2	14%	19%	63%	0%	4%	23%	30%	2%	24%	21%	3%	95%	2%	47%	16%	37%	1%	18%	38%	44%
CS3	2%	20%	53%	10%	14%	22%	8%	47%	23%	0%	10%	79%	11%	48%	9%	36%	8%	22%	35%	43%
CS4	4%	0%	53%	33%	9%	23%	4%	42%	32%	0%	13%	79%	8%	53%	6%	34%	6%	23%	40%	37%
CS5	1%	11%	19%	69%	0%	5%	46%	34%	14%	0%	1%	75%	24%	37%	6%	57%	0%	39%	1%	60%
CS7	3%	2%	67%	14%	14%	24%	22%	13%	34%	7%	16%	77%	7%	57%	5%	27%	11%	30%	41%	29%
CS8	35%	27%	20%	0%	18%	4%	8%	28%	61%	0%	9%	85%	6%	53%	22%	25%	0%	16%	43%	41%

Most impact chains related to 'Environmental Management' were weighted as having a local extent with rare frequency, chronic severity and moderate dispersal (Table 5). Interestingly the majority classes of persistence weightings varied between low in 4 CSs and persistent in 3 CSs providing a rather contrasting picture. Looking into detail, the freshwater related CSs 2, 3 and 7 mainly allocated persistent. This reasonably underlines the important role of environmental management, including activities related to flood defence, waterway construction and land conversion, in freshwater ecosystems. These activities make enduring changes to the habitats within these systems, e.g., by transforming floodplains in to arable land. On the other hand, environmental management in marine systems can include beach replenishment, which is not long-lasting.

Table 5: Proportion of the different weighting categories for the primary activity "Environmental Management" in the AQUACROSS cases studies (CS)

	EXTENT					FREQUENCY					SEVERITY			PERSISTENCE				DISPERSAL		
	EXOGENOUS	SITE	LOCAL	WIDESPREAD PATCHY	WIDESPREAD EVEN	RARE	OCCASIONAL	FREQUENT	VERY FREQUENT	CONTINOUS	LOW	CHRONIC	ACUTE	LOW	MODERATE	HIGH	PERSISTENT	NONE	MODERATE	HIGH
Total	**21%**	**18%**	**35%**	**24%**	**2%**	**62%**	**36%**	**0%**	**1%**	**0%**	**7%**	**86%**	**7%**	**37%**	**18%**	**10%**	**34%**	**26%**	**53%**	**20%**
CS1	23%	19%	32%	26%	0%	50%	50%	0%	0%	0%	3%	91%	6%	42%	22%	10%	25%	21%	55%	23%
CS2	22%	48%	29%	0%	0%	87%	12%	0%	0%	1%	7%	78%	14%	19%	17%	3%	61%	55%	41%	4%
CS3	25%	9%	46%	14%	6%	95%	5%	0%	0%	0%	18%	77%	6%	20%	12%	17%	51%	23%	52%	25%
CS4	0%	8%	85%	3%	4%	57%	43%	0%	0%	0%	20%	71%	9%	49%	7%	11%	33%	36%	50%	14%
CS5	37%	27%	9%	27%	0%	28%	72%	0%	0%	0%	1%	92%	7%	64%	12%	12%	13%	23%	61%	15%
CS7	3%	0%	0%	79%	18%	96%	1%	0%	1%	1%	19%	74%	7%	26%	5%	1%	67%	47%	50%	3%
CS8	33%	0%	67%	0%	0%	45%	0%	16%	39%	0%	5%	89%	6%	38%	20%	17%	25%	22%	47%	31%

Primary activities related to 'Agriculture & Forestry' were identified as mainly exogenous (Table 6). The weighting categories severity (chronic), persistence (low) and dispersal (moderate) showed consensus across the CSs, with highest proportions within the mentioned classes. In turn, frequency was heterogeneously distributed across the CSs.

Table 6: Proportion of the different weighting categories for the primary activity "Agriculture & Forestry" in the AQUACROSS cases studies (CS)

	EXTENT					FREQUENCY					SEVERITY			PERSISTENCE				DISPERSAL		
	EXOGENOUS	SITE	LOCAL	WIDESPREAD PATCHY	WIDESPREAD EVEN	RARE	OCCASIONAL	FREQUENT	VERY FREQUENT	CONTINOUS	LOW	CHRONIC	ACUTE	LOW	MODERATE	HIGH	PERSISTENT	NONE	MODERATE	HIGH
Total	**72%**	**0%**	**8%**	**10%**	**9%**	**23%**	**11%**	**25%**	**34%**	**7%**	**6%**	**94%**	**1%**	**63%**	**14%**	**21%**	**1%**	**3%**	**70%**	**27%**
CS1	73%	0%	3%	25%	0%	29%	9%	11%	51%	0%	1%	99%	0%	63%	24%	13%	0%	0%	68%	32%
CS2	71%	0%	29%	0%	0%	35%	34%	30%	0%	0%	7%	93%	1%	77%	3%	17%	3%	5%	74%	21%
CS3	75%	1%	7%	0%	17%	21%	0%	79%	0%	0%	11%	88%	0%	61%	5%	29%	6%	2%	74%	24%
CS4	23%	0%	41%	7%	30%	29%	0%	17%	53%	0%	12%	85%	4%	59%	6%	35%	0%	14%	62%	24%
CS5	93%	1%	0%	4%	1%	7%	25%	64%	4%	0%	4%	96%	0%	96%	1%	3%	0%	1%	99%	0%
CS7	64%	0%	0%	0%	36%	20%	2%	5%	0%	73%	14%	83%	3%	58%	3%	36%	2%	11%	64%	25%
CS8	100%	0%	0%	0%	0%	5%	26%	0%	69%	0%	2%	98%	0%	53%	22%	25%	0%	0%	67%	33%

The primary activity 'Fishing' (Table 7) was not identified in all CSs and was completely missing in CS7 Swiss Plateau, because fishing here is exclusively recreational. Spatially, 'Fishing' is distributed very unevenly among the case studies, ranging from exogenous to widespread patchy. CS8 Azores has almost all its pressures introduced exogenously by fishing activities (46%) or at a site extent (45%). The frequency maxima ranged from occasional to very frequent. Persistence was low in CSs, indicating that if fishing activities are stopped, the pressures on the ecosystem components will quickly leave the system. Dispersal was mostly high, with the exception of CS5 (none) and CS8 (moderate).

Table 7: Proportion of weighting categories for the primary activity "Fishing" in the AQUACROSS cases studies (CS)

	EXTENT					FREQUENCY					SEVERITY			PERSISTENCE				DISPERSAL		
	EXOGENOUS	SITE	LOCAL	WIDESPREAD PATCHY	WIDESPREAD EVEN	RARE	OCCASIONAL	FREQUENT	VERY FREQUENT	CONTINOUS	LOW	CHRONIC	ACUTE	LOW	MODERATE	HIGH	PERSISTENT	NONE	MODERATE	HIGH
Total	**30%**	**6%**	**14%**	**37%**	**12%**	**10%**	**29%**	**8%**	**53%**	**0%**	**3%**	**92%**	**6%**	**45%**	**21%**	**34%**	**0%**	**17%**	**36%**	**47%**
CS1	31%	0%	16%	41%	12%	9%	33%	2%	56%	0%	2%	93%	5%	43%	23%	34%	0%	17%	35%	49%
CS2	13%	4%	0%	53%	31%	23%	25%	52%	0%	0%	3%	94%	3%	46%	14%	39%	0%	13%	43%	44%
CS3	0%	100%	0%	0%	0%	0%	0%	100%	0%	0%	6%	81%	13%	62%	0%	38%	0%	19%	35%	46%
CS4	0%	0%	100%	0%	0%	0%	100%	0%	0%	0%	5%	76%	19%	60%	2%	38%	0%	31%	31%	38%
CS5	15%	14%	24%	47%	0%	12%	21%	67%	0%	0%	0%	68%	32%	69%	1%	29%	0%	40%	27%	33%
CS7																				
CS8	46%	45%	9%	0%	0%	4%	4%	0%	91%	0%	4%	86%	9%	50%	15%	35%	0%	17%	43%	40%

The majority of extent weightings for 'Residential & Commercial Development' (Table 8) ranged from exogenous in 3 CS through local (3 CS) to widespread patchy in 1 CS.

Table 8: Proportion of weighting categories for the primary activity "Residential & Commercial Development" in the AQUACROSS cases studies (CS)

	EXTENT					FREQUENCY					SEVERITY			PERSISTENCE				DISPERSAL		
	EXOGENOUS	SITE	LOCAL	WIDESPREAD PATCHY	WIDESPREAD EVEN	RARE	OCCASIONAL	FREQUENT	VERY FREQUENT	CONTINOUS	LOW	CHRONIC	ACUTE	LOW	MODERATE	HIGH	PERSISTENT	NONE	MODERATE	HIGH
Total	**34%**	**1%**	**38%**	**28%**	**0%**	**28%**	**11%**	**3%**	**47%**	**11%**	**11%**	**85%**	**4%**	**42%**	**16%**	**23%**	**19%**	**15%**	**49%**	**36%**
CS1	21%	0%	27%	52%	0%	26%	8%	0%	66%	0%	8%	88%	4%	44%	23%	14%	19%	18%	50%	32%
CS2	99%	0%	1%	0%	0%	15%	30%	0%	7%	48%	18%	82%	0%	49%	4%	32%	15%	1%	62%	37%
CS3	28%	5%	68%	0%	0%	34%	0%	20%	30%	16%	9%	88%	3%	34%	11%	37%	17%	13%	40%	47%
CS4	0%	0%	100%	0%	0%	36%	0%	1%	53%	10%	16%	80%	4%	50%	5%	26%	18%	25%	47%	29%
CS5	7%	38%	55%	0%	0%	43%	0%	14%	43%	0%	0%	100%	0%	7%	5%	76%	12%	12%	0%	88%
CS7	100%	0%	0%	0%	0%	46%	0%	0%	7%	46%	28%	72%	0%	44%	0%	24%	32%	0%	72%	28%
CS8	66%	0%	34%	0%	0%	25%	54%	0%	7%	14%	16%	80%	4%	26%	17%	37%	20%	13%	37%	50%

The frequency weightings were mainly identified as rare, very frequent and continuous, with two CSs finding equal proportions of rare and very frequent or continuous weightings. This heterogeneity in the extent and frequency weightings can be attributed to a construction and an operational phase of this activity. Construction rarely happens, but the related pressures are mostly persistent. The operational phase on the one hand can introduce pressures like chemical pollutants frequently or continuously, which are at the same time persistent, and on the other hand nutrient input, which has low persistence. Severity was mainly weighted as chronic. Persistence was either low (CS1, 2, 4, 7) or high (CS3, 5, 8) and dispersal was found to be moderate and high.

2.5 Conclusions based on the linkage framework approach

The application of the AQUACROSS linkage framework in the CSs identified a multitude of human activities and related pressures that affect aquatic ecosystem components across Europe. Thus, this approach was successful to characterise the complex socio-ecological systems and the causalities between the elements of the D-P-S sequence. The linkage framework is highly valuable to provide a conceptual basis for stakeholder dialogues based on the full linkage framework, to understand the complex social-ecological systems, or to discuss parts of the system that are especially relevant to certain stakeholder groups.

The results of the linkage framework underline the importance of considering all relevant human activities and related pressures in the management of aquatic ecosystems. In addition, activities that may be spatially separated from the affected ecosystem component by a certain pressure, should be considered in assessments to fully comprehend the complex relationships in social-ecological systems, and thus, to help in prioritisation of biodiversity protection actions.

The comparison of most relevant activities across the different aquatic realms indicated some differences and realm specificities. Not surprisingly, fishing activities are highly relevant in marine contexts as commercial fisheries are largely restricted to marine environments in Europe. In the comparison of different aquatic realms, this also underlines the need to consider such specificities and to keep context specific solutions in integrated management.

A commonality across the realms was the high connectance of tourism activities. This finding is also emphasised by detailed analyses in CS8. Moreover, activities related to energy production showed relevance across the aquatic realms. Although the renewable energy sector played a role in freshwater as well as marine ecosystem components, the detailed activities are different; in the former hydropower introduces a lot of pressures, whereas wind farms are mostly relevant in the latter.

The results presented here clearly show the importance of considering the origins of pressures that affect ecosystem components. The activity type environmental management proved to be highly influential, especially for ecosystem components in freshwater. This can be related to ‘adaptations’ induced by the society that adjust ecosystems to its needs, such as flood control or waterway construction. Both activities, flood control and waterway construction, are addressed in specific analyses of CS3 Danube to investigate the trade-offs to establish an integrated management of floodplains. Notably, for both activities there are several possibilities to implement them in a way that meets the needs of human society, as well as those of ecosystems.

However, such a potential win-win situation requires firstly a strong commitment to the ecological needs in spite of economic interests, and secondly a comprehensive understanding of how pressures introduced by those activities affect the ecosystem components and interact with other activities. Only with an awareness of such alternatives is the need for detailed data on all these aspects highlighted. Management scenarios can only be compared in detail using quantitative data. In this respect, the role of ecosystem services is a vital one, as this concept provides a nexus to investigate the contribution of ecosystems to human wellbeing.

Furthermore, the linkage framework approach can help to identify activities that are dislocated from the place where a related pressure occurs. Such impact chains that were weighted to be exogenous often contained chronic severity and high frequency. Activities, which affect habitats exogenously, are often not addressed in management measures across (aquatic) ecosystems. As exogenous influence is often difficult to quantify in the presence of several other local activity types introducing similar pressures, the dislocated causes are likely to be overlooked; e.g. the deficit of sediment load in rivers caused by storage hydropower plants.

Activities not directly associated to aquatic ecosystems, such as agriculture, are treated with less importance by policies related to aquatic ecosystems. In the EU WFD the associated pressures are addressed, and symptoms of these pressures can be managed and mitigated. However, in an EBM context an alignment of the policies concerning aquatic ecosystems and agriculture activities would be necessary to manage agronomic practices, so that instead of mitigating occurring pressures, the activity itself would not cause negative impacts to begin with.

Our linkage framework can be seen as a follow-up initiative to the work in the ODEMM project where the focus lay on impact chains in marine ecosystems. In AQUACROSS, we successfully extended the approach to freshwater ecosystems providing a showcase for a comprehensive assessment of impact risk across aquatic realms in Europe. The conceptualisation of human-induced impacts is strongly dominated and skewed by the DPSIR approach in aquatic ecosystems, as DPSIR supports mono-causal views. The prioritisation of single pressures further drives the focus on relatively few elements within the complex and multiple linkages that are found in social-ecological systems.

During the initial stages to implement the linkage framework approach it became obvious that a common typology of human activities, pressures and ecosystem components across aquatic realms that provides a solid basis for cross-realm comparisons was missing. This is probably also related to fragmented policies relevant to the different aquatic ecosystem types and different typologies therein. Such an alignment of typologies (and underlying nomenclatures) represents a quintessential step for the integration of different EU policies across the aquatic realms. Only a common nomenclature and typology can yield a common understanding that is necessary in research and science, as well as in policy and decision-making.

The linkage framework provides a magnitude of further applications to investigate complex social-ecological systems besides the results presented in this report. Therefore, we want to highlight some of the further applications that have already been carried out. Firstly, we calculated an Environmental Impact Risk score based on the impact chain weightings, which combined the different weighting classes into one value indicating impact risk. This work was part of task 4.2 and is published in the contributions of Borgwardt et al. (2019) in the

AQUACROSS virtual special issue 'EBM in aquatic ecosystems' in the journal Science of the Total Environment (see Annex C). Furthermore, the identified impact chains of the AQUACROSS linkage framework do not only contain the dimensions of human activities, pressures and ecosystem components but also cover ecosystem processes, functions and services by supply chains (addressed in WP5 and D5.2 as well as a by Teixeira et al., subm). A combined analysis of impact and supply chains is presented in Culhane et al. (subm.).

Furthermore, the full chains will be used to develop a tool, the so-called AquaLinksTool, that will help identifying relationships between human activities and ecosystem services to be considered in the management of the ecosystems, and will be available through the AQUACOSS information platform. The AquaLinksTool is introduced in more detail in D5.2. Finally, the AQUACROSS linkage framework approach can support the implementation of EBM approaches. It provides a conceptual basis that can be used in stakeholder dialogues by adjusting the framework to relevant activities that should be discussed.

2.6 Recommendations based on the linkage framework approach

In the following, we highlight four major recommendations that are based on the outcomes of the linkage framework approach:

1 Managing aquatic ecosystems across realms implies multiple disciplines and policies. To foster the understanding across these different entities a common nomenclature is highly crucial to assess drivers and pressures in a comparable way, and subsequently clearly communicate results. Thus, a common nomenclature also facilitates the communication between research, policy and stakeholders.

2 An integrated management based on the application of EBM has to consider all relevant aspects that influence the state of the ecosystem, i.e. drivers (human activities) and pressures that may cause changes. The linkage framework provides a holistic assessment considering all relevant elements that helps to understand the complex interactions of social-ecological systems. The application of the linkage framework to the exploratory analysis of the social-ecological system offers the possibility to examine the complexity and connectivity of the linkages that affect ecosystem components deepening the understanding of casual relationships.

3 Spatial separation of human activities and occurrence of related pressures has to be better addressed in management, as well as in policies. This implies a clear communication on the complex interactions and the difficulties to quantify them in real-world situations, as multiple activities cause similar pressures and untangling the single effects is difficult. In data poor contexts the linkage framework provides a valuable basis to identify influential activities and pressures, as well as ecosystem components that are at risk and to highlight the need to gather more data on the impact chains of interest.

4 In terms of communication, the dialogue with stakeholders has to be emphasised. However, the willingness of stakeholders is also related to the demands of underlying policies. The linkage framework can support communication on the one hand to conceptually describe the complex interactions of social-ecological systems advancing from the mono-causal DPSIR view and on the other hand to underline potential synergies of environmental (and economic) policies. A categorisation of the different elements along the cause-effect chain, as implemented in the linkage framework, can provide a policy-oriented tool linking different activities.

3 Use of D-P-S indicators

Following the linkage framework approach presented in Chapter 2, this chapter addresses the specific exploratory analyses performed within the AQUACROSS CSs, as the second approach taken to investigate D-P-S relationships in the aquatic realms.

Indicators and associated metrics and indices play a vital role to describe and quantify drivers and pressures, as well as to identify relationships between drivers, pressures and ecosystem states. In the previous D4.1, most commonly used, sensitive and cost-effective indicators for D-P-S analyses have been identified and reviewed for their suitability to be used for the assessment of the demand-side perspective. Following these recommendations, most of the CSs followed a quantitative approach using the proposed indicators. Whereas most of the case studies used already available indicators from sources from local to global scale, CS5 and CS3 developed additional indicators based on available data.

In most cases availability of status and species related data was more limiting than availability of data related to drivers and pressures (Table 9). Where socio-economic and ecological information was available, variables from both fields were integrated and best indicators were selected. Thereby, the CSs were aware of the recommendations found in the AF "…*that indices and metrics usually can only represent individual parts of the framework at a time […] that metrics can only be used in data rich situations [...and] In [data limited] cases, qualitative approaches can be used, starting from linkages, to make an assessment where relational links are inferred but not quantitatively measured*".

Table 9 Use, processing and development of indicators as well as sources used and limitations of D–P–S indicators in the AQUACROSS case studies.

Process of indicator integration

CS	CS name	Use of available indicators	Indicator processing	Indicator development
1	North Sea	yes		No
2	IBRM	yes	Intense harmonisation, integration and mapping of multiple datasets	For missing data
3	Danube	yes	Integration and mapping	Pressure indicators related to hydrology
4	Lough Erne	no		
5	Aveiro	yes	Integration and mapping	Spatial indicators based on satellite imagery
6	Ringsjön	no		
7	Swiss Plateau	yes	Integration and mapping	
8	Azores	yes		

Limitations

		Human activities, pressures	Ecosystem state
1	North Sea	Data related to main activities available	Status information related to MSFD is widely available
2	IBRM	High data availability in Spain but low in Morocco, where global and open data sources were used	For Spain from HBD and WFD and MSFD. For Morocco no information for freshwater and marine environments available. Local data on species is restricted and global species distribution data available but heterogeneous.
3	Danube	Good availability for the Danube River, but low and heterogeneous for tributaries	Status information from HBD; WFD information partially heterogeneous, Species data from literature and other resources
4	Lough Erne	Qualitative approach – data are limited	Qualitative approach – data limited
5	Aveiro	Data partially available, intense use of spatial data from aerial images	
6	Ringsjön	Qualitative approach – data are limited	Qualitative approach – data limited
7	Swiss Plateau	High data availability	Monitoring data available
8	Azores	Qualitative approach – data are limited	Qualitative approach – data limited. Recommendations for status indicators related to MSFD and HBD are provided

Sources of indicators (examples)

		Global scale	European scale	Case study scale	Other indicator sources
1	North Sea		WindEurope, EEA	ICES	Scientific studies
2	IBRM	OpenStreetMap, Global Human Settlement Layer, MODIS Copernicus Africa land cover, Global Fishing Watch	EUROSTAT, EEA, EMEP, EMODnet	REDIAM, UCACITT	Scientific studies
3	Danube		EEA, EuroNature, UNECE, Copernicus	Danube River Basin Management Plan, FAIRway Danube, WWF Romania, WWF Bulgaria, Slovenian Environmental Agency	Scientific studies
4	Lough Erne				
5	Aveiro	EarthWatch, GeoEye, ESRI, Earthstar Geographics, GetMapping	EEA	Portuguese Environment Agency, Inst. for Nature Conservation and Forests, Regional Direct. for Agric. and Fisher., Hydrographic Inst., Direct. Gen. for Marine Resources	
6	Ringsjön				
7	Swiss Plateau			Federal authorities, cantonal authorities and NGO's	
8	Azores		EEA, EUROSTAT	SREA, Statistics Portugal	Scientific studies

3.1 Driver indicators

This section addresses the driver dimension in the D-P-S sequence. The drivers are represented by human activities that represent the manageable manifestation of drivers in the social-ecological system. Table 9 illustrates that the CSs had varying levels of data availability and types. Therefore, they often had to rely on relatively coarse indicator data for the major human activities exerting pressures on the aquatic ecosystems and their components.

However, data availability significantly differed among countries within CSs, even among EU member states, and in relation to the underlying environmental policy. Hence, the elaboration of a uniform map of an important activity for a particular geographical area covering different countries or even continents represents a major challenge, although this information is quintessential to understand the effects of the society on ecosystem state. This challenge is shown in the following examples originating from CS2 – the Intercontinental Biosphere Reserve in the Mediterranean – (Box 1) and CS3 – the Danube River.

Among the AQUACROSS CSs, CS2 was especially challenging in respect of data availability as it covered not only different countries but also different continents. For the Spanish part, data was available from different European and national monitoring initiatives. In contrast, data for the African part in Morocco was scarce. Thus, data was collected from global sources and harmonised with the data from the Spanish section. This process was accompanied by a strong stakeholder involvement to verify the results (Box 1).

The example from CS3 focuses on the human activity of renewable energy production. Hydropower development represents a main driver of change in the tributary rivers of the Danube in South-East Europe (SEE). Accordingly, this human activity is highly relevant for the sustainable management of the aquatic biodiversity in this region. Information on the locations of current and planned hydropower plants (HPPs) in SEE were collected and mapped to create detailed spatial information on this activity (Box 2).

The results of the CS3 example raises the question whether public financial incentives on the national level for small HPPs are efficient to increase the share of renewable electricity production, as a high number of small HPPs only provide a small contribution to the total electricity output to the renewable sector (Abbasi & Abbasi, 2011). Most planned HPPs in the study region are small in size, although they cause significant environmental damage, as more or less all river systems will be fragmented by the HPPs and their dams (Kelly-Richards et al. 2017; Schwarz, 2015).

In order to achieve the objectives from the EU Renewable Energy Directive, most EU member states have established financial support schemes for renewable electricity production, such as fixed feed-in tariffs and feed-in premiums. These financial incentives are most beneficial for small HPPs (Bosnia and Herzegovina Government, 2016; Croatia Government, 2013; Montenegro Government, 2014; Republic of Serbia Government, 2013; Slovenia Government, 2010), and seem to be sufficiently attractive to trigger the present boom of small HPPs in the study area (Schwarz, 2015). According to a study of the International Monetary Fund (IMF), Serbia and Bosnia and Herzegovina are among the world's top ten countries with the highest percentage of energy subsidies in the Gross Domestic Product (Coady, Parry, Sears, & Shang, 2015).

Hence, this analysis shows that 98% of electricity is produced by only a small share of all HPPs. This indicates a potential pathway for EBM by restricting hydropower production to medium-sized and large dams. This goal could be supported by corresponding adaptation of energy subsidy schemes by state institutions.

Box 1: Harmonisation of indices and metrics to map drivers and pressures across continents derived from different sources including global datasets.

CS 2 (IBRM) covers Spain and Morocco. Consequently, available data to characterise the social-ecological system differed. Thus, data harmonisation was necessary. The data harmonisation process covered to following steps:

- Integration: combining different data sources complementing each other;
- Disaggregation: combining at least two sources to improve the detail of one, e.g. the thematic details of the habitats;
- Aggregation: if data for one section was too coarse, aggregation enabled a good level of consensus between both sections; finally, a 1km reference grid was used.
- Production: if no data was available, but digitisation was possible in a reasonable time, a new dataset was produced, e.g. aquaculture infrastructures and coastal defence infrastructures in Morocco.

Based on the linkage framework relevant activities have been identified and data to describe them was acquired. In total, 70 metrics were used for mapping the activities and pressures at the IBRM case study. Based on the spatial information on human activities that covered the whole area of the IBRM a composite index, the human footprint index, was calculated. Both, the spatial information on single activities as well as the composite index provided the basis to compare the Spanish and the Moroccan sections of the IBRM.

Agriculture, livestock, forestry, urban development, and shore recreational activities are the main terrestrial activities in the case study area.

Two important conclusions are I) that the Moroccan part clearly showed less human activities (Figure 6), and ii) that this can be partly explained by the fact that much more information was available for the Spanish part.

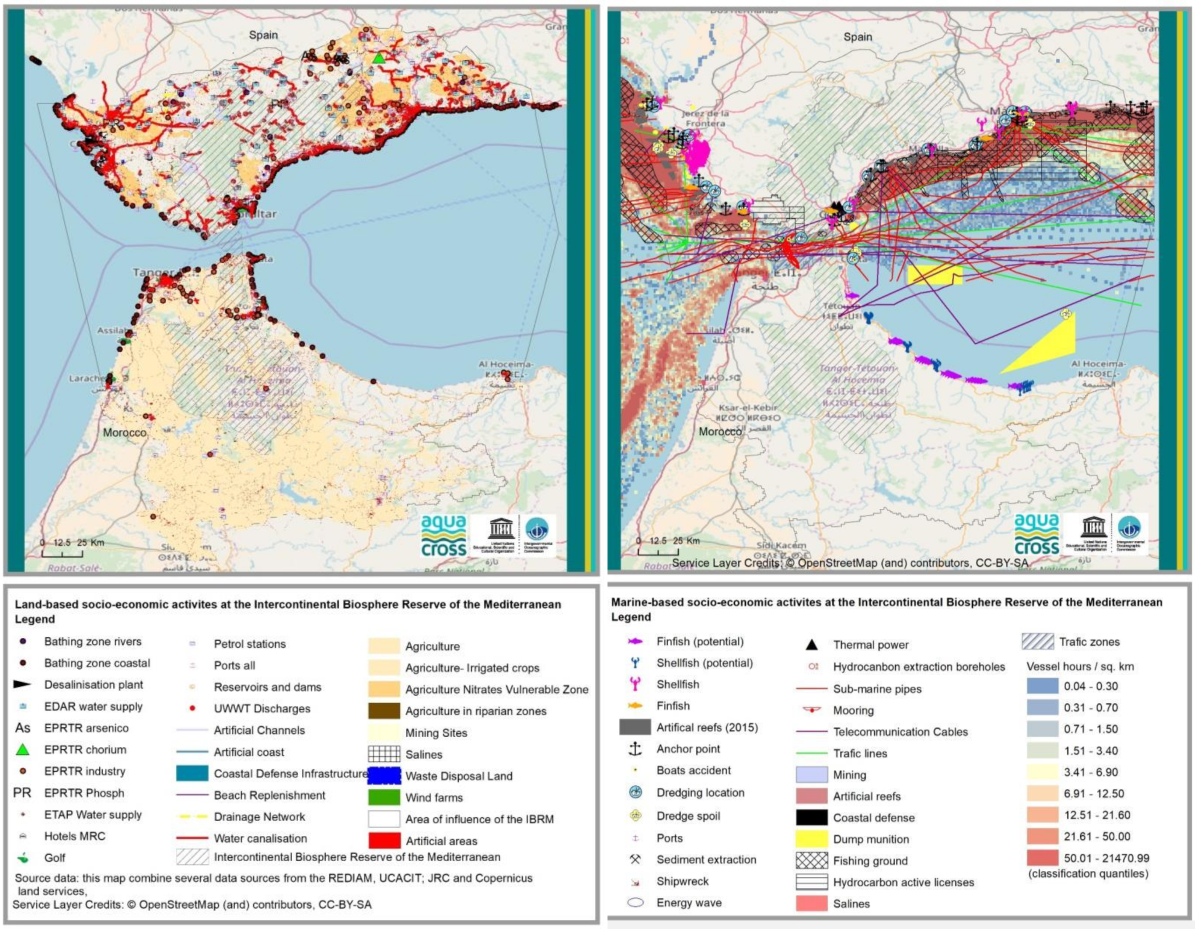


Figure 6: Mapping of the land (left) and marine (right) based human activities in the Intercontinental Biosphere Reserve of the Mediterranean (IBRM)

Box 2: Current situation and development of hydropower the human activity renewable productions based on hydropower in South-East Europe

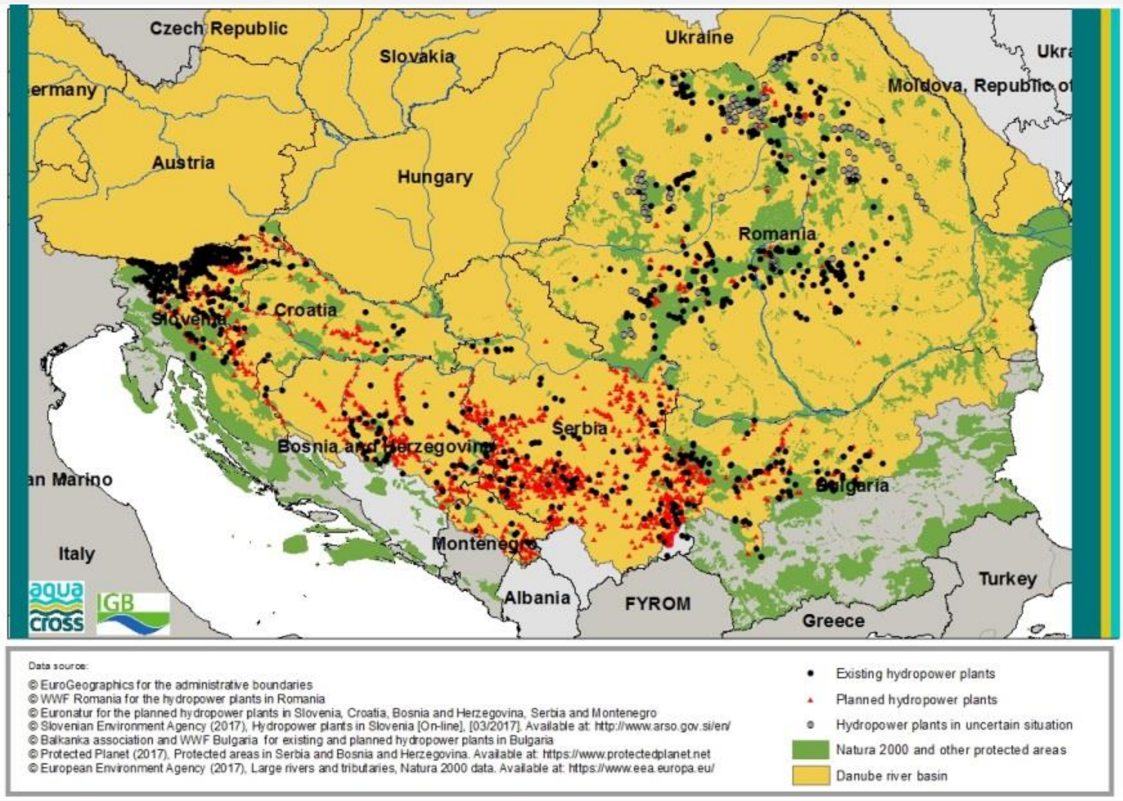
The spatial information of HPPs and created map shows the minimum extent of potential effects of hydropower on rivers in SEE, which hence may hamper or prevent reaching the goals of the EU Water Framework Directive (WFD) and EU Natura 2000 Directive. The spatial information about current state and development of hydropower in SEE covers Slovenia, Croatia, Bosnia and Herzegovina, Serbia, Montenegro, Bulgaria and Romania. A database with information on 2,372 hydropower plants in different stages of approval, construction, or operation was collated. The information as gathered from different sources, namely Euronatur, Slovenian Environment Agency (www.arso.gov.si), WWF Romania based on information provided by the Romanian Environmental Protection Agency (www.raurileromaniei.ro/harta/), Balkanka association (https://dams.reki.bg/ Dams/Map), WWF Bulgaria (www.wwf.bg/) and others.

An analysis of the HPP database showed that from 1,044 operational HPPs, a total of 333 (32%) are currently located in Natura 2000 areas, and from 1,501 planned HPPs, 345 (23 %) would be located in Natura 2000 or other protected areas (Table 10, Figure 7).

Although the "Sustainable Hydropower Development" approach from the International Commission for the Protection of the Danube River (ICPDR, 2014) and the criteria listed in the 'Guidance on the requirements for hydropower in relation to Natura 2000' (EU COM 2018) highlight protected sites as "no-go" areas, 23% of the planned new HPPs are situated there. Furthermore, the amount of protected areas in Bosnia and Herzegovina and Serbia is lower than the European average indicating a need to nominate further protected areas there.

Further analyses of the human activity hydropower production showed that large HPPs provide a highly dominant share (95%) of the total installed capacity in the rivers. These 95% are contributed by only 7% of the total number of HPPs. In contrast, small HPPs represent 82% of the total number and provide only 2% of total installed capacity (Figure 8).

Figure 7: Map of operating and planed hydropower plants in Slovenia, Croatia, Bosnia and Herzegovina, Serbia, Montenegro, Bulgaria and Romania.

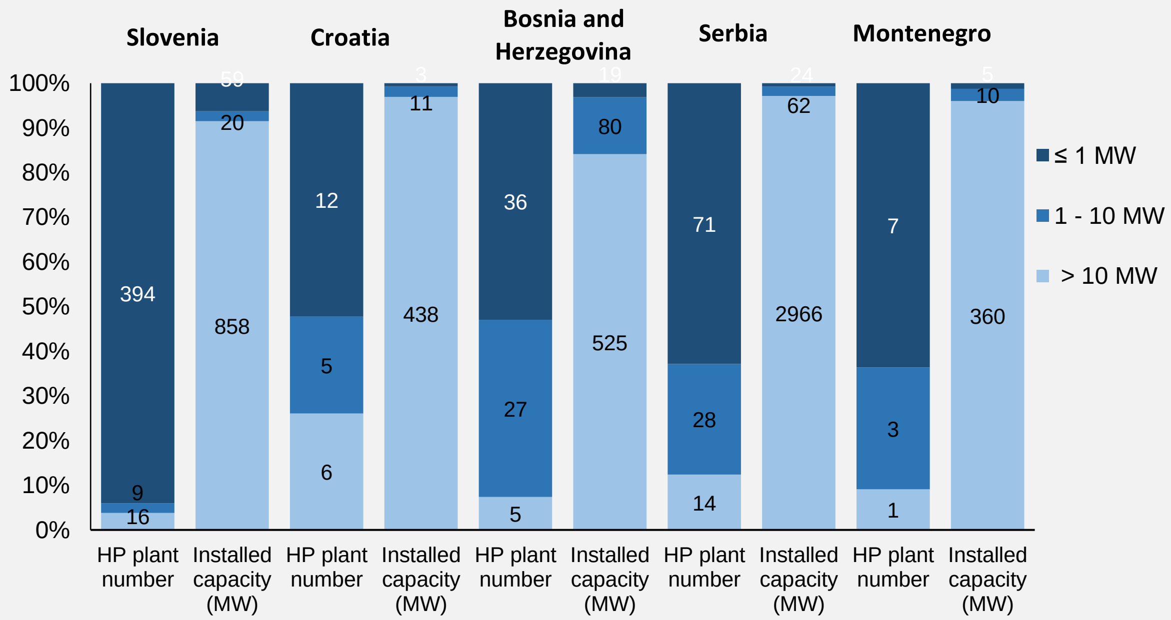


Due to gaps in official data the map is probably incomplete, especially for Romania.

Table 10: Number of the operating and planned HP plants in 7 countries from South-Eastern Europe (SEE) (based on available data)

SEE countries	Existing	Planned	In Natura 2000 areas and other protected areas	Planned in Natura 2000 areas and other protected areas
Bulgaria	84	82	51	42
Slovenia	419	150	110	67
Croatia	23	106	22	57
Romania	326	64	116	31
BiH	68	266	9	18
Serbia	113	780	25	126
Montenegro	11	53	0	4
Total	**1,044**	**1,501**	**333**	**345**

Figure 8: Country-specific distribution of installed electricity generation capacity (MW) among hydropower size classes.



Information available for Slovenia, Croatia, Bosnia and Herzegovina, Serbia and Montenegro in 2017; no data available for Bulgaria and Romania.

3.2 Pressure indicators

Following the D-P-S sequence, this chapter addresses the pressures dimension. Human activities introduce pressures on aquatic ecosystems, which affect them to varying extents. Moreover, many human activities even produce multiple pressures, which also interact with pressures generated by other human activities. Hence, the development of EBM approaches requires the analysis of all pressures produced by a certain human activity, in order to identify mitigation approaches for each pressure. Such an effort has been undertaken in CS3 for a pressure related to hydropower that introduces physical pressures in river ecosystems by changing the hydrological regime.

The alteration of flow regimes is often claimed to be the most serious and continuing threat to ecological sustainability of rivers and their associated floodplain wetlands (Sparks, 1995; Tockner, Pennetzdorfer, Reiner, Schiemer, & Ward, 1999). However, assessments of potential environmental effects of future HPPs in SEE are hampered by the fact that even the current impacts of existing HPPs on the hydrology of rivers have barely been studied in that region (Bonacci & Oskoruš, 2010; Bonacci, Tadic, & Trninic, 1992; Globevnik & Mikoš, 2009; Žganec, 2012). These impacts usually result in the alteration and homogenisation of aquatic and water-dependent habitats in the affected river corridor and in the loss of lateral and longitudinal connectivity, thus affecting the ecosystem state by e.g. a decrease of typical, native species and a spread of non-native species.

Knowledge on the pressures related to new HPPs on the hydrological regime of rivers in SEE also represents a pre-requisite to develop approaches aiming at the mitigation or optimisation of HPP operation to reduce environmental effects of flow regime alterations (B. Gao, Yang, Zhao, & Yang, 2012). Flow regime was detected to be altered at all investigated river reaches downstream of hydropower plants (HPPs). Further detail are found in Box 3.

The analyses showed that the total extent of flow alteration only becomes visible with the availability and use of sub-daily hydrological data. As only a small share of all gauging stations in the study area was actually recording at a sub-daily scale, the actual share of gauged river reaches, which are affected by HPPs cannot be fully evaluated. The combination of several methods provided benefits to perform an objective analysis of the pressures situation. The hydropeaking flow alteration method could be complementary to the other two methods used (Meile et al., 2011; Richter et al., 1998) in order to detect sub-daily changes.

Box 3: Analyses of a pressure on the ecosystem state – developing an indicator for South-Eastern European rivers to identify hydrological alterations due to water storage and diversion at hydropower plants

The study covered several sub-basins within the Danube Basin located in Slovenia and Croatia, which were selected due to the relatively good availability of gauging data there (Table 11) for 15 gauging stations, which enabled the assessment of hydrological pressures related to 10 HPPs affecting 13 river reaches, including river reaches downstream of diversion storage HPPs, downstream of storage and Run-of-the-river HPPs. Additionally, data from 7 unimpacted gauging stations were obtained, which represent reference conditions.

Long-term hydrological gauging stations were chosen that are located downstream of the HPP, with daily data before and after HPP construction, provided by Slovenian Environment Agency (www.arso.gov.si/en/) and Croatian Meteorological and Hydrological Service (http://meteo.hr/index_en.php). We applied the Indicators of Hydrologic Alteration model and a method for the assessment of hydropeaking flow alteration.

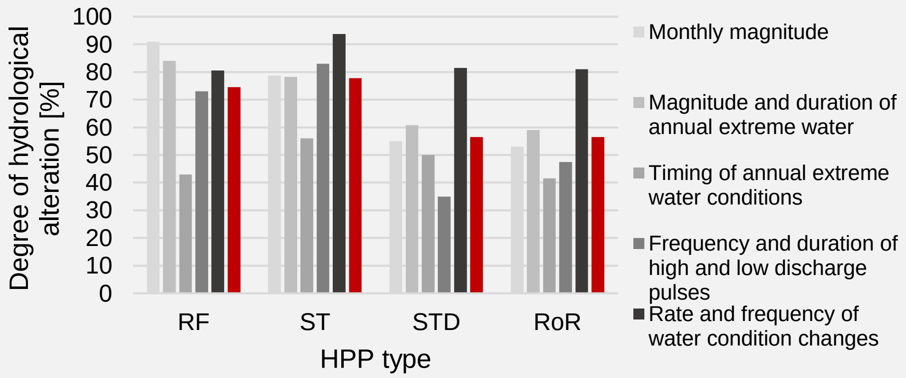
Results showed that the various hydropower plant types have generally strong but varying effects on flow regime, resulting in a flow regime greatly differing from the pre-impact natural flow regime. Medium altered river stretches were located downstream of diversion storage HPPs and run-of-river HPPs, while highly altered river stretches were located in residual flow river reaches and downstream of storage HPPs (Table 11, Figure 9).

Table 10: Hydropeaking indicator values (HP1, HP2) and overall hydropeaking values for each gauging station

DR = depleted reach, STW = Reaches downstream of storage dams either with or without water withdrawal, STDW = Reaches downstream of diversion storage with water withdrawal, ROR = Run-of-the-river HPPs, STD = Reaches downstream of diversion storage without water withdrawal

Gauging Station (GS)	1	5	6	7G	7L	8G	8L	10	13	15/16
HPP Type →	**DR**	**DR**	**STW**	**STDW**	**STW**	**STDW**	**STW**	**RoR**	**STD**	**STD**
HP1	0.2*	0.1	0.8*	1.2*	1.3*	0.9*	1.2*	0.5*	1.3*	0.7*
HP2	3.1*	0.1*	5.2*	7.1*	15.6*	4.1*	12.2*	12.0*	94.2*	40.5*
Overall	2b	1	3	3	3	3	3	3	3	3

Figure 9: Degree of hydrological alteration of the Indicators of Hydrologic Alteration model's flow categories of different HPP types



3.3 Indicators of ecosystem state

This chapter completes the D-P-S sequence by addressing the state component. Although information and analyses of drivers and pressures allow for an evaluation how ecosystems may be impacted, the final assessment has to target the state. However, ecosystem states can be described in multiple ways, and the impact of human activities and pressures on the state can affect very different elements of the ecological system. Thus, the use of adequate indicators is often context dependent. Here we show three examples, covering fresh and marine waters, of how the state can be represented by biological information.

Firstly, a spatial approach to map ecosystem state is presented. This example is based on CS2, where data sources with very different quality have been used to evaluate the ecosystem condition of habitats in fresh and marine waters (Box 4). Structural ecosystem attributes derived from the assessment of conservation status of habitats under the Habitats Directive are particularly relevant for the estimation of ecosystem condition because they can be directly linked to policy and decision-making (Maes et al. 2018).

Secondly, fish communities in rivers are used to evaluate the impact of HPPs in rivers (Box 5). Upstream and downstream of HPPs the river reaches clearly showed fewer fish species than in the reference state. Dominance of brown trout and European bullhead significantly decreased upstream and downstream of HPPs. Notably, other human-induced impacts are unlikely to occur in the studied river reaches. Thus, the effects on the fish communities (alteration of presence and dominance) can be mainly attributed to the human activity of hydropower use.

Thirdly, marine biodiversity and state indicators for the marine ecosystem components of CS8 are presented (Box 6). This example represents a data-poor case strongly underlining the need for further efforts in ecosystem monitoring to provide a robust assessment of ecosystem state. In this example, a biodiversity index and data on conservation status of two species were used to investigate biodiversity trends as well as the current ecosystem state. Interestingly, the information used gave contradicting outcomes: while in official data there is no negative trend, there are indications that biodiversity in the Azores is in fact declining (with high levels of uncertainty). However, major data gaps on the actual species present, their number and abundance in the CS area, make it difficult to assess the state. Data gaps also mean that trends in biodiversity loss are not measured, and therefore, trends cannot be determined quantitatively. However, local stakeholder groups (recreational fishers, commercial fishers, and scientists) anecdotally report decreasing fish stocks (AQUACROSS 2018).

This example therefore underlines two important aspects to be considered in the assessment of ecosystem state: (1) definition of reference conditions. The MSFD established reference condition from the year 1995 seems inappropriate, as fisheries very probably have already changed the ecosystem fundamentally by this time; (2) Consideration of stakeholder knowledge on changes in populations when quantitative monitoring data is missing.

Box 4: Mapping ecosystem state in the International Biosphere Reserve of the Mediterranean (IBRM)

In the Spanish side of the IBRM, conservation status was based on Habitats of Community Interest (Natura2000), according to the local partner (REDIAM information platform; Regional Environmental Government of Andalusia) demand, whereas in Morocco and for the marine habitats within the IBRM area, we used EUNIS habitat classification. Habitat conservation status in Spain was derived from three main different parameters ranging between 1-3:

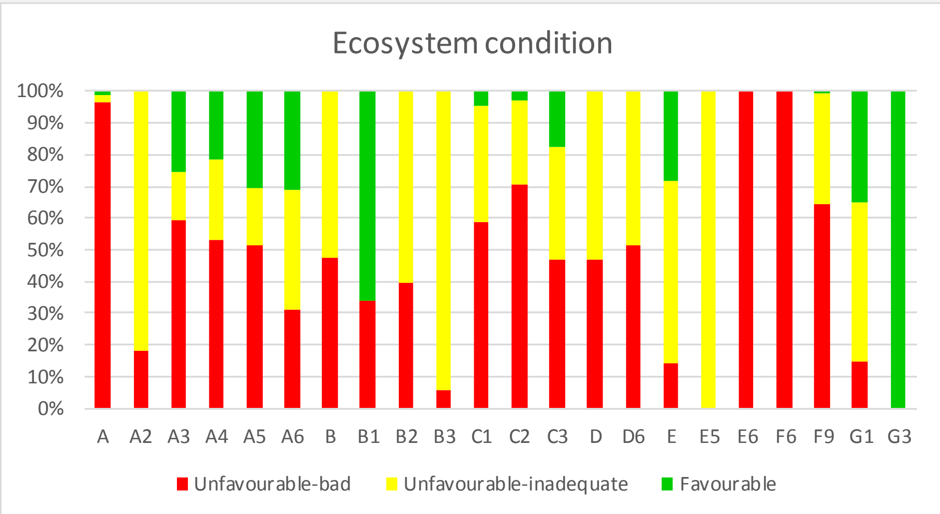
- Area where the habitat occurs within the range (i.e. Andalusia region)
- Structure and function of the habitat
- Future prospects for the habitat

We considered three different classes of conservation status for all kinds of habitats, as 'Favourable', 'Unfavourable-inadequate' and 'Unfavourable-bad'. A detailed protocol to classify the conservation status is found in D9.2.

For habitats located in Morocco, spatial information of the human footprint index was used and transformed into a proxy of ecosystem condition, assuming a strong causal relationship between pressures and ecosystem condition (Maes et al. 2018).

Results showed that aquatic habitats of community interest were only 1% of all habitats in Spain. The proportion of habitats at an unfavourable conservation status was similar in both countries (about 65-70%)(Figure 10). However, only 26% of the habitats were classified at an unfavourable-bad conservation status (n=34,381). Habitats with the largest surface area in bad ecosystem condition were marine habitats, heathland and shrub related habitats, and inland salt steppes.

Figure 10: Relative ecosystem condition per each habitat in the IBRM



Box 5: Using fish-based indicators to assess the impact of hydropower plants on the ecosystem state of rivers

Due to several environmental effects, HPPs alter the aquatic habitats with cascading impacts on stream biota. Here, we aimed to shed light on this cascade. Using reference and impacted sites, change in the abundance and community structure of fish in response to hydropower impacts was assessed. Based on literature search information (see Annex B), the presence and dominance of fish species was collected for Romanian river reaches before the construction of HPPs for 55 sites. The database was completed by data provided by personal communication from the experts who published the mentioned studies (Bănăduc pers. Comm.). Out of the 55, 32 HPPs were located in the trout zone (Bănărescu 1964) where brown trout (*Salmo trutta fario*) and European bullhead (*Cottus gobio*) are the dominant fish species under reference conditions.

The results confirmed that the two fish species brown trout and European bullhead were characteristic for the trout zone. Brown trout was found in the reference state (based on the historic data) in all 32, and bullhead in 21 (60%) sites. Analyses of presence-absence data revealed that among the latter 21 sites, harbouring both species in the reference state, only in 38% did both species remain after the construction of the HP plants. In total 24% - 43% of the sites lack one fish species, and 62% lack both fish species (Figure 11), linked with reduced dominance (Figure 12).

Figure 11: Comparative analyses of presence-absence fish data
Among the 21 stations harbouring both fish species in the reference state with upstream and downstream reaches of hydropower plants

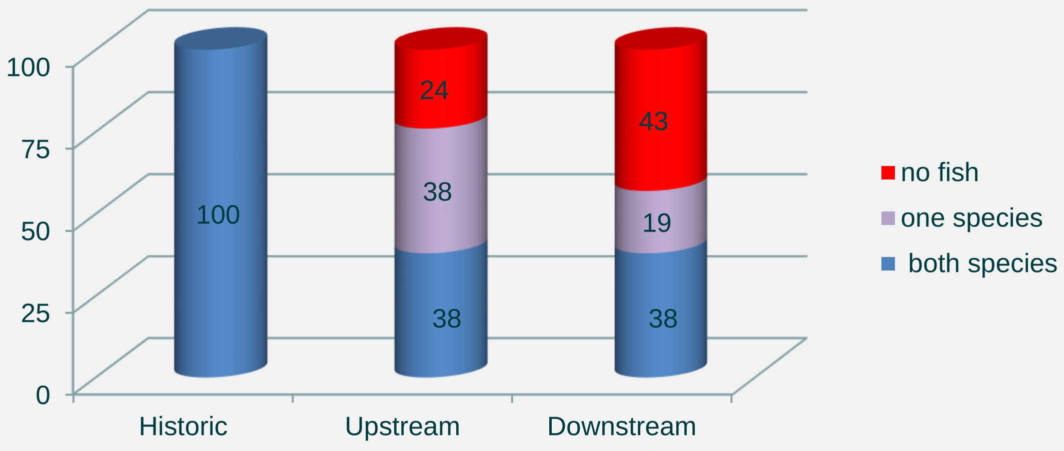
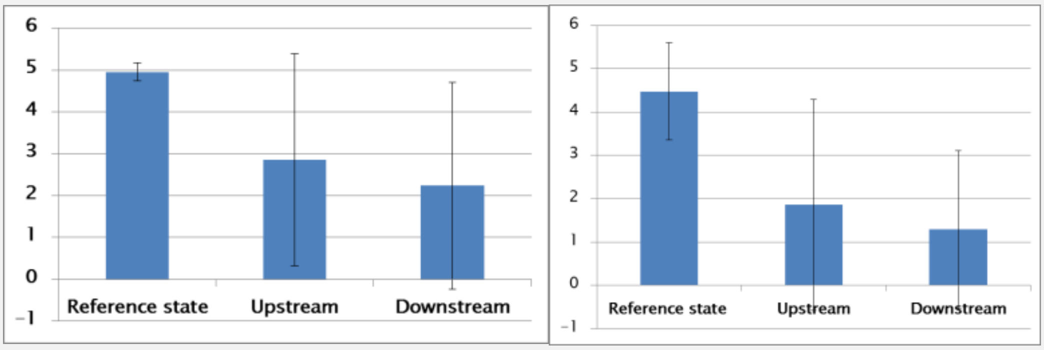


Figure 12: Dominance (average and standard deviation) of trout (*Salmo trutta*) (left) and bullhead (*Cottus gobio*) (right).



Dominance values were coded as follows: ED – eudominant (> 20% number) = 5, D – dominant (10 – 20%)= 4, SD – subdominant (4 – 10)= 3, R – recedent (1 – 3%)= 2, SR – subrecedent (< 1%)= 1, EX-extinct from that river streach = 0

Box 6: Ecosystem state indicators to describe biodiversity under data-scarce conditions

Detailed data from ecosystem monitoring were not available in CS8. Due to these data restrictions, all available information was combined to assess the ecosystem state. Besides the number of commercial fish species and the Simpson diversity, the conservation status of the bird species Monteiro's storm petrel and the bottlenose dolphin were used for the analyses.

At the local level, the available Faial-Pico Channel data showed that population indices are falling for target commercial coastal species in the Channel (Afonso et al. 2014), which is confirmed by anecdotal stakeholder reports (AQUACROSS 2017). Fish species abundances and diversity have been assessed in the Faial-Pico Channel since 1997 in visual censuses and partially been used for assessments for several biodiversity indices (see Schmiing et al. 2014) (Figure 13).

Commercially exploited fish and shellfish populations have been assessed for MSFD descriptor 3 (commercial fish and shellfish) referring to a baseline in the year 1995, the beginning of many monitoring campaigns for commercial fish. However, at this reference point Azores fishing resources had already borne decades of intense exploitation. The assessment of the MSFD descriptor 3 concludes that all assessed commercial fish species are in a good environmental status, just indicating that the state has not significantly worsened since 1995 (Governo dos Azores 2014).

Based on Bottlenose dolphin data, biodiversity and ecosystem state is worse than in the 1950s and even 1980s, but still remains in a moderate to high state.

Table 11: Selected metrics and indices per indicator related to environmental state in the Faial-Pico channel

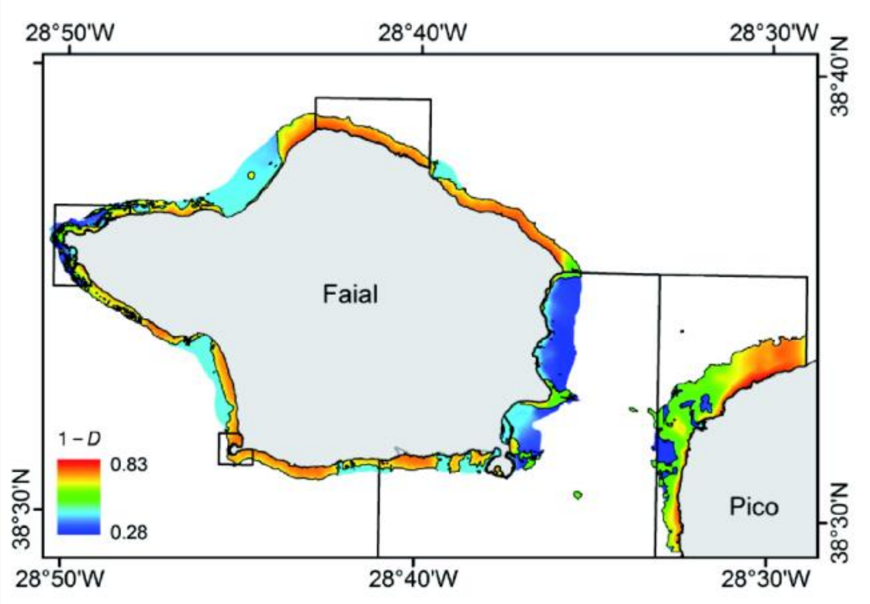
Species	*Metric*	*Indicator*	*Source*
Fish indicators			
Commercial fish	Commercial fish taxa	No. of commercial fish taxa (57 in (Schmiing et al. 2014).	Schmiing et al. 2014, Assessing hotspots within hotspots to conserve biodiversity and support fisheries management
Simpson diversity index (1 – D)	Method to study diversity amongst species	Simpson diversity is weighed towards the most abundant species and is sen-sitive to changes in common species.	Schmiing et al. 2014, Assessing hotspots within hotspots to conserve biodiversity and support fisheries management
Birds as indicators under Descriptor 1[1] of the MSFD			
Oceanodroma monteiroi (Monteiro's storm petrel)	Conservation status Painho-de-monteiro	Conservation status assessed by national authority according to MSFD	*SRMCT (2014). Estratégia Marinha para a subdivisão dos Açores. Diretiva Quadro Estratégia Marinha. Secretaria Regional dos Recursos Naturais. Outubro de 2014*
Habitats Directive Annex II (Marine mammals and reptiles)			
Tursiops truncatus (Bottlenose dolphin)	Conservation status	Conservation status according to HBD	Counts for MSFD assessment under Descritpor D1 (Biodiversity)

The results underline that the Faial-Pico Channel needs a consistent monitoring of biodiversity as well as of commercial and non-commercial fish and other aquatic organisms. Without these data, robust assessments to support ecosystem-based management seem impossible. The understanding of biodiversity trends and the correct evaluation of the current state are essential for setting and implementing policy targets.

These targets are in turn essential to measure the effectiveness and efficiency of environmental protection measures.

[1] Biodiversity is maintained. The quality and occurrence of habitats and the distribution and abundance of species are in line with physiographic, geographic and climatic conditions prevailing.

Figure 13: Predicted spatial distribution of Simpson diversity of coastal fishes in the existing marine protected area network



Coastal fishes refer to subtidal habitat down to 40 m depth, existing marine protected area network indicated by black rectangles for 2 islands of the Azores archipelago. The outline of the rocky substrate is shown as a black contour.

3.4 Modelling approaches

Besides the characterisation of the D-P-S elements by indicators and spatial information about their presence, the methodical approach to investigate their relationships plays a vital role to assess complex social-ecological systems and the impact on ecosystem components.

This chapter addresses different approaches taken in the AQUACROSS CSs to deepen the understanding of D-P-S relationships. In general, the CSs applied tools that have been proposed in D4.1, depending on availability and quality of the data. Fully data based, quantitative approaches were used in CS3 and CS7 where adequate data was available. In data-scarce situations, qualitative approaches were used (CS4, 6, 8). This chapter clearly mirrors the diversity of conditions found in the AQUACROSS CSs and the necessity to consider these differences to approach demand-side analyses. These differences are summarised in Table 12.

Table 12: Overview of qualitative/semi-quantitative and quantitative methods in the AQUACROSS case studies

Methods used in the AQUACROSS case studies				
CS	**CS name**	**Qualitative/semi-quantitative – stakeholder driven**	**Quantitative – data driven**	**Source**
1	North Sea	Linkage framework	Risk-based approach consisting of single impact chains of causal links	Borgwardt et al. (2019) (see Annex C), Piet et al. (subm.)
2	IBRM	Linkage framework	Cumulative pressure index (additive method)	Borgwardt et al. (2019) (see Annex C)
3	Danube	Linkage framework	Bayesian Networks (BBN)	Borgwardt et al. (2019) (see Annex C), Funk et al. (in print)
4	Lough Erne	Linkage framework, Fuzzy Cognitive Mapping (FCM)		Borgwardt et al. (2019) (Annex C), Robinson et al. (subm.)
5	Aveiro	Linkage framework		Borgwardt et al. (2019) (Annex C)
6	Ringsjön	Narrative approach: SE-AS (social-ecological action-situations) framework		
7	Swiss Plateau	Linkage framework	Bayesian Networks (BBN)	Borgwardt et al. (2019) (see Annex C), Kuemmerlen et al. (2019)
8	Azores	Linkage framework, Narrative approach		Borgwardt et al. (2019) (Annex C)

Data-driven approaches incorporated Bayesian network models (Box 7) and trait-based distribution models (Box 10). Stakeholder driven approaches used a Fuzzy Cognitive Mapping (Box 8), as well as a social-ecological action-situations framework (Box 9).

Box 7: Quantitative analyses of causal relationships between human activities, pressures and ecosystem components based on Bayesian network approach in the Danube River

In this example stemming from CS3, a quantitative approach was applied specifically focusing on the navigable main stem of the Danube River, where the interactions of several human activities and pressures related to hydromorphological alteration, are quantified. Following the D-P-S sequence (Table 14) different metrics were selected and analysed within a quantitative Bayesian Network approach following Friedman (1999). Finally the results were compared to the existing knowledge. As the data set was small, we used a score-based structure learning algorithm to analyse the causal structure within the network of interactions between driver, pressure and state variables (N=397 for D-P data and approx. 50 for P-S data). A bootstrapping approach was used to estimate the importance of the possible links in the network and give a probability for certainty of potential links and knots using the approach of Friedman et al. (1999). The search procedure is used in hill-climbing search with random restarts.

The results (Figure 14) showed multiple causal relationships between the different D-P elements. These relationships were generally in good concordance with actual knowledge, thus, providing a proof for the good representability and sensitivity of the metrics and validity of the network approach. Based on the network approach, interrelation of activities related to navigation, renewable energy production, agriculture and environmental engineering were related to pressures and ecosystem components. Accordingly, trade-offs and synergies between these activities that are using the ecosystems and their services including abiotic outputs and the conservation of biodiversity were possible.

Figure 14: Resulting Bayesian Network of the D-P components including causal links calculated via bootstrapping following the approach of Friedman et al. (1999).

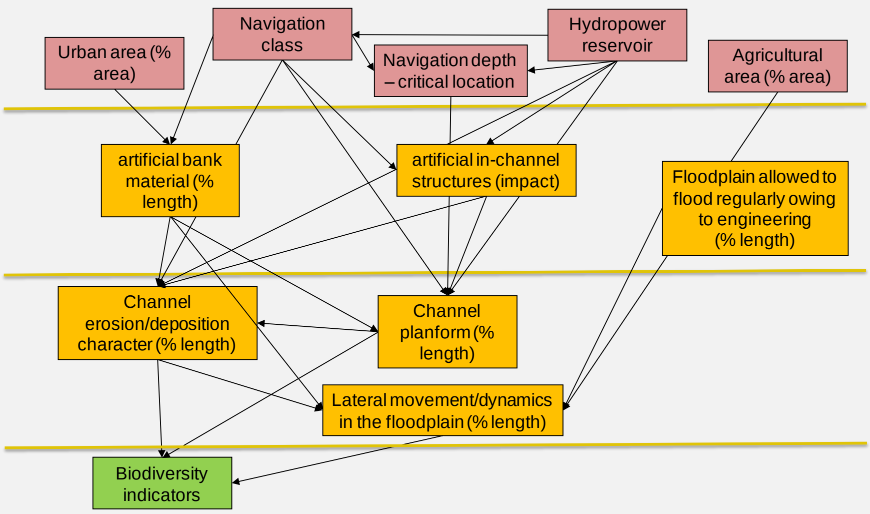


Table 13: Selected metrics and indices per indicator related to hydromorphological (HYMO) alterations considered in the modelling approach

Driver			
Hydropower	river stretch situated within the reservoir area upstream of a hydropower plant	impact of hydropower plant	https://danubis.icpdr.org/
navigation1	navigation class according to the "Classification of European Inland Waterways"	status of waterway	(Economic Commission for Europe, 2012)
navigation2	critical locations for inland navigation where the fairway depth of 2.5m at Low Navigable Water Level was not achieved	status of waterway	(Fairway, Danube, 2014, 2016)
urban	percentage of the potential floodplain area covered by urban structures	Land cover/Land use	Copernicus Land Monitoring Services (land.copernicus.eu)
agriculture	percentage of the potential floodplain area covered by agricultural land	Land cover/Land use	Copernicus Land Monitoring Services
Pressure			
Bank stabilisation	Extent of reach affected by artificial bank material (% of bank length)	HYMO assessment	Schwarz, 2014
planform	Planform of the River channel	HYMO assessment	Schwarz, 2014
Erosion deposition	Erosion/deposition character	HYMO assessment	Schwarz, 2014
Engineering structures	Impacts of artificial in-channel structures within the reach (impoundments, groynes)	HYMO assessment	Schwarz, 2014
flooding	Degree of lateral connectivity of the river and the floodplain (extent of floodplain excluded from floods due to dykes)	HYMO assessment	Schwarz, 2014
connectivity	Lateral movement of the river channel	HYMO assessment	Schwarz, 2014

Box 8: A Fuzzy Cognitive Mapping (FCM) for identifying and prioritising human activities, pressures and changes in ecosystem state in Lough Erne

Fuzzy Cognitive mapping (FCM) was used in the Lough Erne case study to assess the social-ecological system. In FCM positive and negative relationships can be implemented, which are also recorded in a matrix. FCM provides an approach to model system behaviour by manipulating individual system components to explore the effects on the rest of the system. It is a strength of FCM is that nearly all types of information can be included, such as views of multiple stakeholder groups.

The Lough Erne CS addresses different stakeholder groups that have an interest in the services and outputs provided by the ecosystem. Thus, a FCM approach was applied to identify stakeholder knowledge and to understand the stakeholder view on the system.

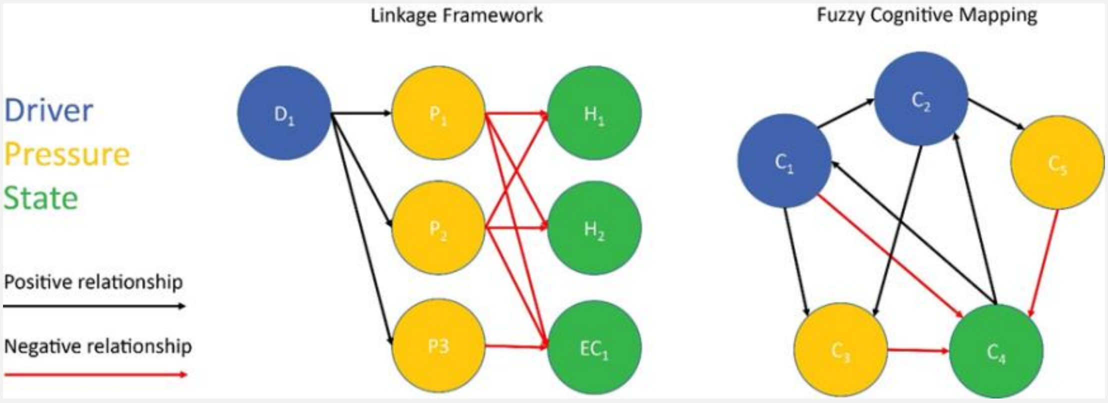
Furthermore, the relationships identified by the stakeholders were used to test the relevance and validity of the more theoretical linkage framework approach.

Data for the FCMs were collected during a stakeholder workshop with 22 stakeholders representing a variety of interests who attended the meeting. FCMs were built on the basis of homogenous stakeholder groups, such as hydropower representatives, or conservation and ecosystem managers.

The FCM maps were generated by starting with a particular element of the socio-ecological system which interfered with the objectives of specific groups (see Blincow 2017), the specific components were agreed by the groups and acted as a starting point for the FCMs. The facilitators used the DPSIR as an organisational frame to elicit connections from participants (though the DPSIR was not directly explained to the workshop participants). Each FCM was written on a whiteboard and all links between all nodes identified were considered and assigned a positive (+) or strongly positive (++), negative (-) or strongly negative (--) weight.

Following the workshop, the maps for each table were digitised using Mental Modeller software. The FCMs of each table were combined to a joint, overall FCM of the whole group (called the JOINT FCM). For the final consensus map, the weight of each connection was determined by adding the weights of all connections from each contributing map. For comparative analysis between the FCM and linkage framework, the concepts and attributes of the JOINT FCM were used (Figure 15).

Figure 14: Comparison of the Linkage Framework and Fuzzy Cognitive Mapping (FCM)



The linkage framework takes a linear perspective connecting nodes from Human activities (Blue) through Pressures (Yellow) to Ecosystem Components (Green). In FCM linkages between nodes can run in both directions, and the signs of the relationships between nodes is weighted.

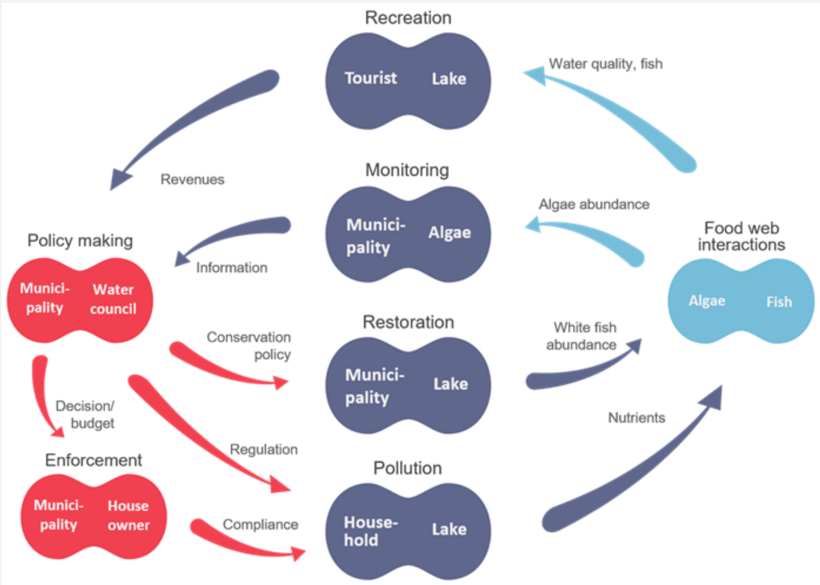
Box 9: Assessing the current state of the social-ecological system in Lake Ringsjön

In this example a social-ecological action-situations framework (SE-AS) was applied to develop a hypothesis about key social-ecological interactions required to enable a successful lake restoration. Lake Ringsjön was evaluated as turbid in the 1970's and resembles a classical example of a shallow lake that has undergone a regime shift (Scheffer 1990).

While multiple measures to reduce the nutrient load in the 1990's have been successful to reduce the nutrient concentration in the lake now, fish communities only recently started to recover (Nyström and Stenberg 2018). Hence, Lake Ringsjön is not yet in the stable clear water state but instead, it is on a trajectory towards it.

In this case, there is no single key social-ecological AS, but interactions between different actors and different aspects of the lake jointly influencing the success of restoration. First, there is the social-ecological AS of nutrient pollution by private lakeshore house owners (Pollution AS) that causes harmful algal blooms and changes the food web towards a dominance of commercially low valued fish species such as bream and roach. Once an awareness of the problem reached policy making, algal abundance was monitored (Monitoring AS) and the municipality and the water council (an expert and stakeholder committee for lake use) agreed on policies for nutrient regulation (Policy making AS). The successful implementation of the regulation, i.e. the installation of new sewage treatment technology as a high cost investment, however, depends on enforcement measures, and how individual house owners were involved in the regulation process (Enforcement AS) (Figure 16). Hence, the study focussed on regulating the release of ecosystem pressures and the expected improvements for water quality and dependent ecosystem services.

Figure 15: Conceptual interactions to explain the success of restoration of the turbid lake Ringsjön



Representation of the main social (red), eco-logical (light blue) and social-ecological (dark blue) interactions hypothesised to explain the success of restoration of the turbid lake Ringsjön.

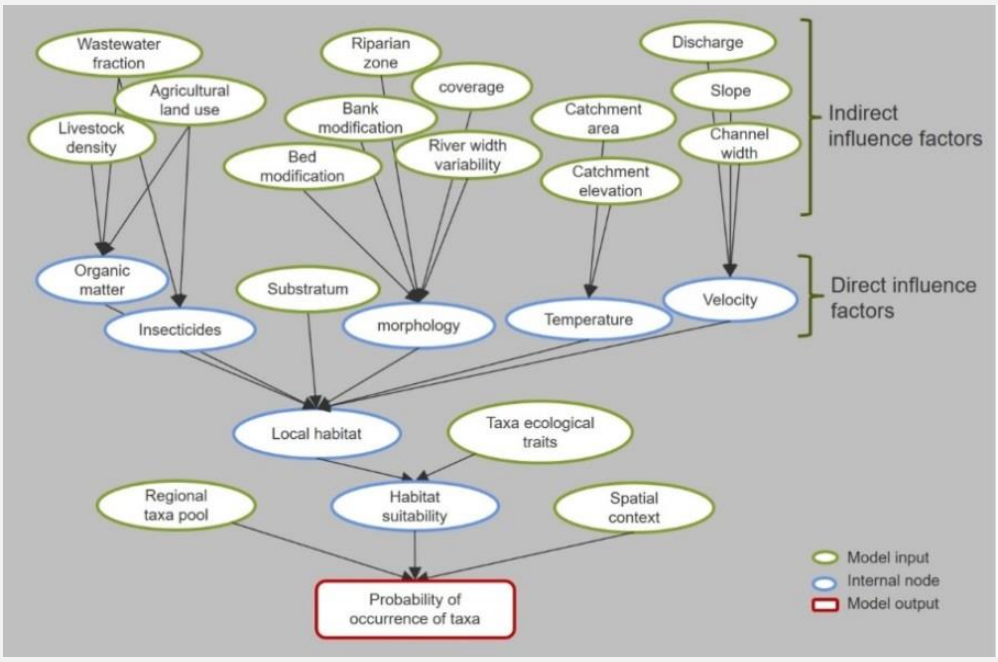
Box 10: Linking D-P-S elements through a trait-based approach to optimise restoration strategies in the Swiss Plateau

Starting from the linkage framework, most relevant activities and resulting pressures have been identified and quantitative data has been collected. In the analyses several pressures such as nutrient enrichment, contamination from micro pollutants and structural (morphological) modification of streams and rivers (e.g. channelisation and network connectivity) were used to predict the occurrence of invertebrate taxa.

Considered activities comprised those generating pollution through diffuse or point sources, such as agriculture, manufacturing and urbanisation, in addition to activities associated to infrastructure that modify or impair natural river structure including artificial flood control, hydropower generation and instream structures (Figure 17). These activities are strongly linked to the physical and chemical pressures used in the distribution models.

To quantify the effects of water quality, hydromorphology and temperature on the macroinvertebrates, a trait-based joint species distribution model was developed. The model makes use of prior knowledge of species' habitat requirements from ecological trait databases and monitoring data from a federal monitoring program (Vermeiren et al., in prep). While the different invertebrate taxa respond very differently to the various pressures, we found most pronounced effects from water quality and temperature (Vermeiren et al. in prep). For further analysis related to improving the restoration strategy in Switzerland, we pay particular attention to the physical, chemical and biological state of rivers at the reach scale, as well as to the ecological state at the catchment scale.

Figure 16: Schematic representation of the trait-based species distribution model for macroinvertebrate taxa and the relationships to direct and indirect factors influencing the occurrence (Vermeiren et al. in prep).



3.5 Conclusions based on the specific exploratory analyses

In this deliverable, the demand-side of the social-ecological systems was addressed by applying two approaches:

- the **linkage framework analyses** across all aquatic realms based in all CSs evaluating activities and pressures on a holistic scale. Further details for the conclusions can be found in Chapter 2.6
- a **specific exploratory analysis of case studies** by applying various qualitative and quantitative tools for analysing the linkages between drivers, pressures and ecosystem state.

The linkage framework built the starting point to characterise the social-ecological system in the CSs. The application of the linkage framework as the basis for the **exploratory analysis** offers the possibility to examine the complexity within the system and link it back to the elements of the D-P-S sequence that may have not been directly implemented into the quantitative analyses, as the relationships were identified by the impact chains. Furthermore, it provides a common framework for categorising a problem domain, along the cause-effect chain. This allocation of problem domains then enables assigning these problems to policy domains, also demonstrating the need for co-operations between several policy domains.

Importantly, results of D-P-S analyses have to be linked back to **social processes and economic activities**, such as agriculture, fishery, environmental management, waste management, residential & commercial development, services (incl. e.g. navigation), renewable energy, and to tourism & recreation. Our analyses revealed that the studied ecosystems were significantly affected by widespread and strong human pressures, such as chemical pollution, hydromorphological alteration and biological alterations.

Even though a broad variety of quantitative correlative **models** exist, focusing on the causal relationships of ecological components and human activities, it was difficult to apply them in all CSs because of the availability of adequate data. The fact that most CSs have used available driver data as a proxy to describe human pressures underlines this gap on real pressure information which was noticed in most CSs.

In some case studies the linkage framework was used as a starting point and further investigated to gain deeper insights into the social-ecological system by applying qualitative or **semi-quantitative approaches,** which do not directly rely on 'measured quantifications', such as fuzzy cognitive mapping (CS4-The Lough Erne), or mapping the activities, pressures and ecosystem state (CS2 – IBRM).

As the pressures identified in CSs are related to several policy sectors, analyses revealed that **political goals** on conservation and management of biodiversity and ecosystem services may only be reached if these goals are considered in other policy sectors too, such as agriculture, waste management, navigation, land use planning, renewable energy production, and tourism.

Harmonisation of these policies would have the potential of reducing immense trade-offs currently occurring due to the widespread fragmentation of the various policies.

These scientific results hence require an adaption of business strategies and social trends in order to exploit ecosystem services within the limitations of **sustainability**. In this context, results reported in this deliverable provide an **integrated knowledge basis** on the causal linkages influencing aquatic biodiversity and ecosystem services. Filling the demonstrated gap in information about human pressures on ecosystems would support taking more informed sectoral and inter-sectoral policy decisions. This could support policy strategies aiming to influence environmentally detrimental societal drivers by showing alleys towards integrated concepts for the conservation and development of biodiversity and ecosystem services.

3.6 Recommendations based on the use of D-P-S indicators and modelling approaches

The specific analysis performed for the AQUACROSS CSs covers all aquatic realms: freshwater systems (lotic and lentic) from the sources until the entry to the sea, coastal and marine, both protected and significantly altered aquatic ecosystems. It spanned systems over nearly 3 orders of magnitude in size ranging from ca. 110 km2 (Lough Erne) to 800 000 km2 (Danube basin).

Accordingly, the availability and type of data for use in analyses greatly differed. A variety of tabular or GIS data are available for the EU member states. However, the availability of data differs among countries, and is worse in non-EU member states, and might be bad even in a EU member state like Romania. Major gaps in data availability makes a homogenous assessment of human pressure across aquatic realms challenging, as well as the development of indices and metrics for the quantification of human activities, pressures and even more for the assessment of the ecosystem state. In the context of these practical challenges, the results elaborated by AQUACROSS may provide answers to several key questions of environmental management:

3.6.1 What are the most relevant socio-economic drivers affecting aquatic ecosystems in the case studies?

The most relevant socio-economic drivers exerting distinctive pressures on the aquatic ecosystem components in the CSs are summarised in Table 14. These analyses revealed that the **most relevant drivers** affecting aquatic ecosystems are related to human activity types (acc. to D4.1 Tab. 3 p.38) agriculture, fishery, environmental management, waste management, residential & commercial development, services (incl. e.g. navigation), renewable energy, and to tourism & recreation. These activities affect the various types of water bodies in different ways (Figure 17).

Table 14 Drivers, pressures and ecosystem components addressed by the AQUCROSS CSs in the **specific analyses**.

Case Studies	Drivers/Primary activities	Pressures	Ecosystem Components
CS2: Intercontinental Biosphere Reserve of the Mediterra-nean (IBRM)	Aquaculture, fishing, navigation, urban settle-ments, and recreational activities on the shores.	Changes of habitat structure and disturbance of species	11 ecosystem components covering coastal, freshwater and marine realms.
CS3a: Danube main stem	Interactions of several human primary activities: Navigation; Hydropower; Land cover/Land use	Hydromorphological alteration- a quantitative approach	Fish, amphibian and birds from the navigable section of the Danube
CS3b: Danube tributaries	Primary activity: hydropower	Hydromorphological alteration - quantitative/ qualitative analysis	Fish
CS4: Lough Erne-channels, nturally eutrophic lake	16 unique (aggregate) drivers, as tourism, agriculture, hydropower and regulation of levels	A qualitative analysis of 11 specific pressures	32 ecosystem components and characteristic comprised of habitats, species, water quality etc.
CS6: Lake Ringsjön - Rönne	Interactions of several human primary activities: agriculture, urbanisation	Nutrient pollution - eutrophication - qualitative analysis	Phytoplankton
CS7: Swiss Plateau rivers	Interactions of a selection of 16 human activities, as agriculture, manufacturing, urbanisation, etc.	A selection of 33 physical and chemical pressures - a quantitative analysis	Six selected ecosystem components (all riparian components)
CS8: Azores, Faial-Pico Channel	Tourism and fishing (commercial and recreational) primary activities	Extraction of fish by fisheries, marine litter, underwater noise and damage of seabed habitats - a quantitative analysis	Commercial fish species, dolphin, marine birds - a qualitative analysis

3.6.2 How do drivers link to environmental pressures?

As a key **approach** of this deliverable, the activity-pressure-ecosystem component linkage framework was elaborated for all CSs as a semi-quantitative approach that was applicable in all circumstances of the CSs. In order to base this framework on real data in the CSs, indicator variables were identified and tested in terms of their representability, sensitivity, validity and comparability within and between the CSs. For example, concerning the emerging driver of renewable energy production, various pressures exerted by hydropower production were disentangled and demonstrated, which may link this activity to ecosystem state documented in monitoring programs. As multiple pressures often affect the same ecosystem component at different spatial and temporal scales, Fuzzy Cognitive mapping (FCM) was applied to structure those influential factors according to their causal linkages. Thereby, such analyses were either supplemented or even fully based on stakeholder consultations and workshops, as stakeholders have crucial roles on the one hand in data collection and harmonisation, as well as in the validation of data, results and conclusions and finally for the implementation of results.

These **assessment approaches** in the various CSs mostly follows the analytical approach 'From pressures (and responses) to ecosystems' structures' represented in the AQUACROSS AF (see Deliverable 3.2, Fig. 9). The approach in CS6 on Lake Ringsjön basically followed a more socio-ecological analytical approach 'From drivers to pressures and responses'. The reason why work mostly followed the first approach was the relatively easy and consistent availability of data on drivers, pressures and ecosystem state. In contrast, data on ecosystem functions, ecosystem services and societal responses are more difficult to elaborate, thus are prone to mistakes and imprecision, and hence were not seen to be promising especially in large-scale case studies.

When evaluating the **current state of ecosystems** and their deficits, the precision and resolution of indicators for ecosystem state turned out to directly depend on data availability. In areas or sectors with low data availability, assessment has to remain coarse, and can only be achieved by use of modelling approaches, which may allow the inference of data gaps (see Chapter 4). Using a trait-based joint species distribution model, scientific knowledge of species' habitat requirements may be combined with monitoring data from a federal monitoring program in order to derive predictions of the effects of management measures.

3.6.3 How can drivers and pressures be best estimated at regional level?

Data availability concerning all levels of the causal chain differed greatly among case studies. Good data availability was available for the CS Swiss Plateau, where a spatially-explicit assessment was even possible for small and moderate-sized catchments (Kuemmerlen et al. 2019), for the Danube main steam river (CS3, for details see Funk et al., subm.), and for the Spanish part of Intercontinental Biosphere Reserve of the Mediterranean: Andalucia (Spain) – Morocco (IBRM) (CS2, for details see AQUACROSS data portal available under http://dataportal.aquacross.eu). Given the amount of information in various data layers, but the relative scarcity of information to understand the causal links between drivers, pressures, and ecosystem state, analytical approaches had to be adapted, and hence a variety of qualitative and quantitative approaches were applied.

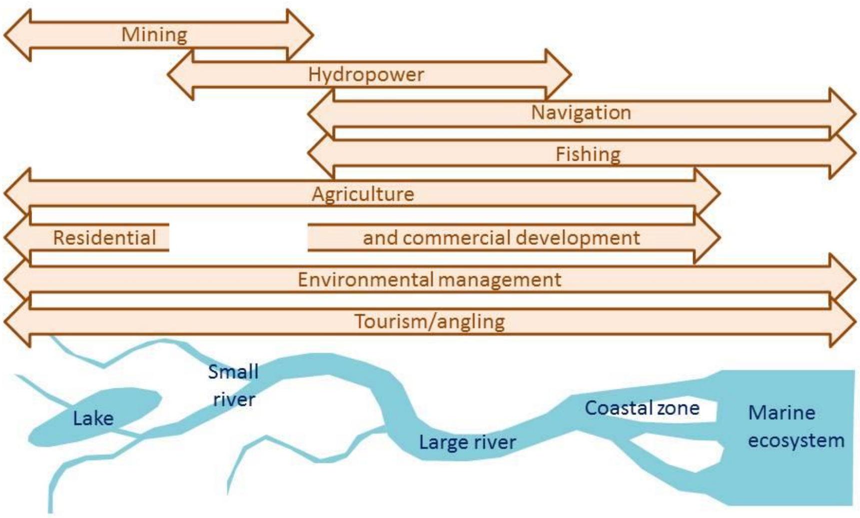
AQUACROSS has made progress in the challenge to move from descriptive to more analytical approaches. Thus, available knowledge on biodiversity, drivers and indicators could be adapted, re-scaled and made available for the specific applied assessments conducted in the CSs.

3.6.4 What can we conclude from applying and testing the AQUACROSS conceptual framework concerning ecological, social, and economic drivers and pressures?

In the various water body types studied in the case studies, according to the activity weighting and connectance in the linkage framework, a number of key major **human activities** could be identified that highly affect the various types of aquatic ecosystems (Figure 17).

- **Lakes** are affected by mining, agriculture, residential and commercial development, environmental management and by tourism/angling.
- **Small rivers** are affected by hydropower, agriculture, environmental management and by tourism/angling.
- **Large rivers** are affected by hydropower, navigation, commercial fishing, agriculture, residential and commercial development, environmental management and by tourism/angling.
- **Coastal ecosystems** are affected by navigation, commercial fishing, agriculture, residential and commercial development, environmental management and by tourism/angling.
- **Marine ecosystems** are affected by navigation, commercial fishing, environmental management and by tourism/angling.

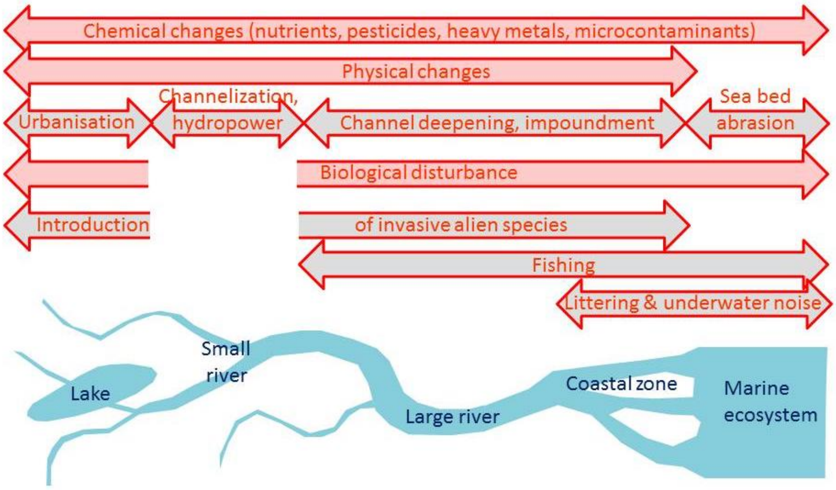
Figure 17: Human activities mostly affecting ecosystem types in the AQUCROSS case studies. Interruption of arrows indicates that this activity is not dominant in the respective water body type.



The results obtained by case studies on dominant human **pressures** affecting aquatic ecosystems show that human activities leading to chemical and physical changes affect nearly all aquatic ecosystems across the aquatic realms (Fig. 18). Additionally each type of aquatic ecosystem is affected by specific typical pressures exerted by typical human uses.

As a result of the listed human activities, the following key human pressures could be identified in the same way that affect the status of the various types of aquatic ecosystems ecosystems (Figure 18).

Figure 18: Pressures mostly affecting ecosystem components in the AQUACROSS case studies. Main pressures (red arrows) are partially subdivided into specific pressures (grey arrows below them) for certain water body types.



Interruption of arrows indicates that this pressure is not dominant in the respective water body type.

- **Lakes** are affected by eutrophication, urbanisation, and arrival of invasive species.
- **Small rivers** are affected by macro- and micropollutants, morphological alterations (incl. channelisation and interruptions of network connectivity) and several effects of hydropower use.
- **Large rivers** are affected by eutrophication, macro- and micropollutants, several effects of impoundment for hydropower and navigation purposes, land use, urbanisation, and flood protection, as well as by invasive species.
- **Coastal ecosystems** are affected by by eutrophication, macro- and micropollutants, several effects of navigation (including navigational dredging), and by fishing and littering.
- **Marine ecosystems** are affected by eutrophication (in shallow coastal seas), by several effects of navigation and tourism, as well as by fishing (incl. abrasion of the seabed), noise pollution and littering of mostly plastic waste.

3.6.5 Potential applicability of the methods and results

The key drivers, activities and pressures identified in AQUACROSS case studies are often linked to **EU policies**. Hence, the achievement of policy goals concerning the protection of biodiversity and ecosystem services of aquatic systems much depend on the harmonisation of other policies with adverse environmental effects (see D2.1, section 4.7 and table 10) with EU environmental policy, especially of:

1 **EU common agricultural policy (CAP**) providing financial support so far mainly through pillar I for crop production,

2 **Directive (2009/28/EC) on the Promotion of the Use of Energy from Renewable Resources**, together with the Regulation (1305/2013) on support for rural development by the European Agricultural Fund for Rural Development which promotes energy crops, and together with the Fuel Quality Directive (2009/30/EC) promoting biofuel production,

3 **Regulation (1301/2013) on Regional Development Funds** which supports urbanisation and tourism,

4 **EU Renewable Energy Directive** supporting small hydropower plants with negligible contribution to energy supply but large environmental damage),

5 **TENT-T** and other plans to improve navigation in rivers where natural channel depths are partially smaller than desirable for a most economic navigational transport with large and fully loaded vessels.

Hence, results indicate that there is a need for an inter-sectoral planning and management approach for the use of land, fresh and marine waters, which considers the whole variety of political and business goals pursued by political sectors and stakeholders. Thereby, the application of the linkage framework offers the possibility to examine the complexity and connectivity in the aquatic ecosystem, and also provides a framework for categorising a problem domain along the cause-effect chain, which could be used as a policy-oriented tool.

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Annex A

Supplemental information of the linkage framework on connectance for activities, pressures and ecosystem components in the AQUACROSS case studies (Figures 19–38) and details on weights of impact chains for adiitional human activities (Tables 15 –19)

Figure 19: Connectance of Activities in CS1.

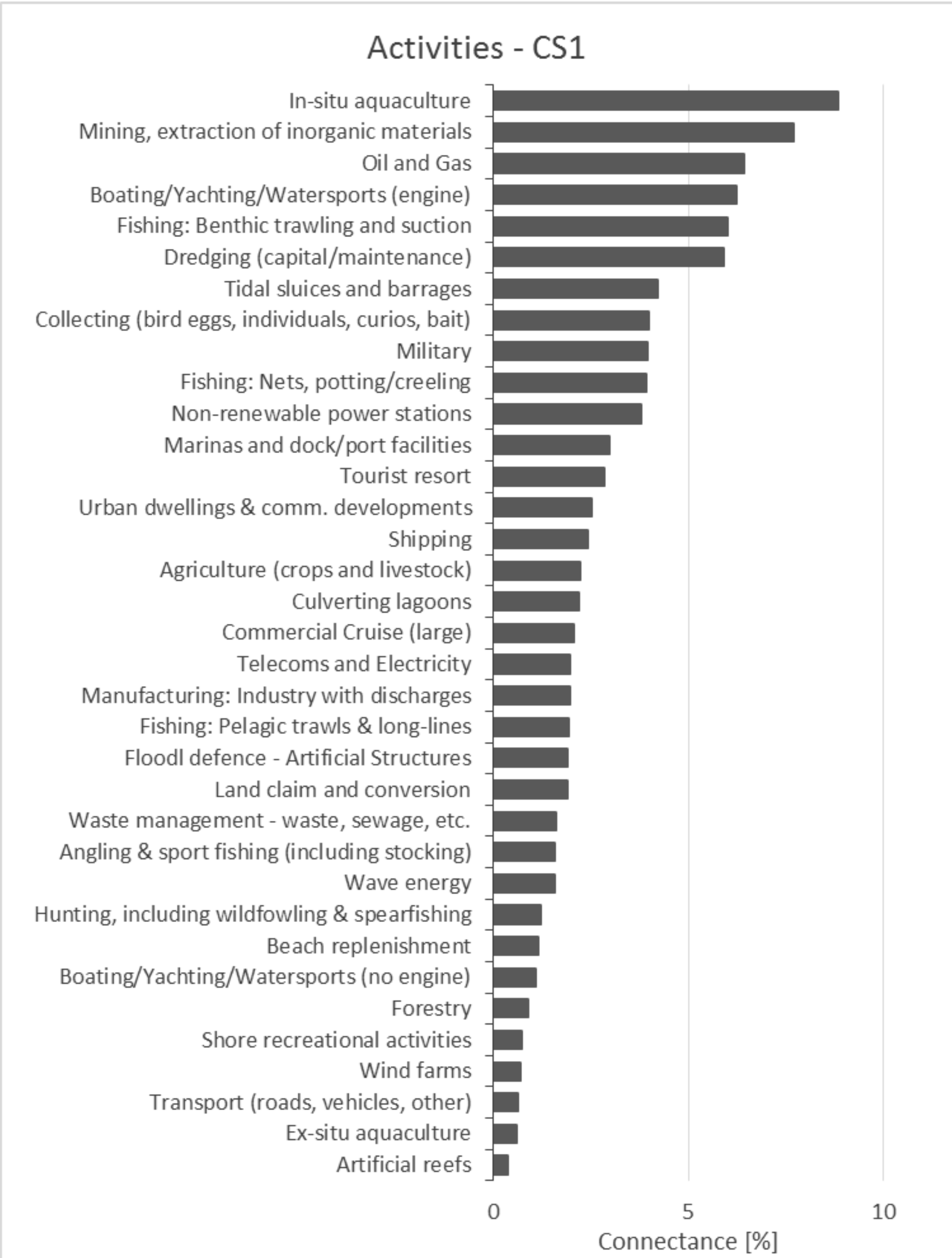

Figure 20: Connectance of Activities in CS2.

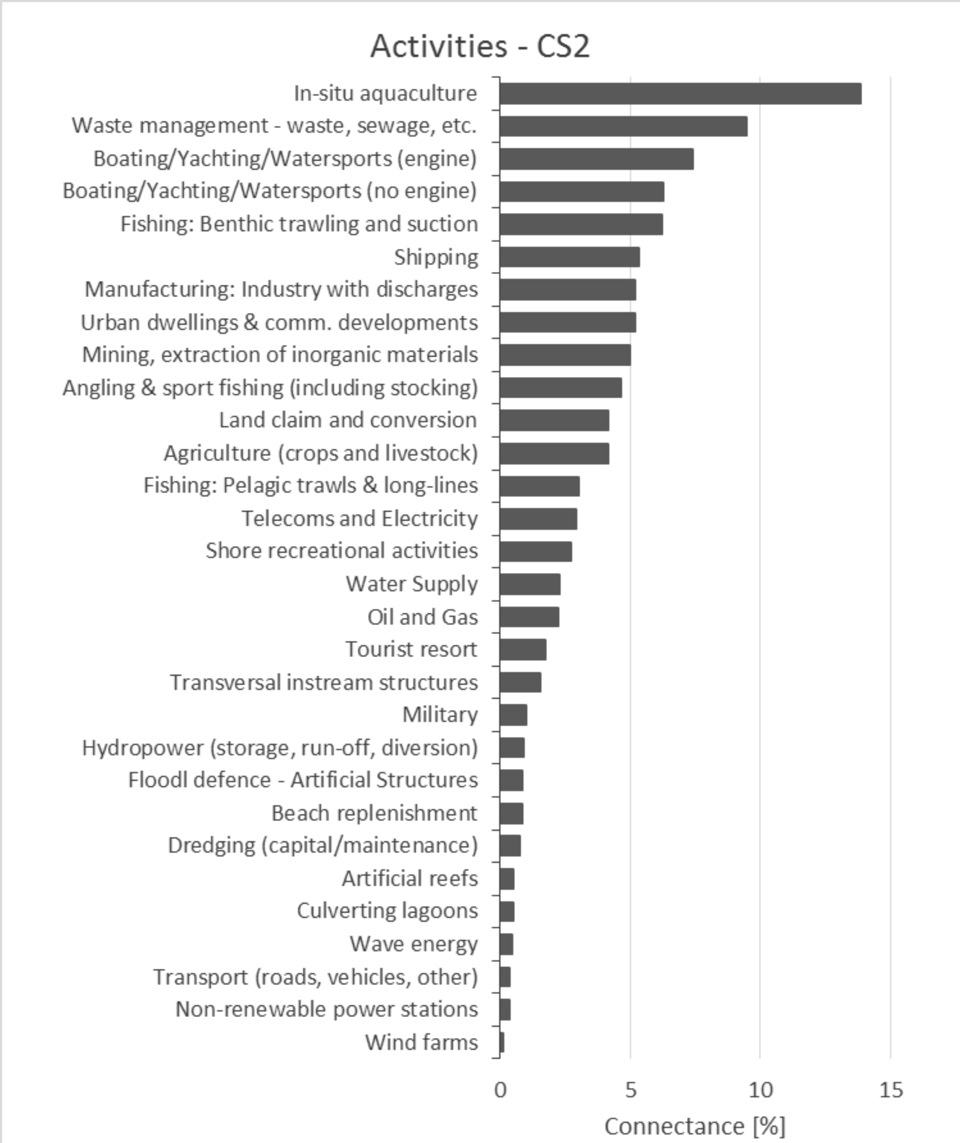

Figure 21: Connectance of Activities in CS3.

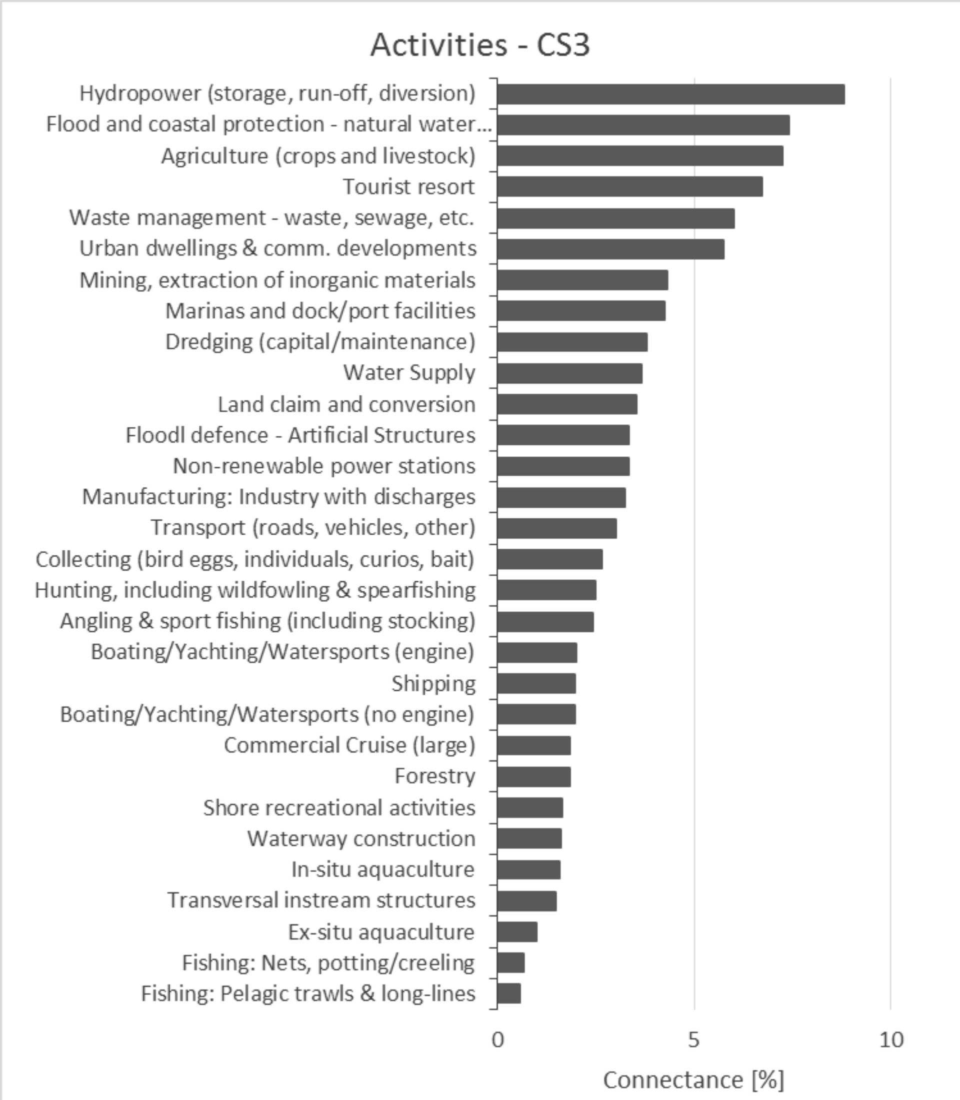

Figure 22: Connectance of Activities in CS4.

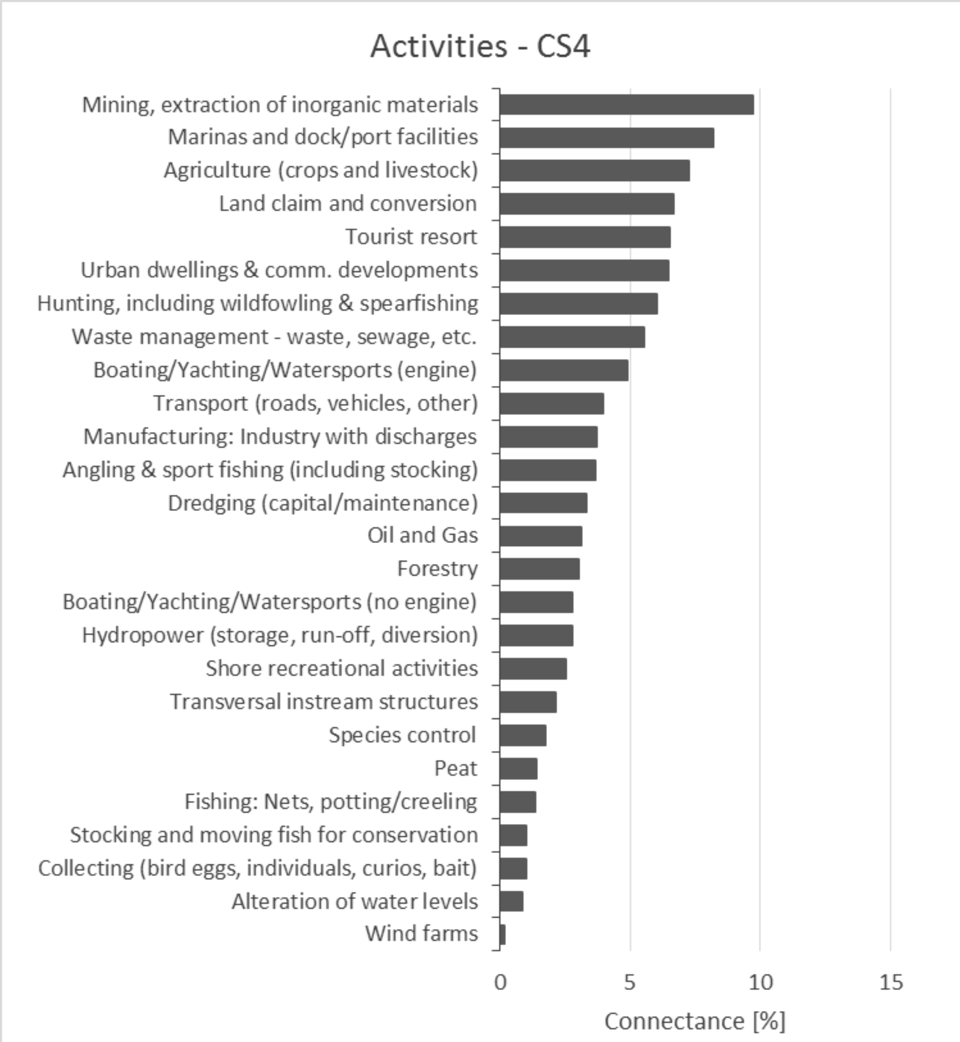

Figure 23: Connectance of Activities in CS5.

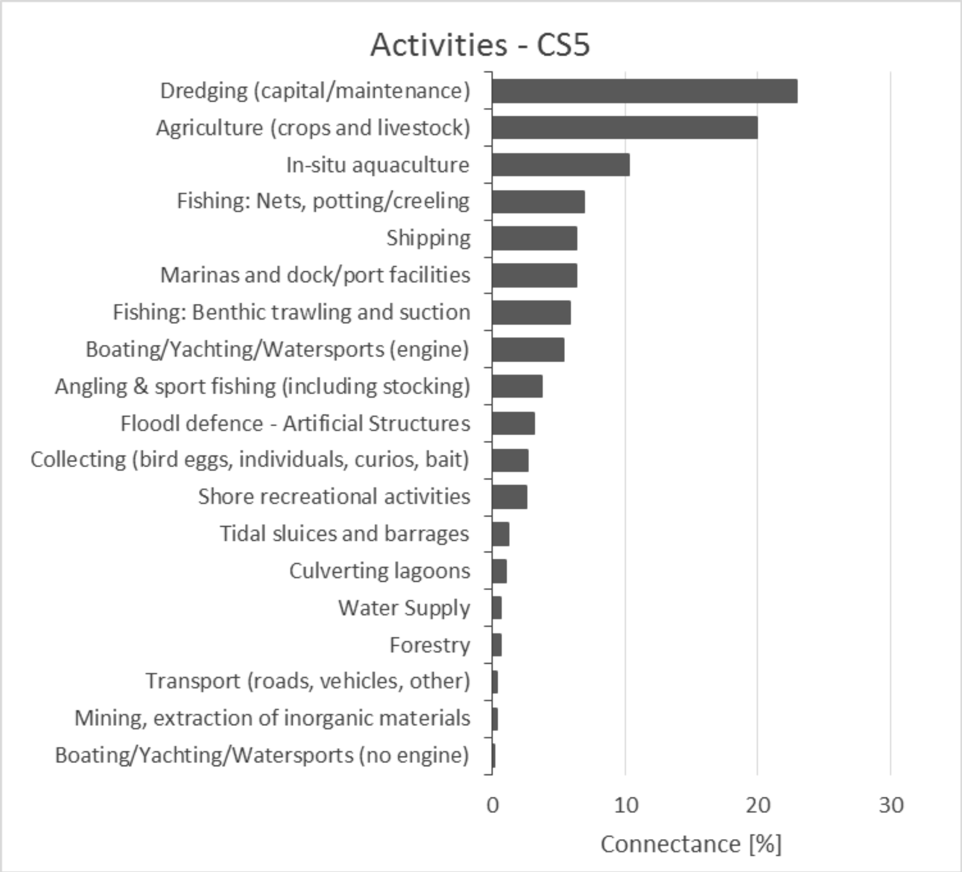

Figure 24: Connectance of Activities in CS7.

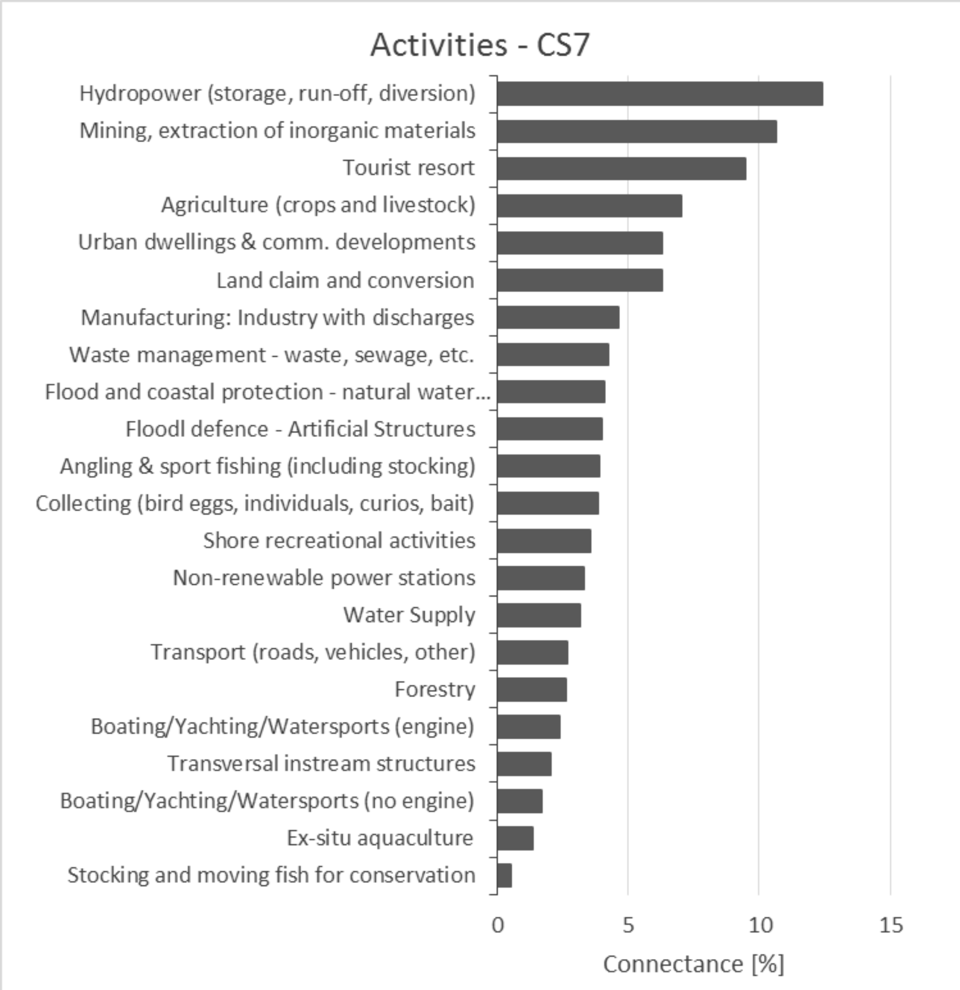

Figure 25: Connectance of Pressures in CS1.

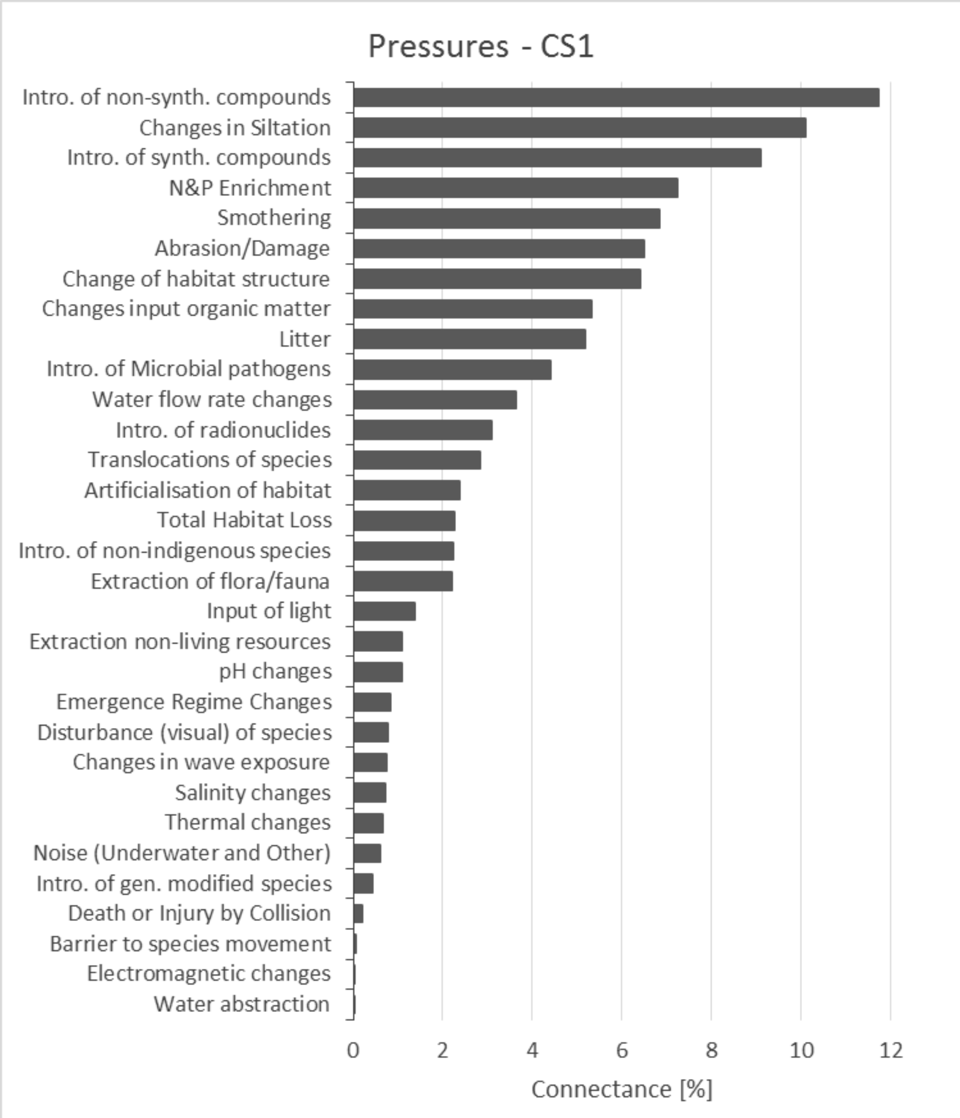

Figure 26: Connectance of Pressures in CS2.

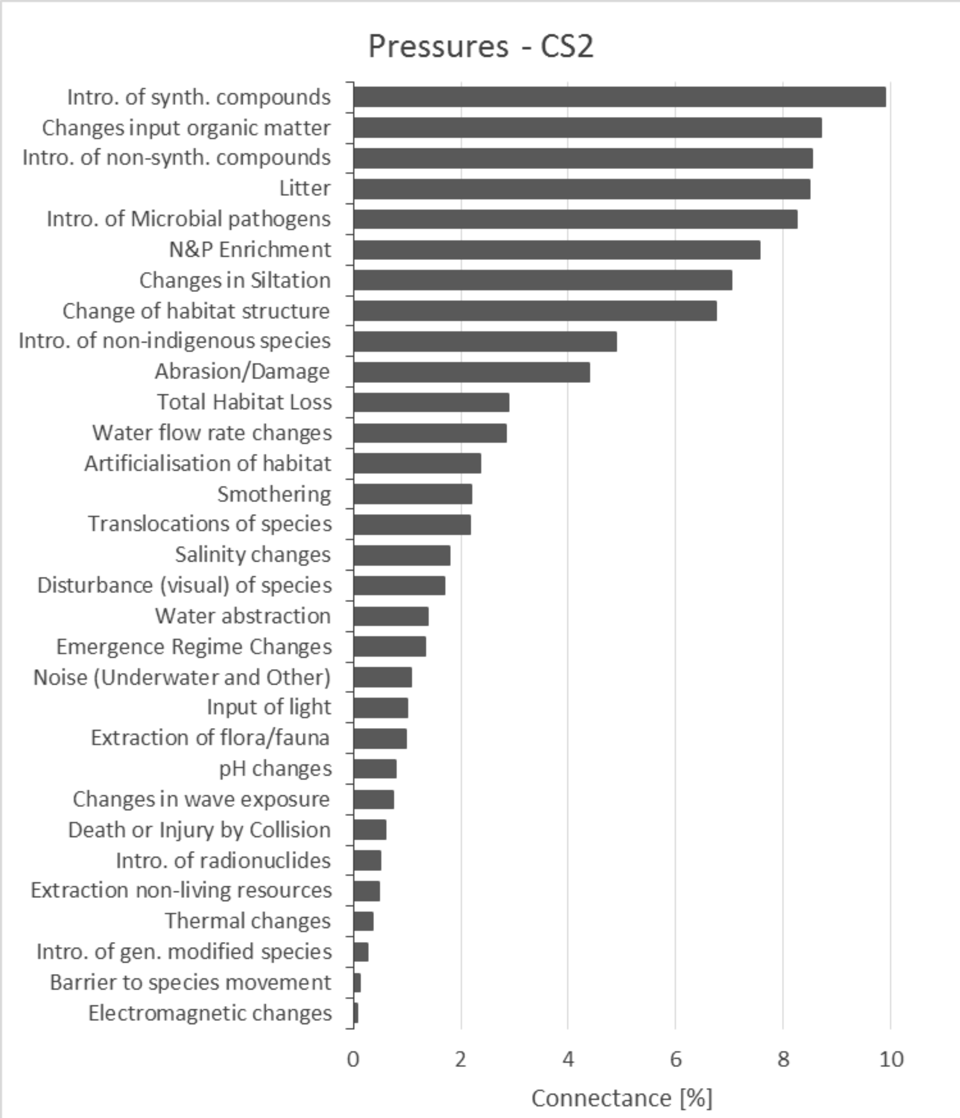

Figure 27: Connectance of Pressures in CS3.

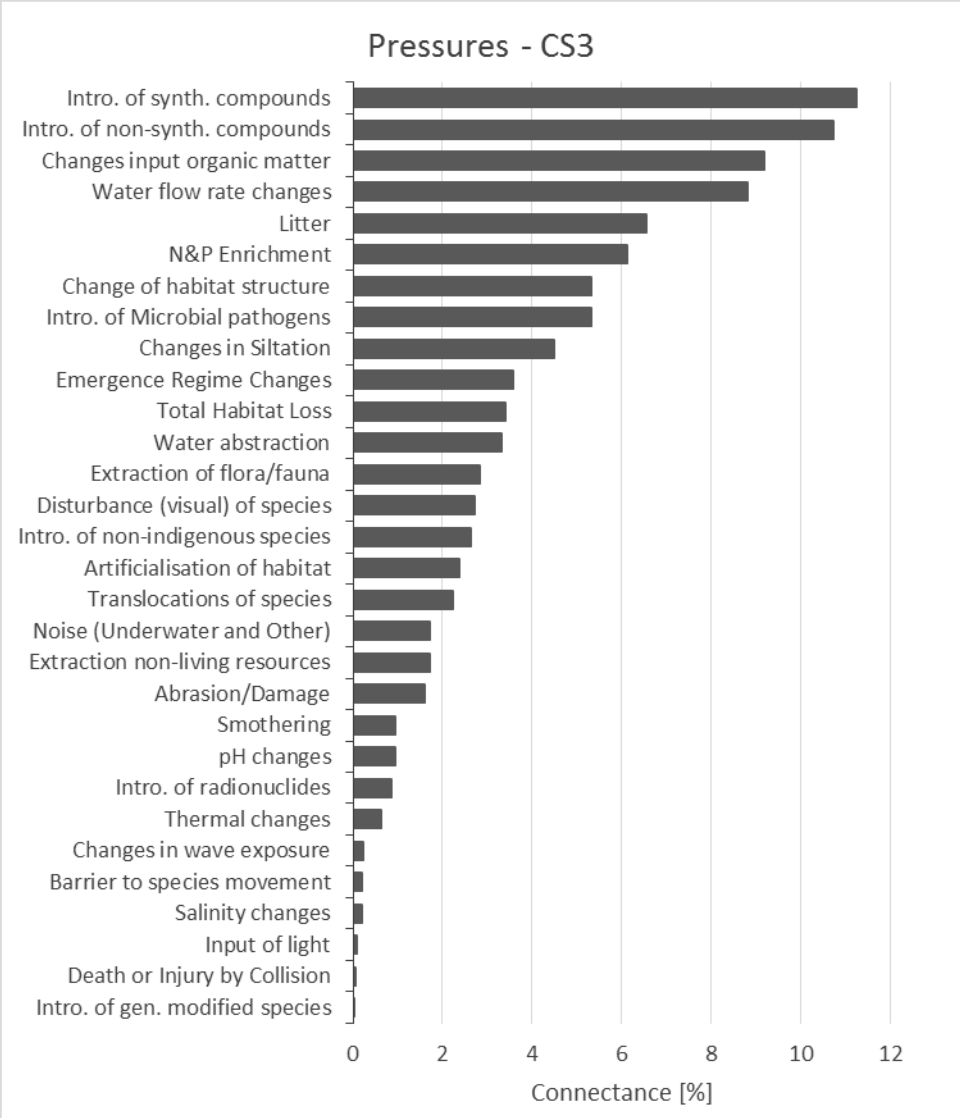

Figure 28: Connectance of Pressures in CS4.

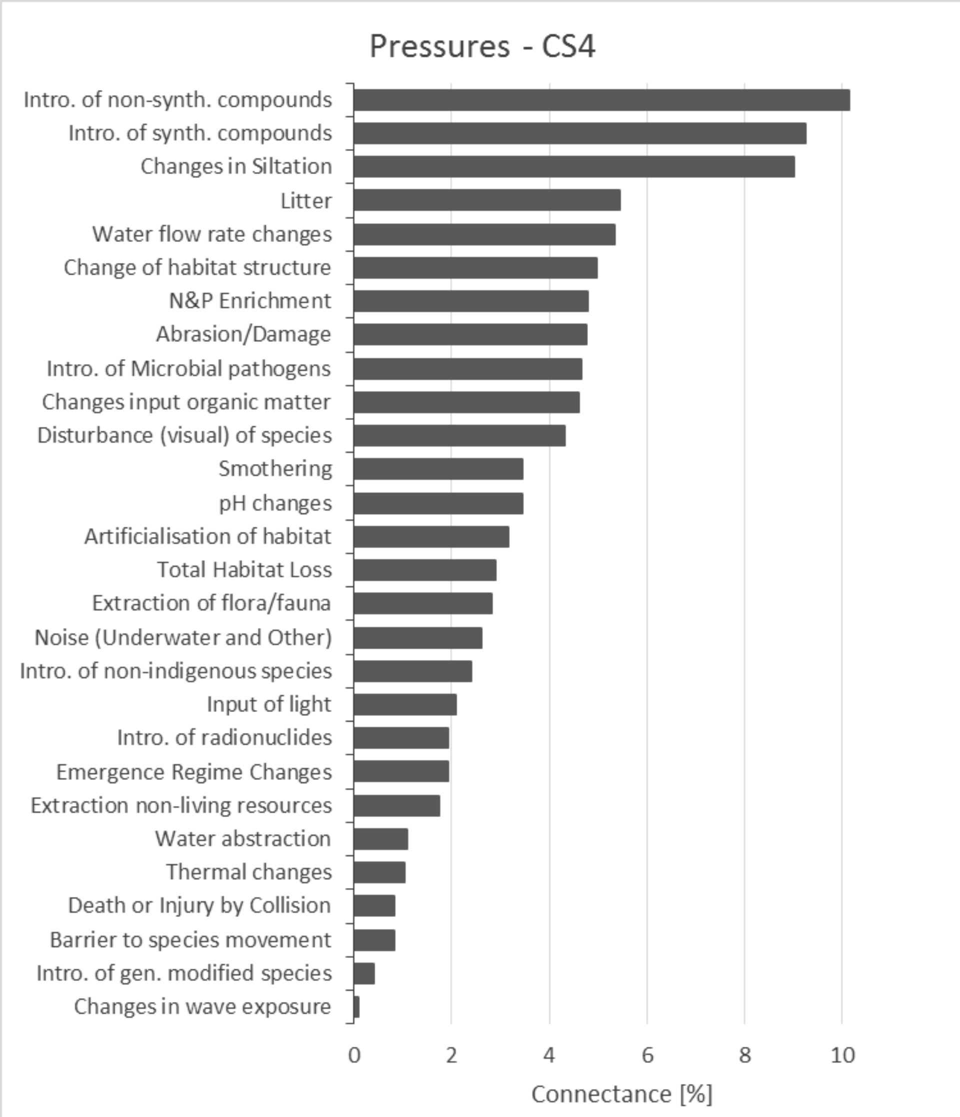

Figure 29: Connectance of Pressures in CS5.

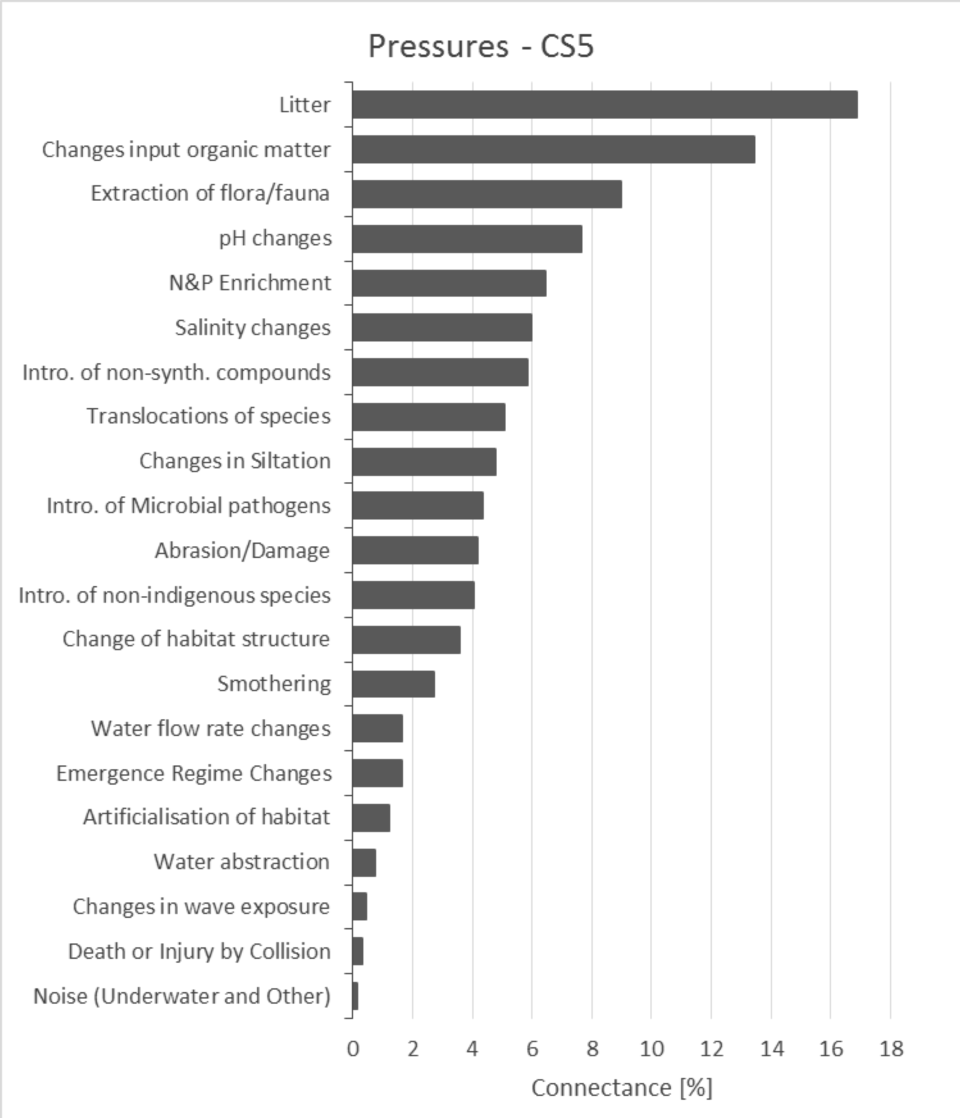

Figure 30: Connectance of Pressures in CS7.

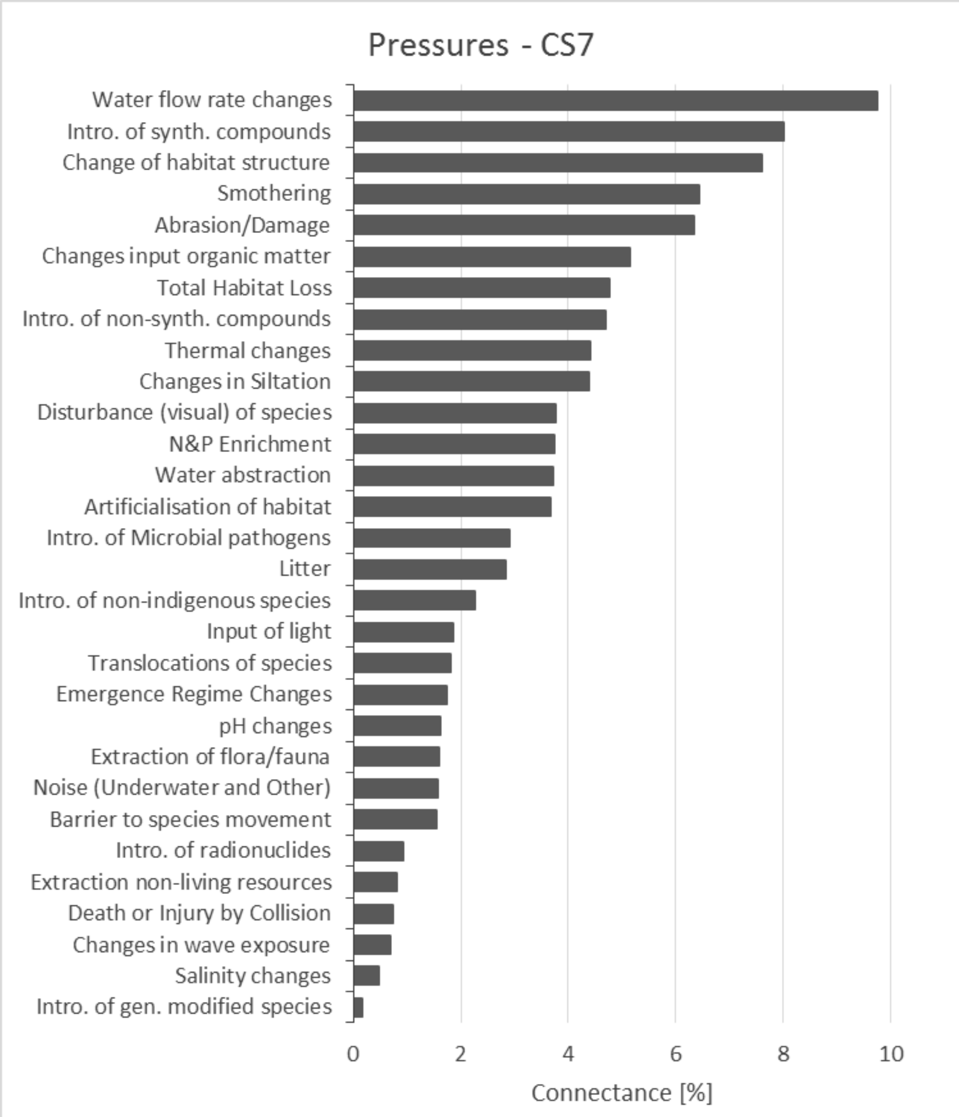

Figure 31: Connectance of Pressures in CS8.

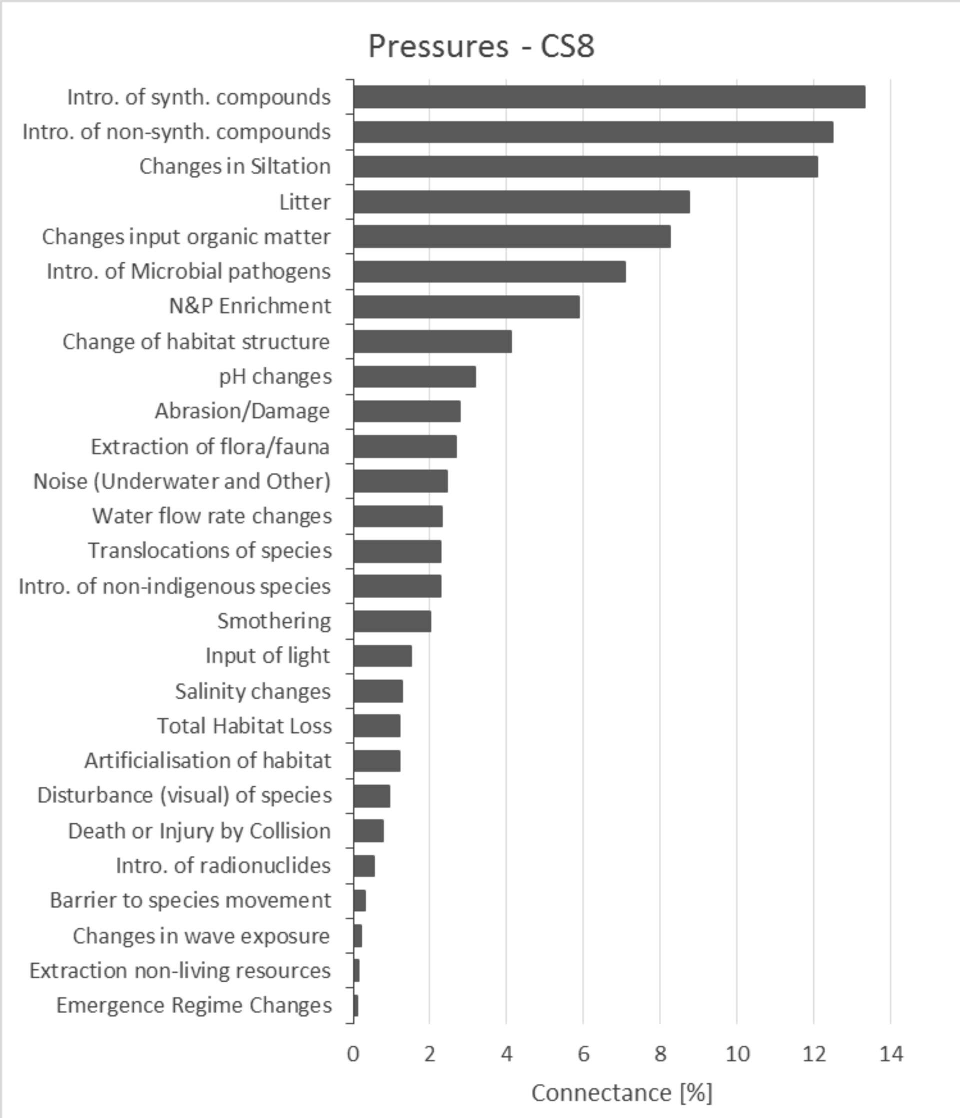

Figure 32: Connectance of Ecosystem Components in CS1.

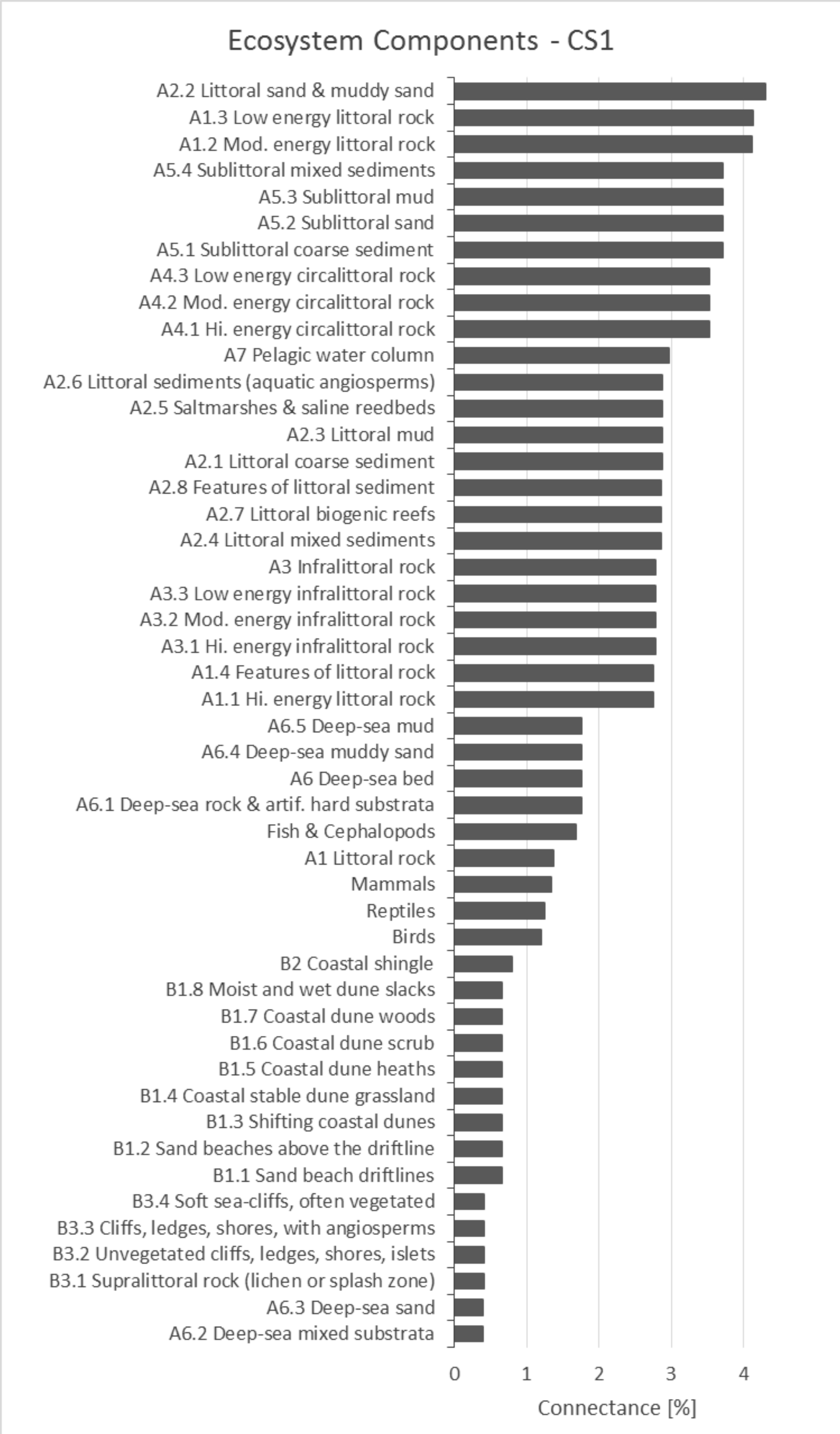

Figure 33: Connectance of Ecosystem Components in CS2.

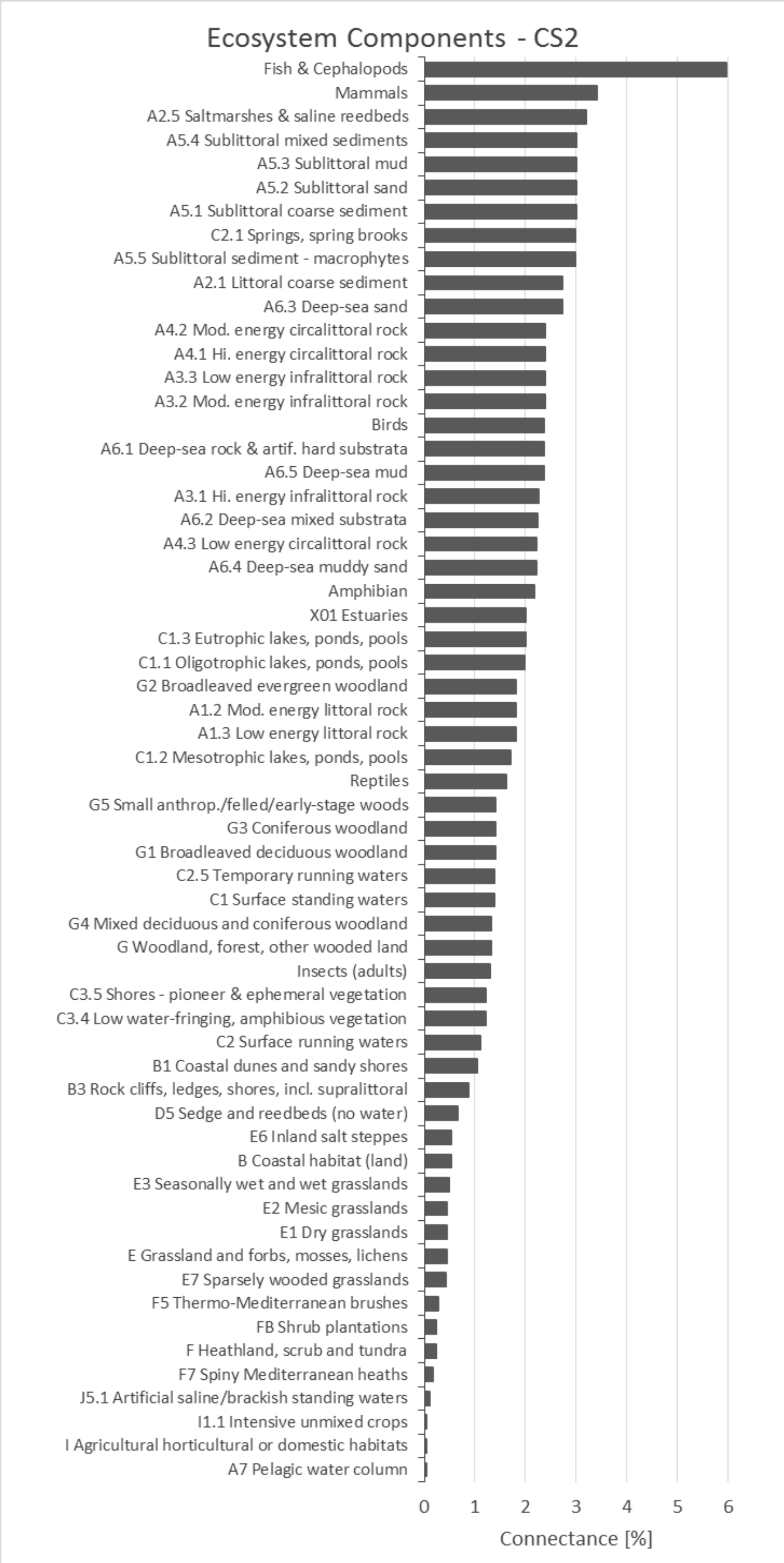

Figure 34: Connectance of Ecosystem Components in CS3.

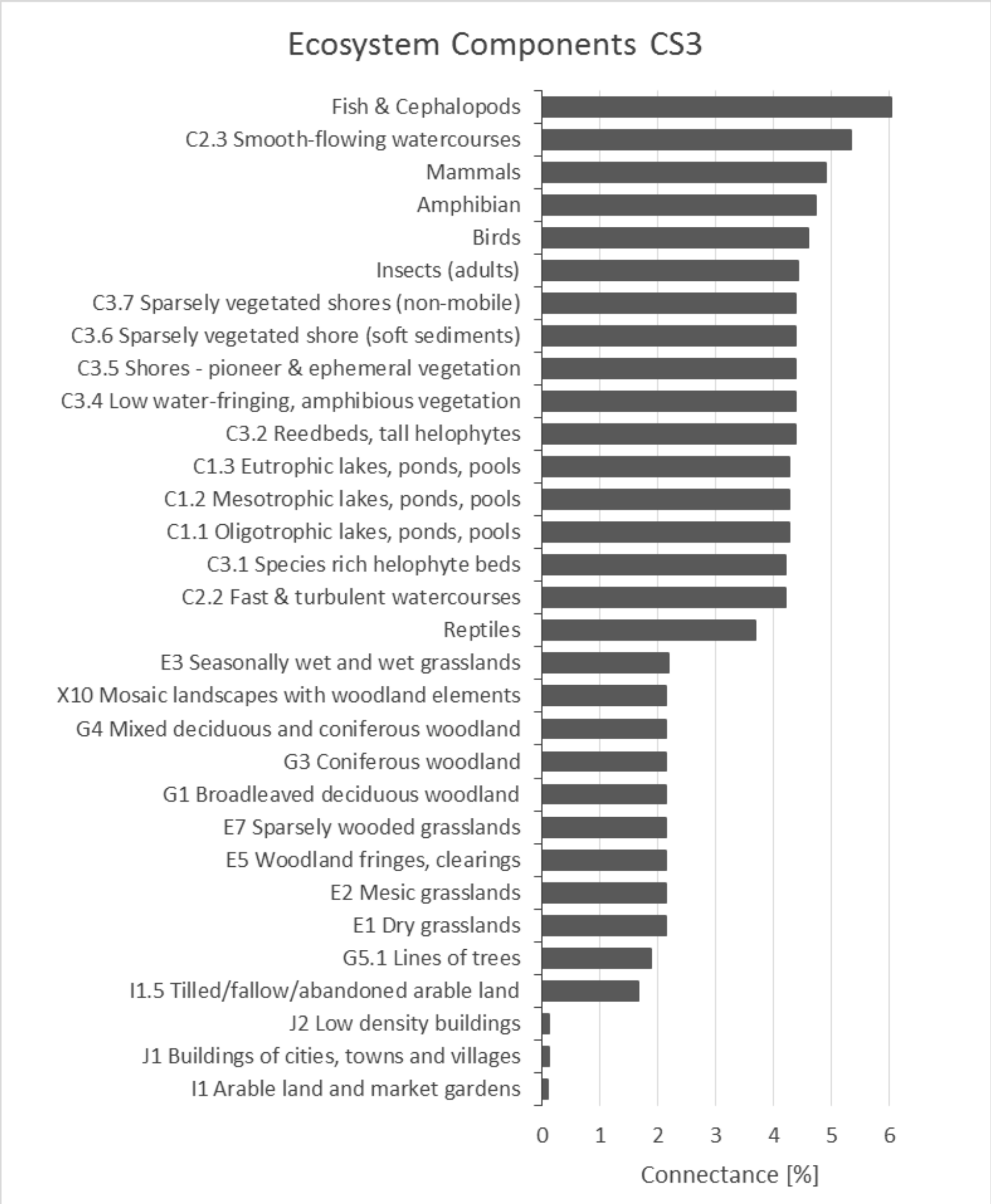

Figure 35: Connectance of Ecosystem Components in CS4.

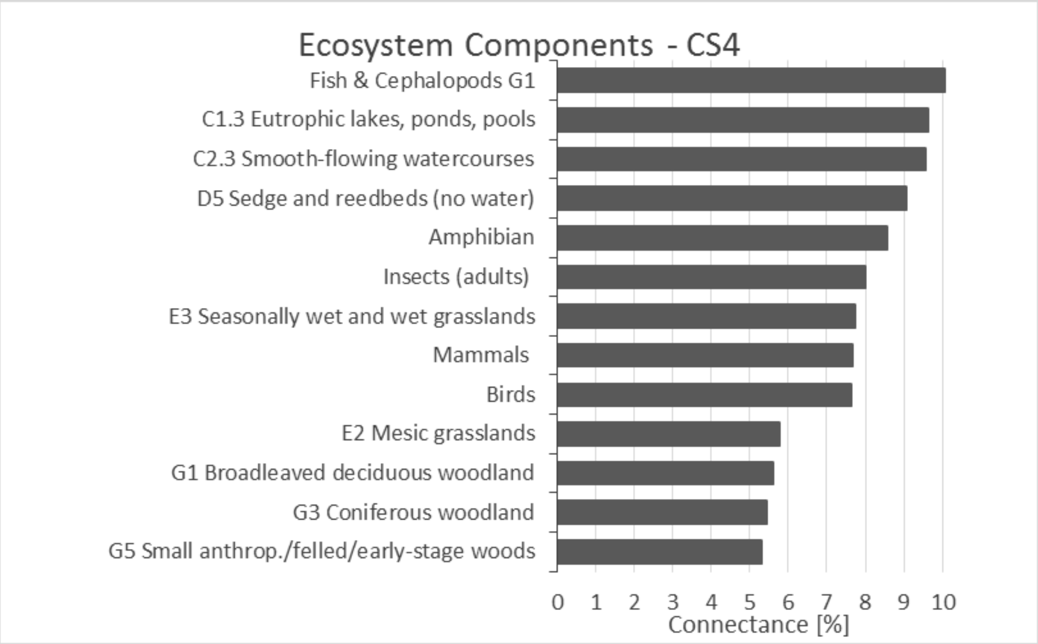

Figure 36: Connectance of Ecosystem Components in CS5.

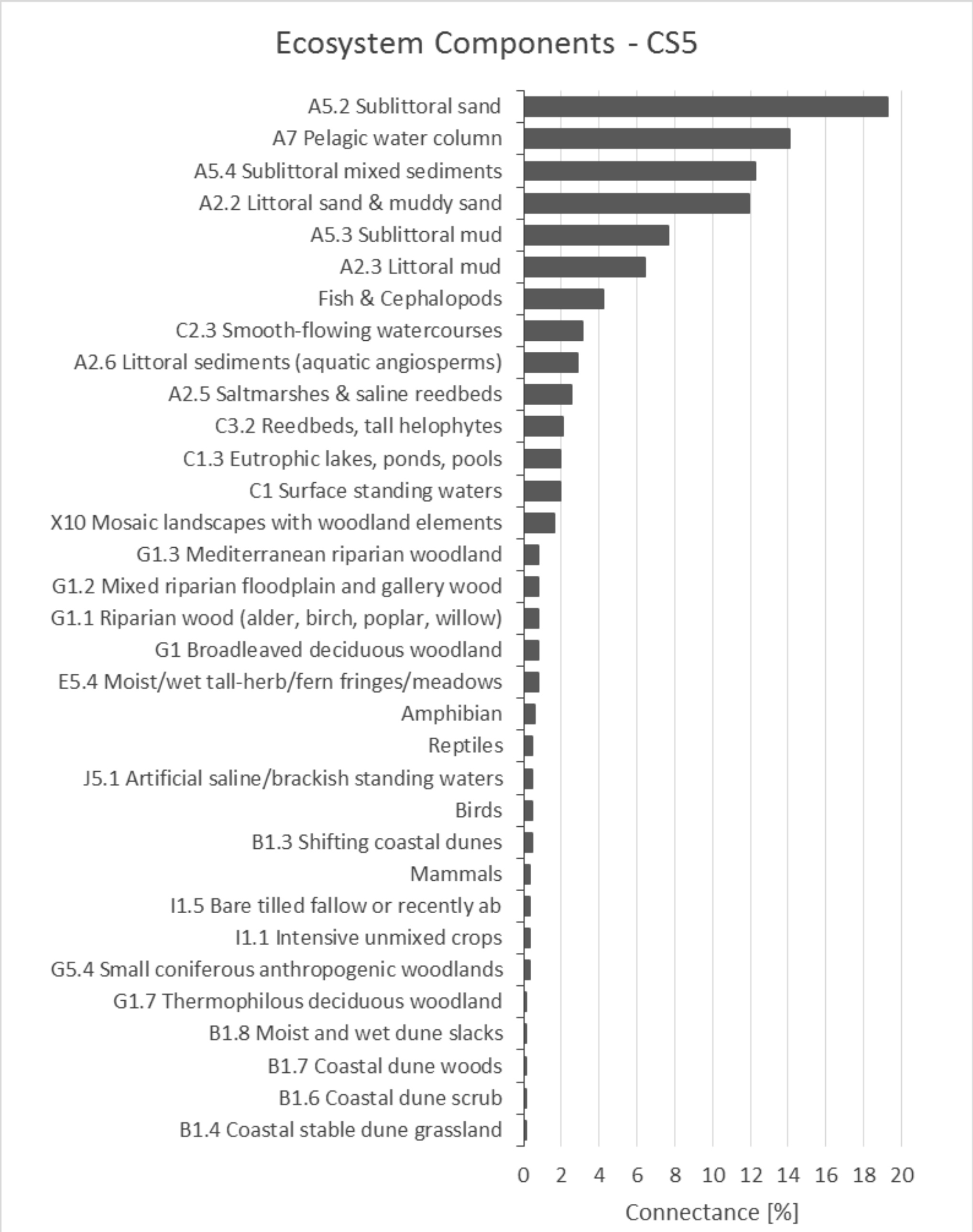

Figure 37: Connectance of Ecosystem Components in CS7.

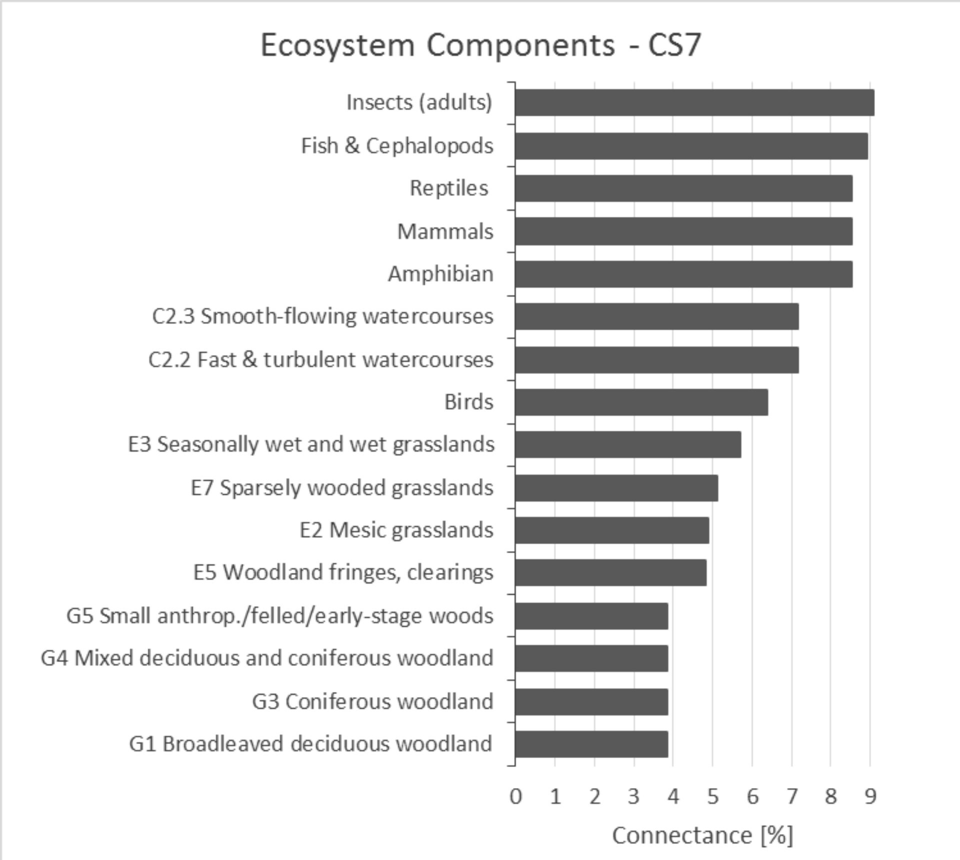

Figure 38: Connectance of Ecosystem Components in CS8.

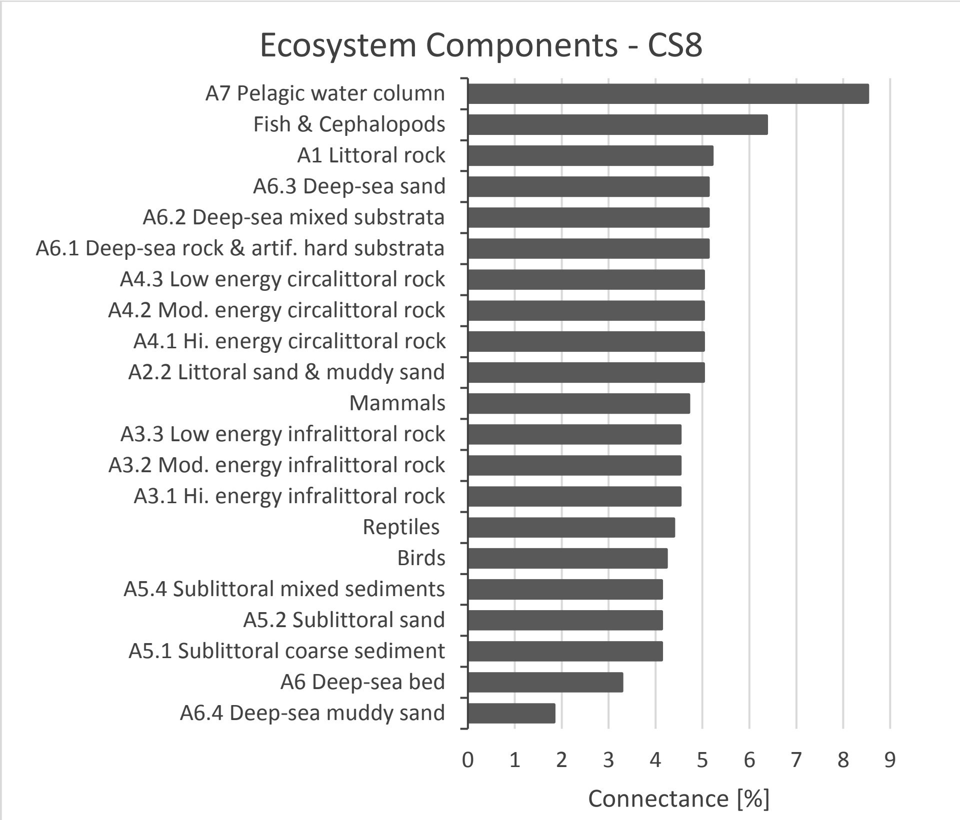

Table 15: Proportion of weighted impact chains over all CS and individual CS for the primary activity “Manufacturing”.

Manufacturing		Total	CS1	CS2	CS3	CS4	CS5	CS7	CS8
EXTENT	EXOGENOUS	**70%**	66%	49%	100	9%		100%	100%
	SITE	**9%**	0%	17%	0%	91%		0%	0%
	LOCAL	**22%**	34%	34%	0%	0%		0%	0%
	WIDESPREAD PATCHY	**0%**	0%	0%	0%	0%		0%	0%
	WIDESPREAD EVEN	**0%**	0%	0%	0%	0%		0%	0%
FREQUENCY	RARE	**29%**	12%	97%	29%	40%		0%	0%
	OCCASIONAL	**9%**	10%	0%	0%	0%		53%	0%
	FREQUENT	**36%**	47%	0%	4%	37%		14%	100%
	VERY FREQUENT	**3%**	0%	3%	8%	9%		9%	0%
	CONTINOUS	**23%**	31%	0%	60%	14%		25%	0%
SEVERITY	LOW	**9%**	9%	7%	4%	19%		25%	3%
	CHRONIC	**90%**	91%	87%	96%	81%		75%	97%
	ACUTE	**1%**	0%	6%	0%	0%		0%	0%
PERSISTENCE	LOW	**66%**	65%	66%	61%	68%		81%	58%
	MODERATE	**10%**	12%	9%	7%	1%		0%	17%
	HIGH	**25%**	23%	25%	32%	31%		19%	25%
	PERSISTENT	**0%**	0%	0%	0%	0%		0%	0%
DISPERSAL	NONE	**1%**	0%	6%	0%	0%		0%	0%
	MODERATE	**66%**	66%	63%	60%	66%		78%	65%
	HIGH	**33%**	34%	31%	40%	34%		23%	35%

Table 16: Proportion of weighted impact chains over all CS and individual CS for the primary activity “Mining, Extraction of Materials”.

Mining/Extraction		Total	CS1	CS2	CS3	CS4	CS5	CS7	CS8
EXTENT	EXOGENOUS	**9%**	3%	40%	0%	47%	0%	0%	
	SITE	**77%**	76%	60%	100%	53%	0%	100%	
	LOCAL	**15%**	21%	0%	0%	0%	0%	0%	
	WIDESPREAD PATCHY	**0%**	0%	0%	0%	0%	0%	0%	
	WIDESPREAD EVEN	**0%**	0%	0%	0%	0%	100%	0%	
FREQUENCY	RARE	**70%**	81%	96%	13%	36%	0%	10%	
	OCCASIONAL	**9%**	0%	2%	87%	43%	0%	9%	
	FREQUENT	**15%**	19%	1%	0%	22%	0%	0%	
	VERY FREQUENT	**0%**	0%	0%	0%	0%	0%	0%	
	CONTINOUS	**6%**	0%	0%	0%	0%	100%	81%	
SEVERITY	LOW	**6%**	3%	11%	14%	12%	0%	12%	
	CHRONIC	**84%**	88%	67%	69%	84%	100%	80%	
	ACUTE	**10%**	9%	22%	17%	4%	0%	8%	
PERSISTENCE	LOW	**56%**	57%	53%	43%	53%	100%	59%	
	MODERATE	**22%**	27%	15%	12%	1%	0%	6%	
	HIGH	**21%**	16%	22%	45%	43%	0%	35%	
	PERSISTENT	**1%**	0%	10%	0%	2%	0%	0%	
DISPERSAL	NONE	**28%**	28%	46%	30%	10%	100%	23%	
	MODERATE	**39%**	42%	31%	20%	44%	0%	40%	
	HIGH	**33%**	30%	23%	51%	46%	0%	37%	

Table 17: Proportion of weighted impact chains over all CS and individual CS for the primary activity “Non-Renewable Energy”.

Non-Renewable Energy		Total	CS1	CS2	CS3	CS4	CS5	CS7	CS8
EXTENT	EXOGENOUS	**15%**	11%	38%	100%	11%		0%	
	SITE	**58%**	61%	18%	0%	89%		100%	
	LOCAL	**2%**	0%	44%	0%	0%		0%	
	WIDESPREAD PATCHY	**25%**	28%	0%	0%	0%		0%	
	WIDESPREAD EVEN	**0%**	0%	0%	0%	0%		0%	
FREQUENCY	RARE	**17%**	15%	40%	0%	69%		4%	
	OCCASIONAL	**9%**	7%	49%	0%	31%		0%	
	FREQUENT	**6%**	7%	1%	13%	0%		0%	
	VERY FREQUENT	**47%**	53%	0%	0%	0%		0%	
	CONTINOUS	**21%**	17%	10%	87%	0%		96%	
SEVERITY	LOW	**7%**	6%	8%	20%	16%		16%	
	CHRONIC	**85%**	86%	88%	80%	76%		73%	
	ACUTE	**8%**	8%	4%	0%	8%		11%	
PERSISTENCE	LOW	**51%**	50%	48%	51%	70%		69%	
	MODERATE	**18%**	19%	13%	6%	1%		0%	
	HIGH	**24%**	23%	34%	43%	30%		27%	
	PERSISTENT	**7%**	8%	5%	0%	0%		4%	
DISPERSAL	NONE	**21%**	23%	11%	0%	18%		15%	
	MODERATE	**43%**	42%	51%	47%	49%		53%	
	HIGH	**35%**	35%	38%	53%	32%		32%	

Table 18: Proportion of weighted impact chains over all CS and individual CS for the primary activity “Renewable Energy”.

Renewable Energy		Total	CS1	CS2	CS3	CS4	CS5	CS7	CS8
EXTENT	EXOGENOUS	**7%**	5%	19%	19%	4%	38%	0%	
	SITE	**63%**	84%	31%	5%	96%	63%	1%	
	LOCAL	**19%**	0%	50%	53%	0%	0%	99%	
	WIDESPREAD PATCHY	**9%**	11%	0%	10%	0%	0%	0%	
	WIDESPREAD EVEN	**2%**	0%	0%	13%	0%	0%	0%	
FREQUENCY	RARE	**78%**	84%	63%	64%	44%	100%	67%	
	OCCASIONAL	**1%**	1%	2%	0%	11%	0%	1%	
	FREQUENT	**3%**	3%	16%	0%	0%	0%	0%	
	VERY FREQUENT	**3%**	4%	0%	0%	1%	0%	0%	
	CONTINOUS	**15%**	8%	20%	36%	44%	0%	32%	
SEVERITY	LOW	**8%**	5%	20%	7%	23%	38%	21%	
	CHRONIC	**84%**	88%	64%	83%	62%	63%	68%	
	ACUTE	**9%**	8%	16%	9%	15%	0%	11%	
PERSISTENCE	LOW	**39%**	33%	66%	50%	59%	0%	57%	
	MODERATE	**15%**	18%	0%	9%	8%	0%	10%	
	HIGH	**9%**	9%	7%	14%	0%	0%	3%	
	PERSISTENT	**37%**	40%	26%	26%	33%	100%	29%	
DISPERSAL	NONE	**32%**	29%	40%	28%	48%	0%	52%	
	MODERATE	**48%**	49%	52%	48%	43%	100%	40%	
	HIGH	**20%**	22%	7%	24%	9%	0%	9%	

Table 19: Proportion of weighted impact chains over all CS and individual CS for the primary activity “Waste Management”.

Waste Management		Total	CS1	CS2	CS3	CS4	CS5	CS7	CS8
EXTENT	EXOGENOUS	**51%**	70%	0%	100%	11%		36%	100%
	SITE	**14%**	0%	49%	0%	0%		0%	0%
	LOCAL	**3%**	4%	5%	0%	0%		0%	0%
	WIDESPREAD PATCHY	**18%**	26%	0%	0%	89		64%	0%
	WIDESPREAD EVEN	**14%**	0%	46%	0%	0%		0%	0%
FREQUENCY	RARE	**35%**	1%	97%	37%	0%		0%	0%
	OCCASIONAL	**13%**	0%	3%	0%	0%		36%	100%
	FREQUENT	**14%**	9%	0%	7%	100%		40%	0%
	VERY FREQUENT	**28%**	90%	0%	7%	0%		2%	0%
	CONTINOUS	**9%**	0%	0%	49%	0%		23%	0%
SEVERITY	LOW	**7%**	3%	5%	8%	16%		12%	12%
	CHRONIC	**93%**	97%	95%	92%	84%		88%	88%
	ACUTE	**0%**	0%	0%	0%	0%		0%	0%
PERSISTENCE	LOW	**65%**	72%	60%	58%	66%		73%	62%
	MODERATE	**13%**	14%	17%	8%	6%		0%	15%
	HIGH	**23%**	14%	23%	34%	28%		27%	23%
	PERSISTENT	**0%**	0%	0%	0%	0%		0%	0%
DISPERSAL	NONE	**5%**	0%	15%	0%	5%		5%	0%
	MODERATE	**64%**	72%	57%	56%	64%		64%	69%
	HIGH	**31%**	28%	29%	44%	31%		30%	31%

Annex B

List of scientific publications assessing the impact of HP plants on biodiversity (fish, macroinvertebrates, or other biota) in Romania

No	Lead Author	Year	Title	Journal	River/Basin
1.	Bănăduc	1999	Data concerning the human impact on the ichthyofauna of the upper and middle sectors of the Olt River	Transylvanian Review of Systematical and Ecological Research	Olt River/Olt Basin
2.	Bănăduc	2000	Ichthyofaunistic criteria for Cibin River human impact assesment	Travaux du Museum d'Histoire naturelle "Grigore Antipa"	Cibin River/Olt Basin
3.	Bănăduc	2005	Fish associations - habitats quality relation in the Târnave rivers (Transylvania, Romania)	Transylvanian Review of Systematical and Ecological Research	Tarnave Rivers/Mures Basin
4.	Bănăduc	2006	The Râul Mare River (Retezat Mountains, Romania) fish fauna	Transylvanian Review of Systematical and Ecological Research	Râul Mare River/Mures/Tisa
5.	Bănăduc	2010	Hydrotechnical works impact on Cyclostomata and Cottidae species in the Rodna Mountains and Maramureş Mountains Natura 2000 sites (Eastern Carpathians, Romania), Repede River - a study case.	Transylvanian Review of Systematical and Ecological Research	Repede River /Vişeu River /Tisa Basin
6.	Bănăduc	2012	The assessment, monitoring and management of the Carpathian rivers fish diversity	Management of Sustainable Development	Carpathian rivers (Cibin, Tarnave, Viseu)
7.	Bănăduc	2013	The Fish Fauna of the Timiş River (Banat, Romania). Transylvanian Review of Systematical and Ecological Research	Transylvanian Review of Systematical and Ecological Research	Romanian length of the Timiş River

8.	Bănăduc	2013	Geographical and Human Impact Elements Influence on the Fish Fauna of the Olteţ River (Romania)	Transylvanian Review of Systematical and Ecological Research	Oltet River/Olt Basin
9.	Bănăduc	2014	“Porțile de Fier/Iron Gates” Gorges area (Danube) fish fauna	Transylvanian Review of Systematical and Ecological Research	Iron Gates - Danube
10.	Bănăduc	2014	The “Porţile de Fier/Iron Gates” Nature Park (Romania) Some Danube Northern Tributaries Fish Fauna.	Transylvanian Review of Systematical and Ecological Research	“Iron Gates” Gorges (Danube River), 4 northern/upstream tributaries
11.	Bănăduc	2018	Technical solutions to mitigate shifting fish fauna zones impacted by long term habitat degradation in the Bistra Marului River-Study Case	Transylv. Rev. Syst. Ecol. Res.	Bistra Marului River/Timis
12.	Bouros	2015	Assessing small hydropower plants impact on Eurasian otter. Case study:the Buzau River, Romania	Studia Universitatis Babes-Bolyai Biologia	Buzau
13.	Curtean-Bănăduc	2001	Aspects concerning Cibin River (Transylvania, Romania) Stonefly (Insecta, Plecoptera) larvae associations	Analele Universitatii "Ovidius" Constanta, Seria Biologie-Ecologie	Cibin River/Olt Basin
14.	Curtean-Bănăduc	2004	Cibin River fish communities structural and functional aspects	Studii si Cercetari Stiintifice-Seria Biologie, Universitatea Bacau	Cibin River/Olt Basin
15.	Curtean-Bănăduc	2004	Aspecte privind dinamica faunei râului Cibin (bazinul hidrografic Olt) în ultimii 150 de ani	Studii si Comunicari, Muzeul Brukenthal Sibiu, Stiintele Naturii	Cibin River/Olt Basin

16.	Curtean-Bănăduc	2005	Târnava Mare River (Romania) Ecological assessment, based on the benthic macroinvertebrates communities	Transylvanian Review of Systematical and Ecological Research	Tarnava Mare River/Mures Basin
17.	Curtean-Bănăduc	2008	Sebeș River Mountainous sector (Olt River watershed) ecological assessment (Transylvania, Romania)	Acta Oecologica Carpatica	Sebes River/Olt Basin
18.	Curtean-Bănăduc	2014	Historical human impact on the Capra Stream macroinvertebrates and fish communities (Southern Romanian Carpathians)	Acta Oecologica Carpatica	Capra River / Arges/Danube
19.	Curtean-Bănăduc	2014	"Iron Gates" Gorges (Danube River), northern tributaries benthic macroinvertebrate communities, Transylvanian Review of Systematical and Ecological Research, 16	Transylvanian Review of Systematical and Ecological Research	"Iron Gates" Gorges (Danube River), 4 northern/upstream tributaries
20.	Curtean-Bănăduc	2015	Eudontomyzon danfordi (Regan, 1911) Species Populations Ecological Status in Maramureş Mountains Nature Park (Romania)	Transylvanian Review of Systematical and Ecological Research	Viseu and some tribuitaries/Tisa Basin
21.	Curtean-Bănăduc	2015	Environmental Aspects of Implementation of Micro Hydro Power Plants – A Short Review	Transylvanian Review of Systematical and Ecological Research	Capra River / Arges/Danube
22.	Curtean-Bănăduc	2017	The Status of Romanogobio uranoscopus (Agassiz, 1828) Species, in Maramures Mountains Nature Park (Romania)	Transylvanian Review of Systematical and Ecological Research	Viseu and some tribuitaries/Tisa Basin
23.	Davideanu	2006	Data concerning the fish communities of the upper part of Bistrita River and tributaries-Romania	Acta Ichtiologica Romanica	Bistrita/Siret Basin
24.	Dimulescu	1998	Managementul pescaresc al râurilor din Bazinul Hidrografic Buzău, Teză de doctorat, Universitatea Dunarea de Jos din Galati, 239 p.	PhD thesis	Buzau

25.	Dumitrascu	2012	Data upon the ichtyofauna of three reservoirs from the Jiu River, Romania	South Western Journal of Horticulture, Biology and Environment	Jiu River
26.	Florea	2014	The assessment of community interest fish species from protected area ROSCI0229	Transylvanian Review of Systematical and Ecological Research	Buzau
27.	Florea	2017	The changes that occurred between 2010-2016 in the community interest fish species from protected area ROSCI0229 Siriu (Romania)	Acta Oecologica Carpatica	Buzau
28.	Florescu	2015	Ecological analyses on benthic diatom and invertebrate communities from the Somesul Mic catchment area (Transysylvania, Romania)	Studia Universitatis Babes-Bolyai Biologia	Somesul Mic/Tisa Basin
29.	Gogoașe-Nistoran	2018	Modeling hydrodynamic changes induced by run-of-river hydropower plants along the Prahova River in Romania	Journal of Energy Engineering	Prahova River/Ialomita Basin
30.	Imecs	2016	Data concerning the fish fauna of the Moldova river based on surveys of ROSCI0321, ROSCI0365, ROSCI0363, ROSCI0364 Natura 2000 sites	Analele Stiintifice ale Universitatii "Al. I. Cuza" Iasi, Biologie Animala	Moldova River/Siret Basin
31.	Khalaf	2015	Microsatellites variation in two different populations of Brown trout (Salmo trutta, morpha fario, Linnaeus, 1758) from Făgăraş Mountains	Scientific Papers, Animal Sciences and Biotechnologies	river from Southern slope of the Fagaras Mountains
32.	Kohout	2013	Genetic diversity and phylogenetic origin of brown trout Salmo trutta populations in eastern Balkans	Biologia	Balkan area (Timis River)
33.	Miron	1983	Lacul De Acumulare Izvorul Muntelui Bicaz - I	Editura Academiei Republicii Socialiste Romania	Bistrita/Siret Basin

34.	Miron	2010	Succesiunea ecologică: râul Bistriţa-Lacul Bicaz, Monografie limnologică II,	Editura Universitatii "Al I Cuza" Iasi	Bistrita/Siret Basin
35.	Nechifor	2017	The *Genetic Profiles* of *two Salmonid Populations* from *Romania Obtained through Nuclear Markers Analysis*.	Scientific Papers, Animal Sciences and Biotechnologies	Topolog River (Olt Basin), Sebesel River (Tisa Basin)
36.	Popa	2013	Brown trout's populations genetic diversity using mitochondrial markers in relatively similar geographical and ecological conditions – A Carpathian case study	Transylvanian Review of Systematical and Ecological Research	rivers in the Northern side of Fagaras Mountains
37.	Popa	2016	Molecular markers reveal reduced genetic diversity in Romanian populations of brown trout, Salmo trutta L., 1758 (Salmonidae)	Acta Zoologica Bulgarica	rivers in the Northern side of Fagaras Mountains and tributaries of Olt River
38.	Pricope	2010	The effects of anthropic activity on ichthyofauna diversity in some reservoirs of the Bistrița River	Studii si Cercetari Stiintifice-Seria Biologie, Universitatea Bacau	Bistrita/Siret Basin
39.	Pricope	2013	The effects of anthropogenic activity over ichthyofauna biodiversity from landscaped area of Siret river	Studii si Cercetari Stiintifice-Seria Biologie, Universitatea Bacau	Siret River
40.	Sárkány-Kiss	2012	The ecological state of the Upper Tisa and the Transylvanian tributaries of the Tisa river – based on characteristics of the physico-chemical parameters, the flora and fauna	Acta Biologica Debrecina Supplementul Oecologica Hungarica	Upper Tisa and main Transylvanian tributaries of the Tisa river
41.	Stoica	2012	Observation on the state of fish communities in the Bistricioara River, right tributary of Bistriţa River	Studii si Cercetari Stiintifice-Seria Biologie, Universitatea Bacau	Bistricioara River/Bistrita Basin

42.	Stoica	2013	Research on the status of the fish communities of the upper course of Bistrita River	Studii si Cercetari Stiintifice-Seria Biologie, Universitatea Bacau	Bistrita/Siret Basin
43.	Telcean	1997	Influenţa barajelor şi amenajărilor hidrotehnice asupra ihtiofaunei bazinului Crişurilor (The influence of the river damming and of hydrotechnical modifications upon the fishfauna from the Crişuri basin).	Analele Universitatii Oradea	Crisuri basin
44.	Telcean	2012	Threatened and rare fishes from upper Tisa Valley and its Romanian left shore tributaries (North-Western Romania)	Pisces Hungarici	Tisa and Romanian tributaries

Annex C

SCI-paper on the analyses of the linkage framework and impact risk introduced by human activities across aquatic realms:

Borgwardt, F., Robinson, L., Trauner, D., Teixeira, H., Nogueira, A.J.A., Lillebø, A.I., Piet, G., Kuemmerlen, M., O'Higgins, T., McDonald, H., Arevalo-Torres, J., Barbosa, A.L., Iglesias-Campos, A., Hein, T., Culhane, F., 2019. Exploring variability in environmental impact risk from human activities across aquatic ecosystems. Sci. Total Environ. 652, 1396-1408. https://doi.org/10.1016/J.SCITOTENV.2018.10.339

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

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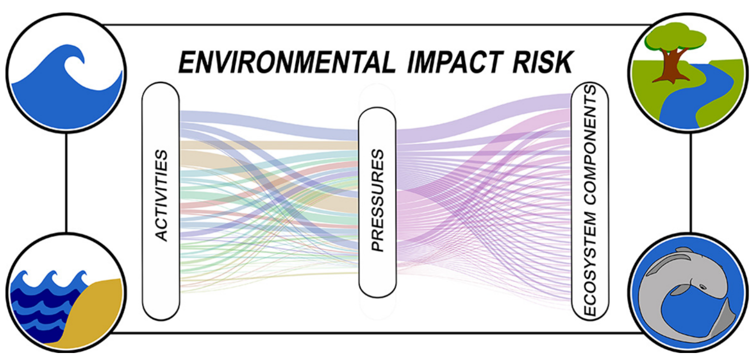
HIGHLIGHTS

- 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



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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

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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.

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

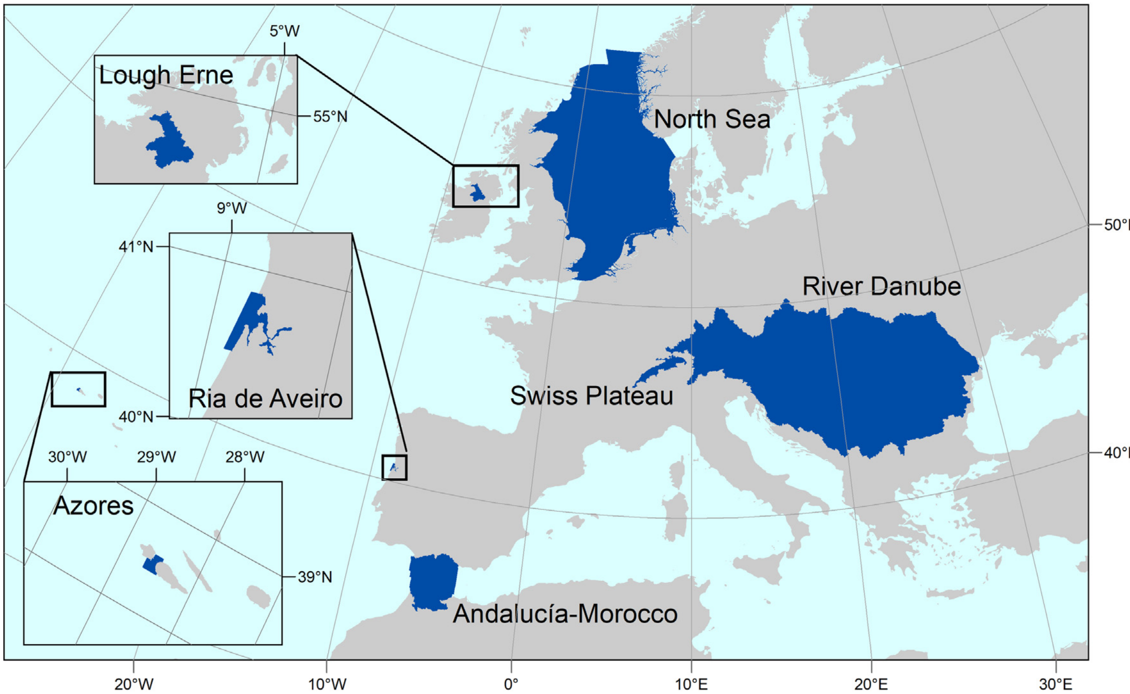

Fig. 1. Map showing the seven case studies and their spatial extent.

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,

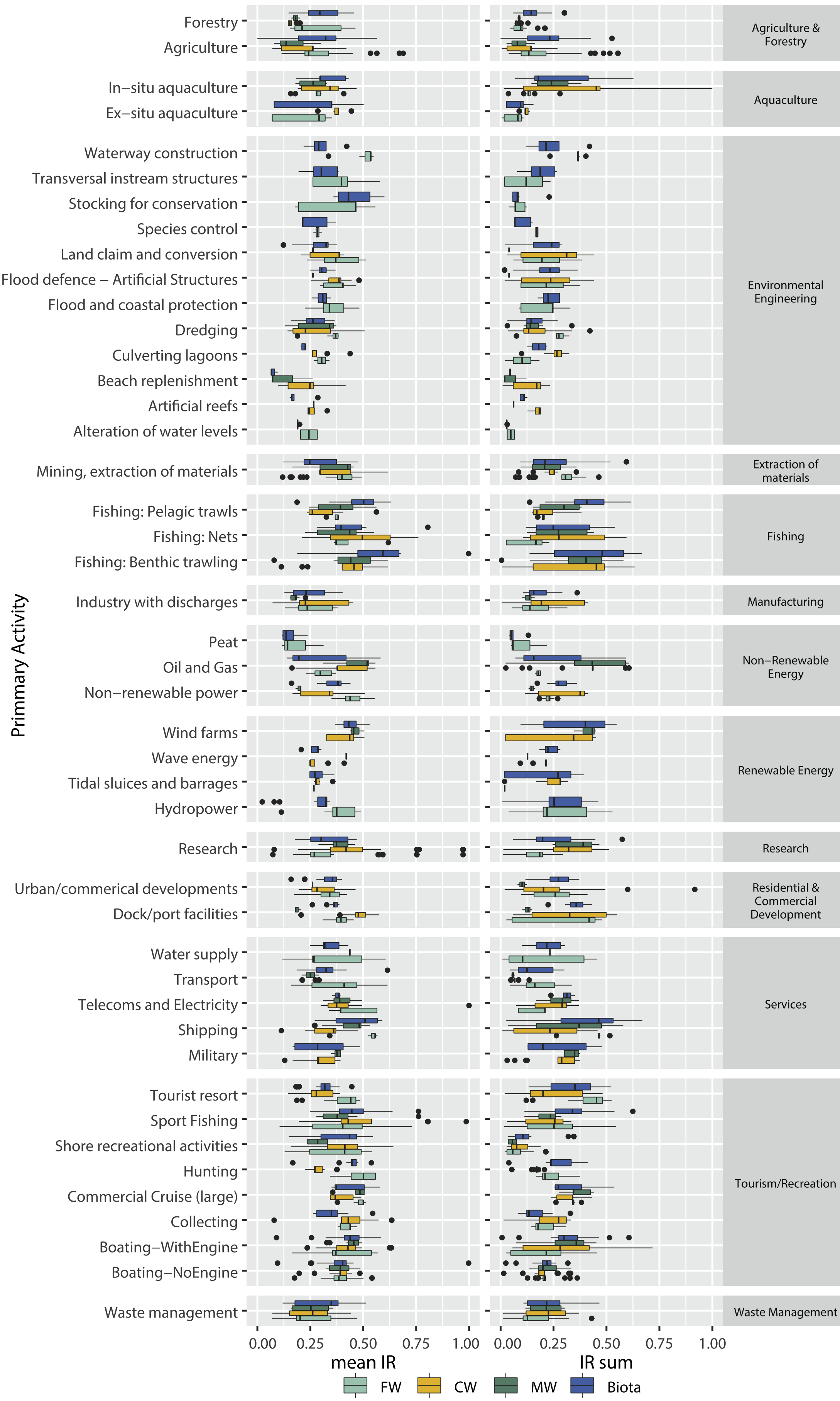

Fig. 2. Box and whiskers plots of mean (left panel) and summed (right panel) environmental impact risk of human activities across the aquatic domains; each value represents an ecosystem component (N = 2774).

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

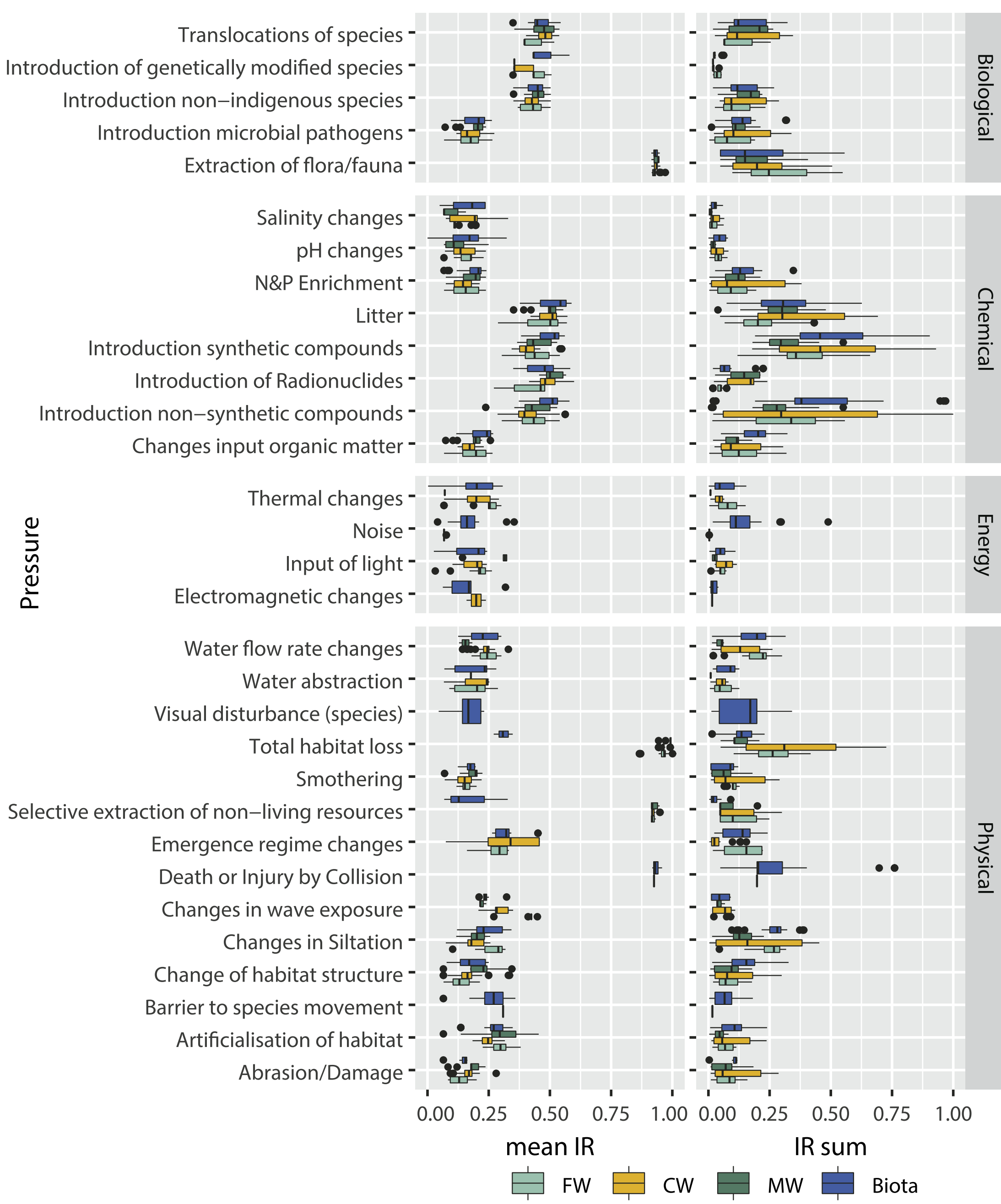

Fig. 3. Box and whiskers plots of mean (left panel) and summed (right panel) environmental impact risk of single pressures across the aquatic domains; each value represents an ecosystem component (N = 2737).

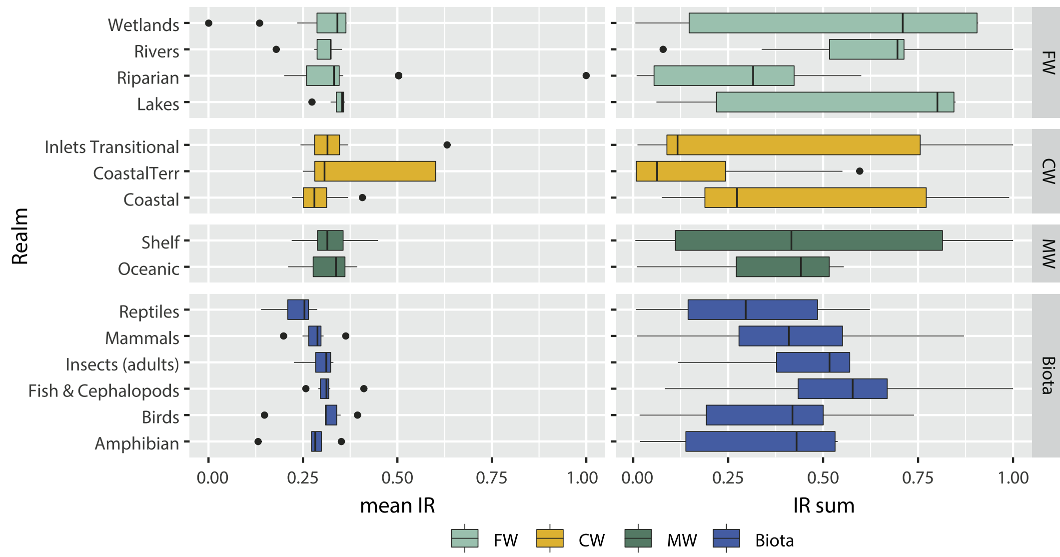

Fig. 4. Mean (left) and summed (right) environmental impact risk of ecosystem components across aquatic realms (N = 163).

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

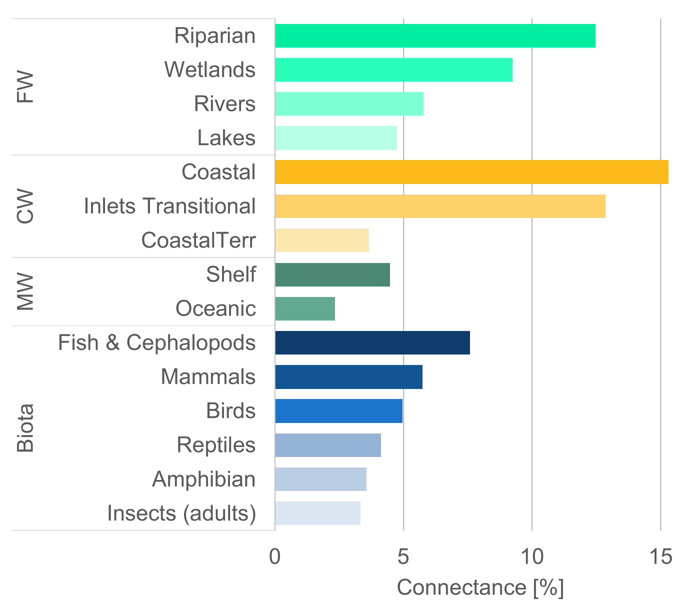

Fig. 5. Connectance of the aquatic realms within the whole linkage framework; FW = fresh waters, CW = coastal waters, MW = marine waters.

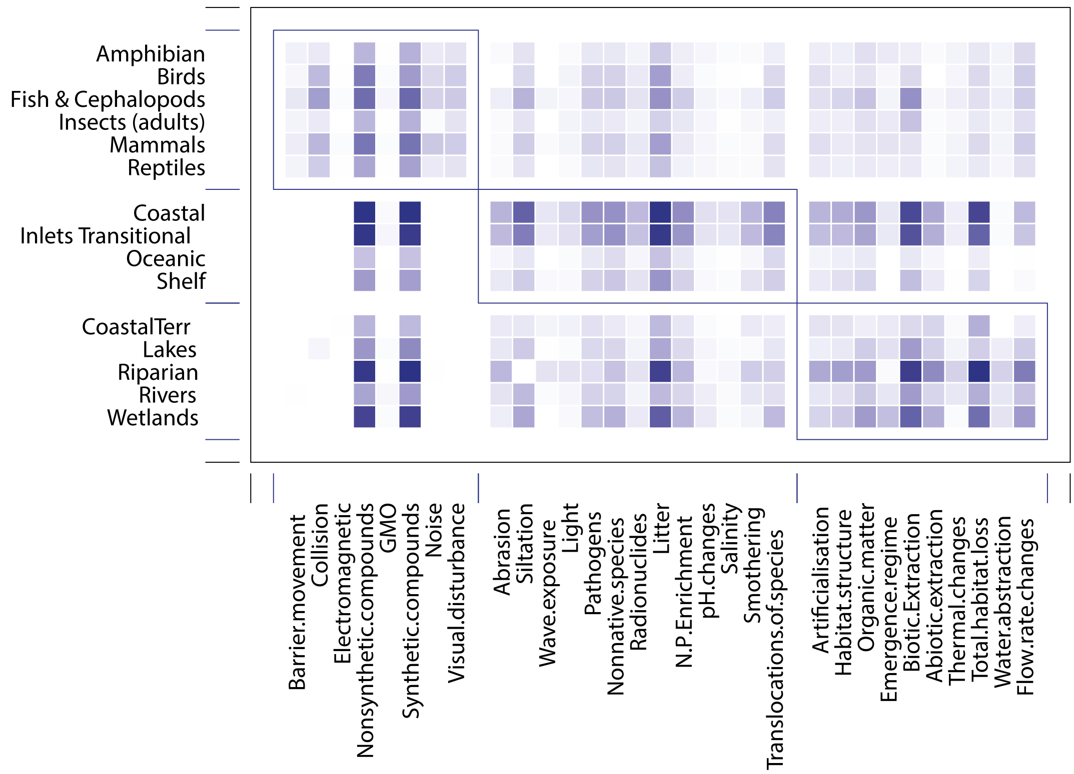

Fig. 6. Modularity of pressures and realms indicating the main modules identified.

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,

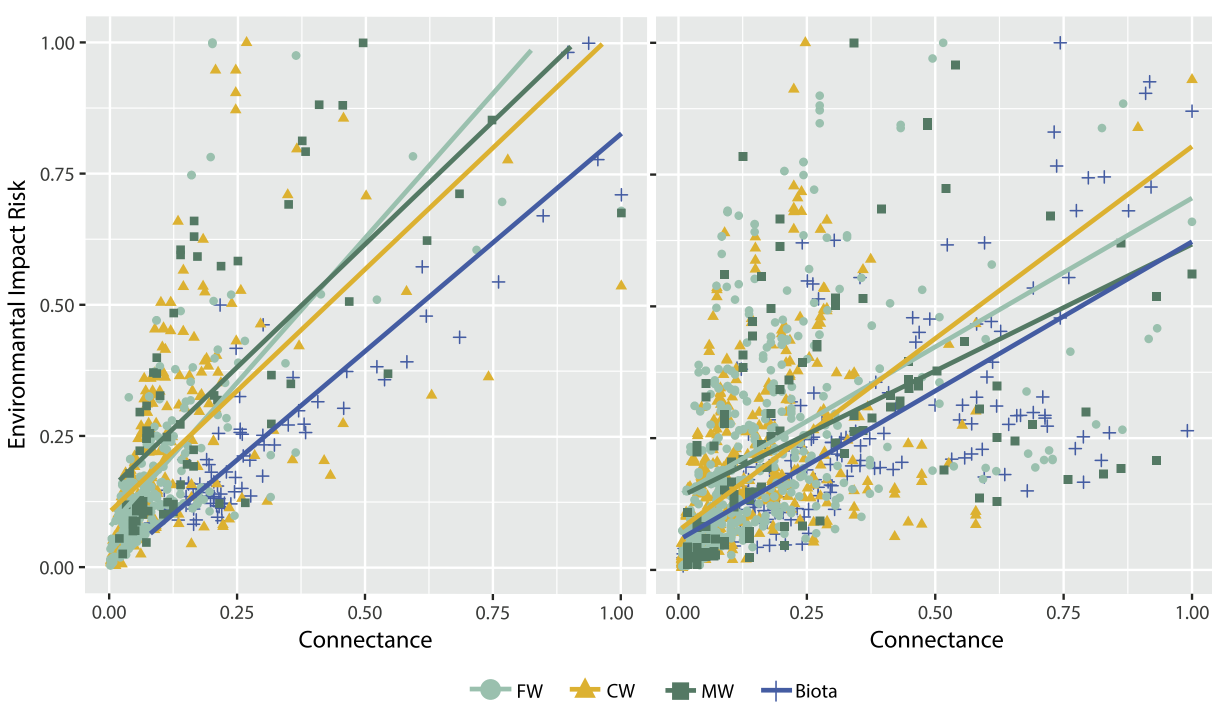

Fig. 7. Scatterplot of connectance vs. environmental impact risk of human activities (left) and pressures (right) in the aquatic realms with linear trend lines; further statistics can be found in Table 4 Characteristics of correlation, regression as well as Wilcoxon signed rank test to analyse the relationship 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.

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Appendix A. Supplementary data

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