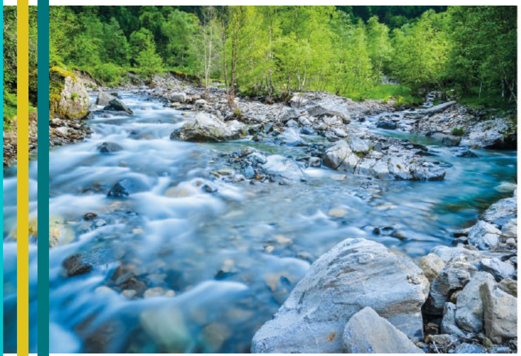

The AQUACROSS Innovative Concept

Deliverable 3.1

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List of abbreviations

AF	AQUACROSS Assessment Framework
AQUACROSS	Knowledge, Assessment, and Management for AQUAtic Biodiversity and Ecosystem Services aCROSS EU policies
CBD	Convention on Biological Diversity
CFP	Common Fisheries Policy
CICES	Common International Classification of Ecosystem Services
DoA	Description of Action
DPISR	Drivers Pressures Impacts Status Responses
EBM	Ecosystem-based Management
EEA	European Environment Agency
EC	European Commission
MAES	Mapping and Assessment of Ecosystems and their Services
MSFD	Marine Strategy Framework Directive
HD	Habitats Directive
R&D	Research and Development
SES	Social-ecological Systems
SPBTT	AQUACROSS Science-Policy-Business Think Tank
TEEB	The Economics of Ecosystems and Biodiversity
WFD	Water Framework Directive

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 natural 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

To fight increasing pressing challenges (e.g. pollution, contamination, invasive species, overfishing and climate change) and build resilience to those pressures, EU environmental protection policy is taking action on multiple fronts to safeguard the status of aquatic ecosystems, as illustrated (among other policy initiatives) by the implementation of the Birds and Habitats Directives, the Water Framework Directive (WFD) and the Marine Strategy Framework Directive (MSFD). However, despite progress towards the individual objectives of these policies, EU directives as a whole have been unable to halt and reverse the trend of declining biodiversity of aquatic ecosystems. Actually, biodiversity is declining worldwide, and at a much faster rate in aquatic than in most terrestrial systems (Vaughn, 2010). This is compelling scientists and policy-makers to act together to identify effective policy solutions. Current and forecasted trends of biodiversity in aquatic ecosystems are raising substantial concerns over the consequences of biodiversity loss on ecosystem processes and functions, which subsequently affect the provision of ecosystem services (ESS), and ultimately affect human well-being (Maes et al., 2013).

International and European policy have quickly moved to set targets for the protection of ecosystems and biodiversity. At the international level, efforts are coordinated by the Convention on Biological Diversity (CBD), the main objective of which is to promote the development of national strategies for the conservation and sustainable use of biological diversity, mainly through articles 6, 7, 10 (conservation of biodiversity and sustainable use of biodiversity), and 17 (exchange of information) at national and European levels. Further efforts include a host of relevant protocols (e.g. Cartagena Protocol on Biosafety; Nagoya Protocol on Access to genetic resources and the fair and equitable sharing of benefits arising from their utilisation) and conventions (e.g. Convention on International Trade in Endangered Species; Bonn Convention on Migratory Species; Bern Convention on the conservation of European wildlife and natural habitats).

Efforts in Europe are framed under the objectives of the EU 2020 Biodiversity Strategy (EC, 2011), which aims to implement the Strategic Plan for Biodiversity 2011-2020 and the Aichi Targets (CBD-UNEP, 2010 and 2013). This strategy identifies six targets that cover the main factors driving biodiversity loss and aim to reduce existing pressures on nature. These are, in summary, (EC, 2014):

- Target 1: conserving and restoring nature through better application of the Birds and Habitats Directives with the goal of halting biodiversity loss and restoring biodiversity by 2020.

- Target 2: maintaining, enhancing and restoring (15% as minimum by 2020) ecosystems and their services, by integrating green infrastructure into land-use planning.
- Target 3: ensuring the sustainability of agriculture and forestry through enabling existing funding mechanisms to assist in the application of biodiversity protection measures.
- Target 4: ensuring sustainable use of fisheries resources by 2015 with the goal of achieving MSFD targets by 2020.
- Target 5: combating invasive alien species.
- Target 6: addressing the global biodiversity crisis and meeting international biodiversity protection obligations.

The "Mid-term Review of the EU Biodiversity Strategy to 2020", which has been recently published by the European Commission (EC) in October 2015, takes stock of progress made towards the strategy's targets and actions since it was adopted in 2011. Whilst the report recognises some improvement in the knowledge base generated and the achievement in the development of some policy frameworks, in relation to the key target of the Strategy, the review concludes that "at the current rate of implementation, biodiversity loss and the degradation of ecosystem services will continue throughout the EU" (EC, 2015a). This fact is illustrated by the comparison of current data observations and the EU 2010 biodiversity baseline indicators (EC, 2015a). The review identifies three main reasons for this failure: i) the weak level of implementation and enforcement efforts by Member States, ii) the need for more effective integration of relevant policies, and iii) the setting of "coherent priorities underpinned by adequate funding" (EC, 2015a).

In contrast to the level of certainty about the gloomy future depicted in the aforementioned mid-term review, the EC report is vague about proposing ways forward to halt biodiversity loss. The document merely states that implementation and enforcement efforts have to become "considerably bolder and more ambitious" and that there is a need to intensify the implementation of measures across all relevant policy targets (EC, 2015a). Overall, the lack of success in EU biodiversity protection policy can be seen as the sad result of the current static view towards EU environmental protection policies, their fragmented implementation, and the management divide between the public and private sector (EC, 2013).

The AQUACROSS project proposes the following actions as ingredients of the final recipe for implementation success in aquatic ecosystems to the specific objectives of the EU Biodiversity Strategy 2020 and the implementation of the Strategic plan for Biodiversity 2011-2020:

- Delivering a consolidated and coherent outlook on EU policy for aquatic ecosystems (Target 1 of the EU Biodiversity Strategy);
- Increasing knowledge on biodiversity and drivers of aquatic ecosystem change (Targets 2, 3, 4, 5, 6);
- Carrying out integrated assessments for all aquatic ecosystems including freshwater, coastal and marine systems and their linkages (Target 4) and delivering explicit mapping of ecosystem service provision (Target 2);
- Better understanding and uptake of (i) the application of blue/green infrastructure (Target 2) and (ii) broader EBM for aquatic ecosystems (Targets 3, 4, 5, 6);
- Supporting the management of Natura 2000 sites (Target 1) and invasive alien species (Target 5); and
- Testing business models for the provision of ecosystem services that will contribute to ecosystem protection (Targets 2, 3, 4, 5, 6).

Ultimately, the key concept in the AQUACROSS project is Ecosystem-based Management (EBM). EBM is understood as any management or policy options intended to restore, enhance and/or protect the resilience of the ecosystem. This encompasses any course of action purposely intended to improve the ability of ecosystems to remain within critical thresholds, to respond to change and/or to transform to find a new equilibrium or development path. Thus, EBM sets the foundations for the development of effective and widely applicable management concepts and practices for aquatic ecosystems. The EBM concept is concerned with ensuring that management decisions do not adversely affect ecosystem functions and productivity, so that the provisioning of aquatic ecosystem services (and subsequent socio-economic benefits) can be sustained in the long-term. EBM is also relevant for maintaining and restoring the connection between social and ecological systems. AQUACROSS also recognises EBM as a way to address uncertainty and variability in dynamic ecosystems in an effort to embrace change, to learn from experience and to adapt policies throughout the management process. EBM measures will need to be supported by an effective policy and governance framework that enables their adoption amongst a wide range of actors from public authorities to businesses, civil society organisations and citizens.

1.1 EBM definitions and policy application

Recent years have seen a vast number of policy related research and development (R&D) initiatives promoting a range of concepts, methods, and models that aim to support the achievement of EU and international biodiversity targets. By explicitly considering the full range of ecological and human interactions and processes necessary to sustain ecosystem composition, structure and function, EBM has become one of the most promising approaches (Tallis et al., 2010), encompassing a whole range of decision-making support tools (e.g. the EBM Tools Network[1]). EBM has, in that context, permeated scientific and policy practice related to the management of (aquatic) ecosystems (Nobre and Ferreira, 2009).

Several policy initiatives explicitly promote the application of EBM. In Europe, EBM is unambiguously mentioned for the implementation of marine and climate change adaptation policies and the design and assessment of subsequent management practices towards the achievement of the stated objectives (see Box 1).

Box 1: Example of policy definitions of EBM

Policy	EBM definition	Reference
Convention on Biological Diversity (CBD)	"The ecosystem approach is a strategy for the integrated management of land, water and living resources that promotes conservation and sustainable use in an equitable way" and which aspires to maintain the natural structure and functioning of ecosystems.	Conference of the Parties (decision V/6)
Marine Strategy Framework Directive (MSFD)	The marine strategies shall apply an ecosystem-based approach, which the MSFD broadly defines as "management of human activities, ensuring that the collective pressure of such activities is kept within levels compatible with the achievement of good environmental status and that the capacity of marine ecosystems to respond to human-induced changes is not compromised, while enabling the sustainable use of marine goods and services by present and future generations".	EC, 2008
EC Climate Adaptation Strategy	"Management, conservation and restoration of ecosystems, as part of an overall adaptation strategy that takes into account the multiple social, economic and cultural co-benefits for local communities. Adaptation is facilitated through both specific ecosystem management measures (e.g. managed	Based on EC, 2013

[1] http://www.ebmtools.org/about_ebm.html

Policy	EBM definition	Reference
	realignment) and through increasing ecosystem resilience to climate change (e.g. watershed management, conserving agricultural species genetic diversity)".	
Common Fisheries Policy (CFP)	The Common Fisheries Policy defines EBM as "ecosystem-based approach to fisheries management' means an integrated approach to managing fisheries within ecologically meaningful boundaries which seeks to manage the use of natural resources, taking account of fishing and other human activities, while preserving both the biological wealth and the biological processes necessary to safeguard the composition, structure and functioning of the habitats of the ecosystem affected, by taking into account the knowledge and uncertainties regarding biotic, abiotic and human components of ecosystem".	EC, 2014

All of these policy definitions promote integration across ecological and social systems, the use of environmentally friendly practices/sustainability, and the consideration of environmental limits and thresholds. Fundamentally, they all have in common that they promote the need to adapt planning and management to the dynamics of whole ecosystems to preserve and enhance their potential or capacity to continue to deliver the services and benefits upon which human societies depend (EEA, 2015). However, they differ in their view of the connections between society and ecosystems; from the MSFD which defines EBM as a way to reduce pressure on the marine environment; to the EU Biodiversity Strategy that focuses the definition of EBM on integrated management; to the Adaptation Strategy that emphasises the resilience dimension (Gunderson, 2001); and the CFP which, arguably, could be seen as the most comprehensive of all reviewed definitions and establishes linkages with the ecosystem services concept.

These policy initiatives have ignited a number of useful tools and products for decision-making, but a major challenge remains in the establishment of an operational framework that links, in a cost-effective way, the assessment of biodiversity and ecological processes and their full consideration in public and private decision-making. EBM remains challenged by conceptual and implementation limitations, in particular regarding i) the lack of explicit consideration of the ecosystem services concept (Jordan et al., 2012), which would critically help link ecological assessments with the achievement of human well-being, thereby enhancing the relevance of achieving biodiversity targets for a range of public and private actors; ii) a primary focus on ecological dimensions rather than on social-ecological processes (Berkes, 2012), which would enhance the integrated understanding of relevant dynamics and feedbacks; and, in this context, iii) the lack of attention to trade-offs, uncertainties, and thresholds inherent in the management of (aquatic) ecosystems (Curtin and Prellezo, 2010).

In summary, there is a policy need for a consolidated practical definition that addresses the different dimensions in the interpretation of EBM. These dimensions are: i) understanding complex/integrated social-ecological systems (SES), ii) factoring in resilience, and iii) accounting for ecosystem services.

1.2 Expanding knowledge in the practical application of EBM approaches for the achievement of biodiversity targets in aquatic ecosystems

Sustainable and innovative management solutions to achieve biodiversity targets for aquatic ecosystems are most effective and efficient if coordination and cooperation between different policy areas are ensured. At the same time, innovative business solutions and engagement with private efforts working with policy and other relevant societal actors are essential to protect aquatic ecosystems and to ensure that biodiversity is maintained at levels needed to provide ecosystem services and human well-being (OECD, 2012).

Ultimately, an advanced understanding and new science to assess aquatic ecosystems and the complex interactions they hold is needed to generate better descriptions and quantifications of the linkages between socio-economic and ecological systems, so that practitioners can begin to consider the practical application of EBM approaches across aquatic ecosystems. In practical terms, this includes a better understanding of the aquatic ecosystem state (and functioning), the services these ecosystems deliver, the pressures that impact them, and the causes of these pressures (economic and social, as well as the outcomes of ecosystem processes), including their thresholds and tipping points when impacted by changing drivers and pressures (Barbier et al., 2011; Borja, 2014; Dolbeth et al., 2016). Data and information from different European initiatives need to be compiled and combined with new findings and research to enhance the impact of research and to ensure the efficient use of state-of-the-art knowledge and science for policy, management, business, and society. This approach is in line with the goals of the EU

2020 strategy –'*A strategy for smart, sustainable and inclusive growth'* (EC, 2010), foreseeing Europe to emerge stronger from the economic and financial crisis.

The AQUACROSS concept introduced in this deliverable aims to make EBM an ecosystem-service and resilience-oriented concept that can be made fully operational in the context of the management of aquatic ecosystems (inland, coastal and marine). The AQUACROSS Assessment Framework (AF) will, for the first time, generate consistency of analysis across aquatic realms. These conceptual developments will be uniquely embedded in practice and ground-proofed via integrated and coordinated policy assessments, as well as stakeholder engagement and the consideration of management options through case studies.

1.3 Objectives of this Deliverable

In order to reach AQUACROSS' ambitious workplan, a critical first step consists of developing the AQUACROSS innovative concept: a structured set of ideas and hypotheses aimed at steering research efforts.

The key purposes of the AQUACROSS innovative concept are:

- Representing scientific consensus on ecosystem services, structure and functions and their connections with socio-economic systems in such a way that can be understood and taken up by end-users and policy-makers;
- Integrating scientific fields with different concepts, data, information tools, methods and approaches into a holistic framework to inform policy-making;
- Facilitating collaborative model development through meaningful communications between scientists, stakeholders and other end-users, and policy-makers;
- Identifying opportunities linked to biodiversity conservation, protection and restoration of ecosystems processes and functions, which can improve human well-being, and are socially relevant to foster cooperation amongst stakeholders across policy domains;
- Assessing barriers, trade-offs and synergies of the different alternatives available to change current practice and to design and implement EBM approaches;
- Assessing drawbacks of traditional approaches and making the advantages of holistic approaches more visible;
- Representing and analysing uncertainty about scientific outcomes and developing criteria and methods to assess the robustness of alternative courses of action;

- Supporting the development of articulated targets in terms of managing ecosystems and the services they deliver, as well as to manage risks in the long-term.

The particular objectives of this document as part of the AQUACROSS strategy are:

- Reviewing available concepts and approaches that are relevant to the project objectives, as above;
- Examining key concepts and knowledge gaps aimed at improving EBM approaches along the continuum of freshwater-coastal-marine systems;
- Developing a glossary of terms to (i) foster common understanding and agreement and further applications across multiple disciplines, areas of expertise, and the relevant realms and (ii) to ensure that these concepts are consistently used;
- Specifying key research questions for the achievement of the practical objectives of the project and paving the way for a smooth uptake of outcomes by end-users;
- Using these concepts to build the basic structure of the AF, a collectively built knowledge base that will be the conceptual and operational backbone of the project.

Box 2: The AQUACROSS concept and beyond

The above-mentioned objectives will be collectively pursued from the beginning to the end of the project.

According to the Description of the Action (DoA), the innovative AQUACROSS concept is part of Task 3.1 (Framing the AQUACROSS Assessment Framework), and aims at providing a solid foundation for the initial scientific consensus within the project consortium (Deliverable 3.1: The AQUACROSS Innovative concept – this document).

The output of this task will be used as the foundation for the development of the Assessment Framework (AF) to be delivered at the end of month 15 (Task 3.2). The AF will ultimately present the scientific consensus on the AQUACROSS concept and on the methods and tools to be developed in the different Work Packages (WPs) and implemented in the project's Case Studies (CSs).

The AF will be updated and upgraded on the basis of lessons learnt and the findings and experiences from WPs and CSs, as well as on expert judgements and recommendations from end-users, stakeholders, including the AQUACROSS Science-Policy-Business Think Tank (SPBTT).

In brief, this document presents the basic concepts and outlines the research strategy to be followed. Section 2, below, focuses on the AQUACROSS innovative concept itself. It aims at mobilising and weighing up existing scientific knowledge to provide a comprehensive view of social and ecological systems and on the way they interact. On the basis of this, Section 3 presents the AQUACROSS architecture, a comprehensive analytical structure to make the AQUACROSS concept operative so as to better inform policy-making processes regarding biodiversity conservation and ecosystem services delivery. Section 4 presents the key conclusions and the way forward.

2 The AQUACROSS Concept

AQUACROSS' holistic approach to sustainability considers social (including economic) and ecological systems as being complex, adaptive, and mutually interdependent. Hence, AQUACROSS builds upon the understanding of both systems and their interlinkages to develop innovative management approaches and tools focused on the restoration and protection of critical aquatic ecosystem components as a means to sustain biodiversity and the delivery of ecosystem services in the long-term.

Over the past century, socio-economic and ecological systems have become increasingly interconnected and a wide majority of environmental issues have unveiled their global nature. The growing scale of economic activities, market globalisation, population change, coupled with progress in poverty mitigation and improvements in living standards in wide areas have led to gradually more complex developmental issues associated with a declining resource base, mounting uncertainties and a range of environmental and human development challenges (i.e. climate change, biodiversity loss, floods, droughts and other risks).

This has revealed the reliance of society and the economy on the environmental services provided by ecosystems (MEA, 2005; TEEB, 2010; MAES, 2013 and 2014) and has made the importance of those ecosystems to shape production and consumption patterns at local and global scales even more evident than ever before. In actuality, the transformations on Earth induced by economic and social change might have turned humankind into a major force able to shape nature both at local and global scales (Folke, 2005) to such extent that it may have defined the dawn of a new geological era: the Anthropocene (see Steffen et al., 2007; Hamilton et al., 2015). All this brings forth the discussion of mankind's collective capacity to manage the transition towards a sustainable balance between humankind and nature (Steffen et al., 2011; Chakrabarty, 2009) and the need for new forms of governance, better suited to the new circumstances.

2.1 Complex adaptive systems

The challenges above are difficult to handle, as social and ecological systems are mutually interdependent and form complex adaptive systems (Levin et al., 2013), whilst being components of the whole system as such. A holistic approach may provide the basis to analyse how society and nature, as complex adaptive systems, are linked to each other both at the micro and the macro levels and how these linkages give rise to the dynamics we observe at the system (macro)level. In addition, it may help analyse the role of mutual adaptation/co-evolution. Moreover, the study of social and ecological systems as complex and adaptive ones is still an emerging research programme.

The comprehensive assessment of all the pathways and feedback loops through which society and nature may interact at local and global scales remains an impracticable task. However, a holistic approach is still feasible and may result in promising research developments when applied to specific policy challenges in well-defined temporal and spatial contexts and taking into consideration a set of significant ecological and social interlinkages (as it is the case of AQUACROSS project).[2]

Within this context, a good starting point to set up the basis for an ambitious analysis of the interlinkages between society and nature is to question what social and ecological systems have in common and whether or not using shared concepts and methods could pave the way for their study. From AQUACROSS' standpoint, complexity and adaptive systems' theory provides this common ground.

Box 3: What does a complex adaptive system stand for?[3]

Complex adaptive systems (such as an economy or an ecological system) consist of many local or micro-level adaptive agents making predictions of one another's behaviour and responding to information and signals from their neighbouring environment. The structure, functions and dynamics of the system at the macro-level are not planned by a central control but emerge from the interaction and interconnectedness of their constituent parts and of the system with other complex adaptive systems. Complex adaptive systems are self-organising entities.

The notion of complexity refers to the interaction, interrelationships and interconnection amongst the multiple parts of a system and between a system and its environment. Actually, both social and ecological systems are **shaped by micro-**

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[2] The notion of complex adaptive systems combined with the resilience approach for their study and management have served to structure a multi- and transdisciplinary research program that advances through the application of emerging concepts and methods towards an increasing number of domains and places (such as marine ecology, river ecology, coastal management, etc.). For an account on how these concepts have co-evolved through applied research since they were coined in the early 60s, see for example Folke (2005).

[3] The notion of complex adaptive systems has its origins in information theory but its extension to the analysis of "real" natural and social system is attributed to the 1969 Nobel prize-winning physicist Murray Gell-Mann (1994).

level interactions amongst, for example, buyers, sellers, firms and households in the different markets or between individuals from the same and different species throughout different space and time scales in an ecosystem. Both systems can be represented as networks formed by many individuals or units acting in parallel and responding to the signals, stimuli or additional information received from their surrounding environment.

Ecological systems, like contemporary economies, do not have a central governing unit in control of the system's behaviour. Rather, to a significant extent, the system's control is scattered and decisions are largely made by individual units. Each unit behaves according to simple rules of thumb - for example, buying or not a good or service depending on its price in the case of a customer; following the herd, the stream or a heat gradient in the case of migratory species; finding the fastest way downhill in the case of water runoff. This implies that all these simple actions or decisions are **interconnected** and that all elements in the system could change based on the interactions among their parts and between each part with its neighbouring environment. At this micro level, rather than by static equilibrium, the system is characterised by the continuous change induced by actions and reactions of its constituent elements.

Most individuals, either actively or passively, adapt to changes in their environment and to others' adaptive changes by changing behaviour, migrating, dying, mutating, etc. Thus, it is important to understand how short-term, local, individual behaviour leads to system level and/or longer-term consequences. However, the interaction and interconnection of individual units within the system and between the system and its environment creates a **complex system** overall.

Complex systems can be represented and described by their fundamental components, the structure and the functions performed by each of them or the overall performance of the entire system. The lack of central control does not entail chaos, and the system still shows order. Coherence may result from the constant non-equilibrium movements and actions despite the fact that each agent follows its own interest, as in the market economy, or reacts only to its closer environment. In this sense, ecological systems are relatively **autonomous, self-organised systems,** just as economies and markets (Krugman, 1996).

2.1.1 Interlinkages between ecological and socio-economic systems (and the cost of overlooking them)

The increasing interconnections between socio-economic and ecological systems challenge the conventional separation of natural and social sciences. Evolution in biological sciences is not tractable anymore, if restricted to the study of undisturbed environments. Similarly, the study of economic development is increasingly uninformative and meaningless, if considerations about resource availability and environmental conditions are not factored in the analysis of the other. Plausibly, the increasing interdependence of nature and society highlights the well-established idea that social and ecological systems are only the interacting components of a whole SES shaped by the mutual adaptive dynamics of its parts.[4]

The AQUACROSS concept considers the two main components of this whole system (i.e. social and economic system on one side and the ecosystem on the other), and comprehends them as complex adaptive systems in themselves. Therefore, all analytical models should account for trade-offs implied by the interaction between these two intertwined adaptive systems.

AQUACROSS aims at mobilising and integrating knowledge, so as to understand how social and ecological systems are linked, both at the micro- and macro-levels. Elaborating these linkages enables the understanding of how these linkages give rise to the dynamics seen at the SES level and to deepen the knowledge on the role of mutual adaptation/co-evolution. Furthermore, AQUACROSS aims at contributing to bridge this knowledge gap without ignoring the basic fact that yielding analytical results on, and modelling of, all complex processes involved in social and ecological systems is a chimera.

Rather than setting our research questions at this ambitious and abstract level, the AQUACROSS strategy turns the spotlight on a more practical question: making the best out of existing knowledge to develop a comprehensive understanding of both social and ecological systems and their mutual interactions, what are the practical lessons to be taken into account to provide a better political response to current sustainability challenges in all policy domains linked to water and biodiversity? This entails considering the inherent limitations and challenges of existing knowledge so as to develop a better response to how a complex adaptive system -characterised by self-organisation and nonlinear dynamics- must be managed and to overcome common attempts at controlling selected variables that are doomed to failure.

Opportunities linked to a holistic approach, such as the one adopted by AQUACROSS, take the benefits of accounting for the mutual interdependencies between social and

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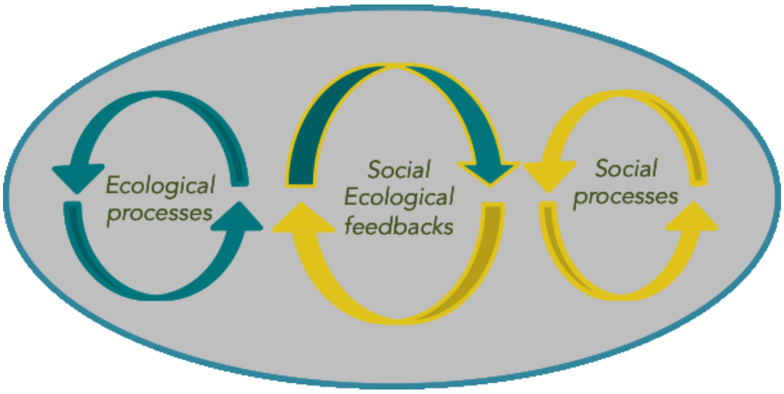
[4] See for example Gual and Norgaard (2010) for a review of the theory of coevolution of ecological and social systems, an old intuition that can be traced back to Darwin (see Hodgson, 2010) but that still is an important foundation for future research (Waring, 2010).

ecological systems to the policy arena. At these early stages of the project, the best prospects must be found in cases where the costs of ignoring the critical adaptation feedbacks are more evident and have already led to major detrimental effects over biodiversity and human well-being.

One important hypothesis is that economic (and decision support) models that do not consider complex adaptive natural and social systems may well lead to socially and ecologically undesirable outcomes. In fact, disregarding these interconnections – as it commonly happens both in individual and collective decisions – may often exacerbate problems.

Figure 1: Ecological and socio-economic systems as two interconnected complex adaptive systems



Source: Own elaboration based on Biggs et al. (2015), p.8

Prevailing best practice consists in optimising the delivery of particular ecosystem services (food, energy, safety, etc.) and seeks to maximise the production of specific components of the system (such as water quantity or fish biomass), through controlling others (water storage, flood risk, etc.), at a limited scale (mostly local), and for a limited time frame (mostly in the short-term). This practice sets aside or assumes that no changes in the functions and structure of ecosystems occur on broader spatial scales and through the medium- and longer-term (Walker and Salt, 2006; Levin et al., 2013).

Despite what optimal resources management models may suggest, dynamic systems cannot stay steadily in an ideal optimal status chosen to deliver maximum sustainable yields of fish, freshwater or wood, just to mention a few examples. Furthermore, ecosystems and natural resources are not affected by single disturbances, like extraction rates or pollution loads, but rather by disturbance regimes represented by the pattern and dynamics of disturbances that shape the ecosystem itself in the long-term (see Pickett and White, 1985).

Although minor changes in complex systems are often linear and incremental, ecosystems are only stable within critical thresholds and might change into alternative stable states due to disturbance regimes (Beisner et al., 2003; Beisner, 2012). Permanent disturbances and extreme events such as droughts, floods and storm surges are able to reorganise system properties and affect biodiversity. For instance, different studies of aquatic, forest and other ecosystems show that smooth changes can trigger sudden variations in regimes, and lead to the irreversible loss of ecosystem services (Scheffer et al., 2001). Similarly, minor changes in sediment transport may trigger a catastrophic drift of stream invertebrates (Gibbins et al., 2007).

These perspectives widen the opportunities for targeting policy interventions but also come along with new policy-relevant research questions. One of these questions refers to the complex feedback between ecosystem structure, functioning and services and biodiversity and, in particular, on how disturbance determines community diversity, and in turn, how diversity, in turn, determines the reactions to disturbance severity (Hughes et al., 2007).

Hence, common practice to manage aquatic ecosystems -mostly focused on single major pressures, with partial analysis focussing on single provisioning services, and assuming marginal incremental changes and linear dynamics- increased the risk of leading the system close to a critical threshold (non-linearity), and then to be exposed to a regime shift in the face of an extreme event. For instance, agricultural subsidies and water scarcity may have led to the overallocation and overexploitation of water use rights and might have increased water scarcity and droughts exposure (Gómez and Pérez, 2012). In a similar way, business and policy models of commercial fisheries management led to demand and supply levels that exceeded the natural productive potential. This has increased pressures over new fishing grounds located in biodiversity hot spots (World Bank, 2004).

In a similar way, acknowledging SES as dynamic and adaptive should lead to a redefinition of realistic and forward-looking management targets. Therefore, rather than focussing on sustained yields and static equilibrium, management strategies should focus on **persistence** or the ability of the SES to stay within critical thresholds and to adapt and reorganise when necessary, in order to provide essential functions.

2.1.2 Policy implications of complex adaptive social-ecological systems

The notion of complex adaptive systems represents a radical departure from managing single control variables aiming at optimal deterministic state variables. It helps overcome some relevant drawbacks of conventional mechanistic and deterministic approaches. These approaches consider optimal solutions, linear dynamics, and marginal changes in the surroundings of a single equilibrium under complete information and almost perfect foresight on resource and environmental management.

Holistic approaches call for a shift towards a more dynamic and organic way of thinking in which non-linear changes, uncertainty, and even surprise are intrinsic characteristics of the system. Whilst making this approach operational is still work in progress (see Biggs et al., 2015), the notion of social and ecological systems as complex adaptive systems already sheds light on the limitations of deep-rooted approaches to governance and policy-making, let alone on the risk of going further with traditional approaches to respond to new environmental and social challenges (see Levin et al., 2013).

This is the case of the many risks linked, for instance, to assuming **perfect foresight** in freshwater management. The usual practice of projecting past rainfall and runoff patterns into the distant future, and using these projections as the baseline to design and assess policy interventions, is the equivalent of leaving the main drivers of current changes in water ecosystems aside from the policy-making process; in practice, this will result in increasing exposure of the economy and ecosystems to climate and weather extremes, and water-related disasters and regime changes.

Similarly, assuming **linear dynamics** will render the analysis unable to explain sudden regime shifts, such as in coral reefs affected by turbidity (Crépin, 2007), and more generally in lakes, rivers and marine environments (e.g. Haghighi and Kløve, 2015; Naeem and Wright, 2003). Non-linear dynamics imply that multiple potential steady states and transitional dynamics outside equilibrium and among alternative regimes may be analysed, as they are all relevant to decide the type of policy intervention. Thus, policy options may be aware of initial conditions, past actions, etc., and may lead to opening or broadening choices in the future.

Additionally, neglecting the **interconnectedness** of the components of an ecosystem may lead to ignoring the risks of managing single species (i.e. flagship species) or individual ecosystem services, while ignoring how they are connected with other components of the system. For instance, ignoring the interaction of species in fisheries management may leave uncertainties out of the policy-making process and increase the risk of collapse of commercial and non-commercial species (Carpenter and Brock, 2004; Crépin, 2007). More generally, neglecting the interconnectedness between social and ecological dynamics can lead to wrong assessments of the likelihood of a regime shift as shown in Lade et al. (2013) and/or to design and implement policy responses that are prone to failure due to neglecting adaptive responses at both the social and ecological level (Hill et al., 2015).

Overlooking **spatial patterns and dynamics** may lead to incorrect policy responses. In actuality, choosing the adequate scale of intervention in complex systems is a critical factor that may determine the outcome of policy options. For example, managing water at a farm level may lead to undesirable outcomes if the links with the catchment hydrology are ignored. This happens, for instance, when shifting towards a more water efficient irrigation technique; while desirable at a plot level, this reduces physical return flows, hence groundwater recharge and surface runoff downstream (Ward and Pulido-Velázquez, 2008).

Besides leading to wrong policy recommendations, regulating part of a system without regard of the interlinkages to the other parts may lead to the neglect of opportunities to improve well-being linked to the protection of ecosystems and biodiversity. For example, when ecological and economic components are factored into the analysis, marine protected areas (MPAs), even in areas of low net primary productivity and low fishing costs, may become effective marine spatial management instruments to increase revenue and profits of fisheries locally, but also at regional and global scales (Sanchirico et al., 2006).

Uncertainty is inherent to complex adaptive systems and their management. In addition to the known unknowns in consolidated management approaches that are burdened by the lack of data on species and past trends, complex systems come with new uncertainties. Under this new perspective, the role of ecosystem features and components such as water interfaces (e.g. ecotones) on biodiversity and ecosystem resilience needs to be properly understood and mainstreamed into policy-making. Furthermore, appropriate policies should be assessed, defined and implemented at relevant spatial scales. Yet, limited knowledge on ecosystem functions and dynamics and how systems adapt to policy interventions, (e.g. how close they are or may be to critical thresholds) are good examples of the new unknowns that cannot be tackled through standard sensitivity analysis[5] (Polasky et al., 2011a and 2011b).

[5] Also known as irreducible uncertainty.

2.2 Resilience as a management criterion to build sustainability

In the face of ongoing changes and their uncertain future consequences, given the inescapable exposure to uncertain shocks, the key to sustainability consists in enhancing the resilience of the whole social-ecological system (SES). Within this context, the main governance challenge lies in preserving the capacity of SES to remain within a certain range of conditions to meet collective and individual development goals, and to ensure the continuous provision of a desired set of ecosystems services we and our economy depend on.

Box 4: What are resilience and resilience thinking all about?

- **Resilience** is a general characteristic of a system that results from its ability to respond to change, perturbations and disturbance regimes (adaptability), and transform when necessary. It is closely connected with the diversity of ecosystems and species (heterogeneity), the capacity of a system to contain or spread a perturbation along its constituent parts (which depends on the system modularity), and the capacity of a particular part or population to recover after a shock has taken place (which is linked to the system connectivity).
- **Persistence** is the tendency of a SES's ability to change to remain within a stability domain, continually changing and adapting yet remaining within critical thresholds.
- **Adaptability**, a defining component of resilience, is the capacity of a SES to adjust its responses to changing external drivers and internal processes and, thereby, allow for development within the current stability domain along the current trajectory. **Transformability** is the capacity to create new stability domains for development and a new stability landscape, and to cross thresholds into a new development trajectory.
- **Resilience thinking** is a framework approach to sustainability that emphasises the interdependency of humans and ecosystems, in which SES are complex adaptive systems and that cross-scale dynamics matter to support the deliberate transformation of SES. Resilience thinking aims at: 1) assessing the relative merits of the current versus alternative, potentially more favourable stability domains, and 2) fostering resilience of the new development trajectory. It focuses on the three aspects of SES: resilience as persistence, adaptability, and transformability (Folke et al., 2010).[6]

[6] Biggs et al. (2015b) identified 7 elements that must be enhanced through deliberate transformations. 3 are characteristics of the social-ecological system to be governed: diversity (which includes redundancy), connectivity (which includes modularity), and managing slow variables and feedbacks. The other 4 are characteristics of the governance system (complex adaptive systems thinking, learning, participation and polycentric governance).

In other words, this is equivalent to building the resilience of SES as a means to make human development sustainable (Biggs et al., 2015b). The following three defining characteristics of resilience and resilience thinking (see Box 4) are of particular relevance for the AQUACROSS concept and for the project research strategy:

1 *Resilience thinking is a framework to support policy decision-making processes aimed at overcoming the vulnerability and the long-term negative consequences of current practices over human development*.

   Since adaptability and the value of preserving options for the future have been largely ignored in traditional policy decisions, these choices have resulted in reduced diversity and heterogeneity. Market conditions have favoured most profitable crops and animals at the expense of less productive ones. Land use practices, driven by policy and market forces, have fostered uniform ecosystems at the expense of valuable environmental services such as water regulation, pollution control, health security, or biodiversity support.

   These practices are nevertheless vulnerable to a change in current environmental conditions, as they promote the reduction of biodiversity levels interfering with ecosystem function and the services they deliver (Altieri, 1999). For instance, the transition to simplified invertebrate fisheries, favoured by fishing practices aimed at maximising the production of targeted species, has triggered severe shifts to ecological states that are undesirable against both economic and ecological criteria. Further, they accelerate biodiversity decline in broader marine areas, threaten food security and leave the species remaining exposed to the risk of collapse due to disease, invasion, pollution and climate change (Howarth et al., 2014).

2 *Resilience thinking is a framework to mobilise existing knowledge and to identify critical knowledge gaps* that may enhance the capacity to manage the transformation of SES by deliberate interventions over specific components at selected scales but with the potential to enhance the resilience and the sustainability of the entire SES.

   It favours the combination of different sources of information and knowledge to surf over different scales, to halt detrimental pathways, and to foster a regime change in the desired direction.

   Resilience thinking supports taking advantage of focused interventions at smaller scales with the potential to activate resilience at larger scales. For instance, even small marine reserves in remote and relatively well-conserved areas could allow for the restoration and protection of essential marine ecosystem services. As a result of that, the impacts may spill over to biodiversity and fish populations in the broader ocean (Sumaila et al., 2015; Thurstan et al., 2013) and that may be the source of economic benefits at local and global scales to an extent that, in fact, may exceed the foregone rents of fishing effort in the area (Sumaila et al., 2015).

On the other hand, resilience at higher scales can improve the capacity to transform at smaller scales. Change in larger scales may favour interventions at lower ones. Besides contest from stakeholders that may bear the opportunity costs of high seas marine reserves, such as those around Pitcairn and the Eastern Islands, their implementation was actually largely impeded by the lack of means to deter industrial illegal trawling until a global governance breakthrough based on innovative satellite monitoring technologies (such as the "Eyes of the Sea" project based on the Catapult software) allowed a regime shift and both reserves were recently declared and enforced.[7]

3 *Resilience thinking stresses upon the importance of governance and institutions as the keystone that explains the adaptive capacity of socio-economic systems.*

Rather than choosing optimal paths and decision rules in a deterministic framework, facing current risks and considerable uncertainties requires governance frameworks able to adapt to the multiple circumstances that may prevail in the foreseeable future.

This leads to the promotion of governance frameworks able to reconcile the conflicting interests and visions of different stakeholders in a transparent and accountable way, so as to foster cooperation among them and enhance their ability to commit to legitimate and transparent policy objectives (Dietz et al., 2003). In addition, they should also pave the way to achieve collectively agreed goals through robust institutions with stakeholders able to adjust regularly to changes in the ecological and the socio-economic systems (Nelson et al., 2006).

Yet, whilst the notion of building resilience may be generally accepted as the backbone of sustainability, the means and ends of a resilience strategy are far from being the outcome of a technical or a scientific deliberation. This issue actually belongs to the policy-making process, hence to the social and economic side of the system. The following reasons explain why choosing the means to build sustainability and enhance resilience is, after all, a governance challenge:

[7] See, for example: http://www.pewtrusts.org/en/about/news-room/press-releases/2015/01/21/pew-unveils-pioneering-technology-to-help-end-illegal-fishing

- *Building a sustainable future requires deliberate transformation of the SES as a whole.* Required transformations must encompass changes in both the socio-economic system, to enhance its adaptive capacity, or the ability of institutions and individuals to respond to change, and also in the ecological system, to enhance its capacity to seamlessly deliver critical environmental services.
- *Choosing the means and tools to build resilience implies making a decision over different governance Catch-22s.* Trade-offs stem from different sources, such as the conflicting interests amongst stakeholders, the balance between short- and longer-term benefits, the need to forgo current rents in exchange of future security, or the local opportunity costs and the benefits.
- *Actually, changing detrimental trends and making a system more adaptable entails significant trade-offs that can be factored in with the help of the resilience thinking approach, applied to both social and ecological systems* (see, e.g. Janssen and Anderies, 2007; Stepanova and Bruckmeier, 2013; Villamayor-Tomas et al., 2014).

  Restoring or preserving the ability to absorb change may have sizeable opportunity costs in the short-term that should ideally be weighed against long-term benefits of sustainability. For example, soil conservation practices may contribute to resilience by reducing flood and drought risks (through natural water retention), by stabilising farmers' income and might also have significant co-benefits in terms of water quality and terrestrial and aquatic biodiversity. Nevertheless, they might also reduce crop yields while increasing production costs and exposure to pests (Rodríguez-Entrena et al., 2014).

  For instance, when improving the connectivity and decreasing the intensity and frequency of flooding in urban floodplain restoration, there are trade-offs with drinking water production as the risk of contamination might increase (Sanon et al., 2012). Similarly, building dikes to cope with flood risk would increase short-run resilience to small periodical floods and investment security, but would not be effective at all to tackle large floods, making the same people more vulnerable to climate change in the long run (Palmer et al., 2008).
- *Adaptability also implies a tension between the benefits of adapting economic and social decisions to current priorities and demands and/or preserving the options for the future to maintain sufficient variation to respond to new environmental challenges* (Norberg et al., 2001; Levin et al., 2013).

  Likewise, adaptability implies a trade-off between **modularity**, which prevents harmful properties to spread throughout a system, such as invasive species in ecosystems and recessions in economies (May et al., 2008), and **connectivity** of local populations that may help recover depleted populations after an extreme event, such as a storm or a wildfire. This may also be the case for economies that may smooth the downturn after a financial crash, but can also contribute to systemic risk through spreading disturbances (Biggs et al., 2012; Crook et al., 2015).

- *Globalisation reshapes the connection between ecosystems and socio-economic systems in positive and negative ways*. It may favour a more efficient allocation of critical resources by conveying information about water and energy scarcity into global markets and by creating incentives for resource efficiency and innovation, in particular if local and global prices reflect current scarcities. However, it may also ignite detrimental dynamics like freshwater overexploitation, water quality degradation, invasion of alien species, damming, land use in floodplains and mining. In many cases, globalisation can result in scale mismatches causing disconnections between the scales of economic drivers and environmental pressures (Cash et al., 2006; Henle et al., 2010; Veldkamp et al., 2011).

Additionally, mainstreaming the resilience thinking approach into policy-making requires the design and implementation of innovative research strategies that are able to deal with crucial methodological challenges involved in operationalising the resilience thinking approach, such as the following ones:

- Assessing the resilience of a complex system involves a basic trade-off between the analytical approaches required to understand critical linkages, particular disturbances at local scales, etc., with the ambition of understanding systemic interactions at a global scale. Any attempt to make resilience thinking operational comes along with the dilemmas that are inherent to scientific research (analysis-synthesis, general-specific approaches, etc.). Some authors have pointed to the difference between "specified resilience", from "something to something" and "general resilience" that neither focuses on a particular system's component nor on a set of disturbances (see, e.g. Carpenter et al., 2001; Folke et al., 2010).
- *Applied resilience thinking is only feasible when dealing with particular environmental problems (specified resilience).* These specific problems may arise, for example, from well-defined disturbances offering opportunities to the analyst to balance the need to find meaningful explanations about the critical interlinkages at play with the ambition to frame his/her research into a holistic framework.
- *Nevertheless, resilience thinking sheds light on the disadvantages of being too specific*. In particular, it brings to the forefront the risk involved in making policy

decisions based upon research outcomes that leave relevant scales, critical thresholds, linkages to other systems, etc., aside and ignores irreducible uncertainties and surprises leading to wrong policy responses. This actually entails a compromise between the apparent accuracy of fully specified models and tools and the need to frame policy-making into holistic frameworks (hence, conforming with abstract models, qualitative analysis, unbounded uncertainties, responses that are not necessarily operational at the scale or to the process to which they must be implemented, etc.).

Summing up, a resilience approach to sustainability assumes a close and strong interaction between socio-economic systems and ecological systems, which are both complex adaptive systems subject to sudden and unpredictable non-linear changes. It also recognises that ecological and social processes are interconnected across multiple scales, both in time and space. Hence, resilience thinking calls for governance approaches able to deal with uncertainty, to curb down unsustainable trends, to build capacity to sustain human well-being in the presence of uncertain changes by absorbing shocks, and adapting or transforming in response to change (Biggs et al., 2015b; Walker and Salt, 2006). Building resilience for a particular system, thus, implies policy decisions on balancing heterogeneity, redundancy, modularity and connectivity at appropriate temporal and spatial scales (Elmhirst et al., 2009; Levin et al., 2013). Within this context, research strategies aiming at supporting policy-making must cope with the challenge of making a holistic approach operational and to support managing specific ecosystems and processes within existing institutional setups at local scales relying on imperfect and incomplete information.

2.3 Ecosystem-based Management

Managing complex interactions between socio-economic and ecological systems calls for governance approaches to focus on ecosystem resilience, that is to say, on the capacity of ecosystems, including their structure and functions, to continue delivering ecosystem services in the event of gradual variations and abrupt changes.

Ecosystem-based Management (EBM) stands for any management or policy options intended to restore, enhance and/or protect the resilience of an ecosystem. This encompasses any course of action purposely intended to improve the ability of the ecosystems we care about to remain within critical thresholds, to respond to change and/or to transform to find a new equilibrium or development path.

EBM must be assessed, designed and implemented to maximise contributions to the resilience of the overall socio-economic and ecological systems.

Box 5: Ecosystem-based Management: one concept, several definitions

Ecosystem management is "an approach to maintaining or restoring the composition, structure, function, and delivery of services of natural and modified ecosystems for the goal of achieving sustainability. It is based on an adaptive, collaboratively developed vision of desired future conditions that integrates ecological, socioeconomic and institutional perspectives, applied within a geographic framework and defined primarily by natural ecological boundaries" (MEA, 2005).

"The ecosystem approach is a strategy for the integrated management of land, water and living resources that promotes conservation and sustainable use in an equitable way. It is based on the application of scientific methodologies focused on levels of biological organization, which encompass the essential processes, functions and interactions among organisms and their environment. The ecosystem approach aspires to maintain the natural structure and functioning of ecosystems and recognizes that humans and their action are an integral component of ecosystems" (Naumann et al., 2011).

"An approach to maintaining or restoring the composition, structure, function and delivery of services of natural and modified ecosystems for the goal of achieving sustainability. It is based on an adaptive, collaboratively developed vision of desired future conditions that integrates ecological, socioeconomic and institutional perspectives, applied within a geographic framework, and defined primarily by natural ecological boundaries." (MEA, 2005; Meffe and Carroll, 1997; Kettunen et al., 2007).

The Ecosystem Approach is a resource planning and management approach that integrates the connections between land, air, and water and all living things including people, their activities, and institutions (Farmer et al., 2012).

Hence, EBM consists of actions to enhance, restore and/or protect the ability of ecosystems to contribute to sustainability through the secured provision of a valuable set of ecosystem services, when facing either gradual changes or sudden and unexpected perturbations (see Box 5). It includes strategies to maintain and restore natural ecosystems, protect vital ecosystem services and reduce water and land degradation and the management of habitats to ensure reaching biodiversity targets (World Bank, 2006).

Though EBM approaches are designed to improve the structure and function of an ecosystem to enhance its resilience, they are assessed against criteria linked to human well-being, such as sustainability, efficiency, equity and legitimacy.

EBM approaches differ from traditional management approaches that are not rooted in holistic approaches over SES (see below for a comparison). To stress this difference, AQUACROSS will provide examples of policy failures linked to common practice and also evidence on the consequences of ignoring critical linkages, as well as the interaction between multiple stressors.

Traditional approaches to manage ecosystems and EBM fundamentally differ in the following aspects:

- Their focus on flagship species, hotspots, single pressures, specific impacts, etc. Despite achieving measurable outcomes, these approaches face the risk of degrading resilience and increasing ecosystems' vulnerability. For instance, if applied to conservation, EBM requires selecting optimal focal species, currently mostly chosen according to socio-economic criteria such as charismatic value, high public interest or market value (such species are often expensive to preserve and ineffective as indicators to restore their living environment), or keystone species (selected by the critical role they play in an ecosystem) (Shannon et al., 2004).
- The fact that they are based upon sectoral and partly conflicting policies (water, energy, climate change, food security, spatial development, etc.) that pursue biased objectives at the expense of worsening prospects in other policy realms may result in unsustainable cumulative pressures. Within this context, EBM rather than sectoral policies has the promise of making visible the multiple co-benefits linked to the improvement of an ecosystem's condition. Subsequently, it opens new opportunities of pursuing different policy objectives simultaneously (in water provision, energy, land use, food, climate change adaptation, etc.). EBM also contributes to designing cooperative instruments and policy synergies to take advantage of these opportunities (i.e. the current research on the water, energy, food and climate change nexus; Biggs et al., 2015a, 2015b; Howells et al., 2013), or the recent interest in the contribution of nature-based measures for EU policies on biodiversity, freshwater or the marine environment (EC, 2012).
- Maximising the provision of **some ecosystem services** (drinking water, water for irrigation, urban soil, dilution of pollutants, etc.) whilst impairing the capacity of the ecosystem to deliver other valuable services in the present and in the future (including those services linked to self-regulation and support). In contrast, EBM seeks to maximise the value of natural assets and, thus, the **joint value of all the flows of ecosystem services** it could provide in the future. Traditional management has gone too far in transforming ecosystems for a single purpose; emerging strategies find more relevant opportunities in the benefits attached to restore natural features, for example, to reduce flood risk, contribute to groundwater recharge or soil formation, improve water quality or support life and other simultaneous benefits linked to the recovery of ecosystems' structure and functions (EC, 2015b).
- The neglect of the inherent uncertainties of social and ecological systems and the attachment to a basically deterministic perception of future challenges. In

contrast, instead of focusing on optimal solutions, EBM acknowledges irreducible uncertainties. Hence, EBM acknowledges the importance of building adaptation[8] capacities not only through restoring critical ecosystems but also through building social abilities to respond to a range of possible futures, as well as to preserve the option to make decisions adapted to the condition that may prevail in the future. EBM highlights the trade-offs between the benefits of foresight and planning for the distant future and the risk of being caught by an irreversible decision, institutional and technical lock-in and lack of adaptability (e.g. Marshall, 2013; Lukasiewicz et al., 2015). Within this context, EBM belongs to the kind of policy actions that are able to maintain the provision of ecosystem services through the maintenance of ecosystem processes and functions. EBM enhances and restores ecosystems to reduce social vulnerability and preserve the multiple co-benefits of preserving the environment, such as flood mitigation, protection of livelihoods, and ensuring the delivery of ecosystem services in a wide range of future conditions (Munang et al., 2013).

EBMs and aquatic ecosystems

The above-mentioned arguments support the idea that ecosystems, and particularly those providing water related services, need to be governed. In particular, aquatic ecosystems have distinctive traits that can only be sustainably managed through planned, collective and coordinated decisions made and implemented by governing institutions, rather than by spontaneous, individual, and uncoordinated decisions made by self-interested individuals acting in an unregulated socio-economic system (Hanemann, 2006; Lund, 2015; Ostrom, 2009).

Implementing a holistic approach thus requires building up a fundamental collective agreement (i) on the set of ecosystem services that must be sustainably provided, and (ii) on the structure and functions of the ecosystem that must be aimed at by any resilience-building strategy (see Robards et al., 2011). Therefore, successful EBM requires encompassing objectives regarding **robust governance** in the social system and **ecosystem enhancement and protection** in the ecological system (Leslie and McLeod, 2007).

[8] Adaptation is the ''adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities'' (IPCC 2007). According to Lukasiewicz et al. (2015) in terms of land and water management, adaptation actions involve reducing non-climate threats that increase the resilience of populations to a changing environment in situ as well as enabling the species concerned to migrate to a more suitable habitat under a changing climate (CBD, 2010).

EBM is only feasible within a strong and enabling institutional setup. Decisions on which ecosystem services to sustain are inherently political and should be made in a **transparent and inclusive** way. Indeed, these decisions are **based upon existing knowledge** of complex links and on the **capacities of social actors** within the institutions in place to assess complex trade-offs, to arrive to cooperative responses and to balance diverse perceptions and vested interests.

Additionally, focusing on ecosystems rather than on single species or resources requires defining specific spatial and temporal scales of supply of ecosystem services. This, along with rivalry and excludability, has implications for the scales and structures of appropriate management institutions.

However, all the above-mentioned requirements (transparency, inclusiveness, knowledge based, design appropriate for the scale of intervention, finding a way to manage public goods, and non-rivalry and non-excludability), are not exclusive of EBM, but rather defining characteristics of good governance overall. EBM measures require good governance and an enabling institutional setup.[9]

Whilst traditional measures can be and have been effectively implemented in a variety of governance setups, EBM can only be the outcome of robust institutions. Gradually improving current decision-making processes is an integral part of building individual and collective capacities and improving governing institutions is an integral part in the transition towards enhancing sustainability. In other words, the effective implementation of EBM requires adapting prevailing institutions and policy-making processes, and overcoming significant barriers to be able to meet policy-making challenges, such as:

- First of all, defining the objectives of EBM. This requires an identification of what set of ecosystem services may be sustainably provided and their importance. As these services are asymmetrically valued by different users this implies trade-offs between users. Trade-offs amongst ecosystems services are pervasive and inherent to any resource management decision. What is special about EBM is that this approach gives prominence to this social decision. It thus favours transparency and a better framework to confront people, businesses and governments with the consequences of their own decisions.

[9] For this reason EBM, *sensu stricto*, is defined as any alternative intended to restore and enhance the functions or the structure of an ecosystems (Maes 2013; MEA, 2005).

- Secondly, balancing trade-offs implies finding the best way to meet any environmental objective. As above, the defining components of resilience and the trade-offs amongst modularity, connectivity, heterogeneity and redundancy, must be considered in the decision-making process.
- Third, choosing between manifold alternatives. Besides the objectives of EBM, assessing individual alternatives involves complex social choices and trade-offs (i.e. short-term opportunity costs vs. long-term benefits; reduced pressures and lower provision of commercial services vs. enhanced security, reduced risk, better adaptation prospects, etc.).
- Fourth, taking advantage of the array of different opportunities linked to EBM. While traditional measures (such as flood prevention infrastructures) are designed to respond to a particular problem, EBM is linked to multiple co-benefits and may simultaneously contribute to various policy objectives, such as biodiversity conservation, water quality and quantity, health, flood and drought risk reduction, climate change adaptation, and energy savings. Their advantages, compared to traditional approaches, rely on the actual opportunity to seize the benefits of synergies or simultaneous advances across different policy and biophysical realms. However, current methodologies, such as single-purpose cost-effectiveness or optimisation models, might be blind to EBM co-benefits. Additionally, advantages of EBM may remain hidden in institutional silos, where sectoral policies are currently made.

Moreover, despite their multiple benefits, the existing institutional setups and assessment methodologies explain why EBM is often ignored or discarded in favour of traditional options:

- Institutional lock-in: opportunities are linked to synergies of multiple benefits across stakeholders and policy domains that can only be reaped through cooperation instead of competition. Yet, alternative courses of action are defined, assessed and selected on institutional silos (such as water, energy, agriculture, fisheries, transport, land planning and other policy domains) where co-benefits are overlooked, if not completely ignored. Rather than sectoral measures, EBM's advantages are better appreciated in the so-called nexus across policy domains (such as the water, energy, climate change, risk reduction and biodiversity nexus).
- Technological lock-in: rather than calling for radical changes in individual and social responses, dynamic, social and ecological problems call for improving control over natural resources and for going beyond in harnessing existing technologies.

- Analytical lock-in: traditional cost-benefit and cost-effectiveness approaches are designed to focus on single benefits and costs rather than on sets of ecosystem services – EBM poorly competes with specialised traditional alternatives.

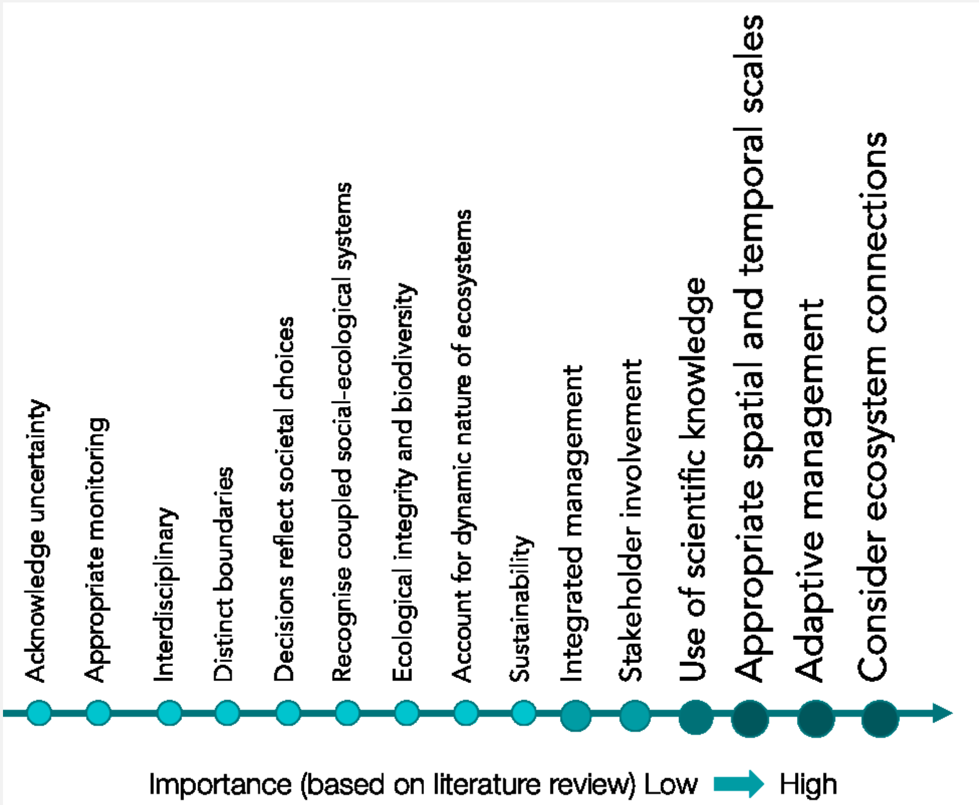
EBM requires institutional changes to build cooperation to foster collective action, to share the array of ecosystem services obtained across different stakeholders and policy domains, and to break institutional silos along with disciplinary borders and short-sighted, short-term, commercial interest.

Box 6: EBM definition and principles

The following definition proposed by Long et al. (2015), based upon a thorough revision of the extensive literature around EBM, comfortably fits within the AQUACROSS concept:

"Ecosystem-based management is an interdisciplinary approach that balances ecological, social and governance principles at appropriate temporal and spatial scales in a distinct geographical area to achieve sustainable resource use. Scientific knowledge and effective monitoring are used to acknowledge the connections, integrity and biodiversity within an ecosystem along with its dynamic nature and associated uncertainties. EBM recognizes coupled SES with stakeholders involved in an integrated and adaptive management process where decisions reflect societal choice".

According to the recurrence of its presence in peer-reviewed papers, this figure shows the relative importance given so far to the principles of EBM (Long et al., 2015).



3 AQUACROSS Architecture: Information, Models & Tools

AQUACROSS architecture stands for the methodological approach that allows us to operationalise the aims highlighted by the AQUACROSS concept, and integrate as well as synthesise scientific knowledge in a fashion that is familiar to stakeholders and managers and that is suitable to inform EBM approaches to jointly manage complex SES.

This architecture or heuristics of the AQUACROSS project is primarily oriented towards improving management. Beyond taking stock of existing knowledge and synthesising the state-of-the-art of different fields (i.e. marine and freshwater realms, socio-economic and ecological systems), it aims at mobilising scientific knowledge for improving social capacities to provide better responses to ecosystems and biodiversity management challenges.

In practical terms, AQUACROSS architecture aims at mobilising knowledge to (1) confront stakeholders and institutions with the outcomes of their current decisions and (2) to support collective decision-making to integrally manage ecosystems by comparing and assessing alternative courses of action.

Along these lines, the main methodological challenge to realise the first general objective consists in making a conceptually holistic approach truly operational through the identification, effective design and successful implementation of EBM approaches to respond to the challenges of biodiversity across freshwater, coastal and marine ecosystems.

This first aim is linked to the following specific objectives of the AQUACROSS architecture:

- *Integrating diverse disciplines* that cover the wide spectrum of natural and social sciences and (which have different concepts, definitions, methods, assessment criteria, analytical models and research programmes) into a comprehensive framework to make the different pieces of knowledge suitable to serve to a common social purpose.
- *Standardising and integrating concepts and metrics across different scales across time, space and policy domains.* This improved communication is expected to help overcome knowledge and institutional barriers, facilitate the identification of new opportunities linked to ecosystem-based approaches and foster the

cooperation between stakeholders and policy areas required to take advantage of synergies and co-benefits associated with biodiversity and ecosystems improvement and protection across different water realms.

- *Representing the outcome of cumulative pressures of biodiversity and ecosystems as a means to confront stakeholders with their own decisions*. This is expected to result in a better understanding of impacts on ecosystem structures, processes, and functions and of the ensuing detrimental effects on human well-being. This comprehensive analysis would contribute to increase the visibility of the opportunity costs of ecosystem degradation and declines in biodiversity along with the benefits of their preservation.
- *Developing a common understanding of SES and a shared vision of the current trends and vulnerabilities as per ecosystems and biodiversity* with a special focus on the economic and institutional failures that must be addressed in the social system and the evaluation of non-linear feedback loops, critical thresholds and the existing risk or hysteresis and irreversible regime shifts.
- S*upporting the identification of well-defined targets in terms of biodiversity, ecosystem services, functions and structures,* and the development of appropriate indicators, and information and decision systems to support their achievement in a cost-effective, efficient and equitable manner.
- *Providing a framework to represent and convey uncertainty* on scientific knowledge, the foreseeable dynamics of SES and the impact of individual and collective policy responses.

The second general objective consists of developing a management framework by making the above-mentioned architecture operational, so as to fulfil the following decision support objectives:

- *Framing management challenges* (such as decline in biodiversity and fish populations) within precise ecological (geographic area, relevant ecological processes, etc.) and institutional boundaries (stakeholders, regulations in place, property rights, development trends, etc.).
- *Identifying and agreeing on the management objectives*, considering primary EBM objectives as well as ulterior objectives within the SES.
- *Identifying opportunities and barriers* linked to alternative ways to pursue management objectives (such as synergies among policy domains, opportunities linked to reinforced ecological processes, barriers linked to crowding out or rebound effects, co-benefits, and forward and backward linkages).

- *Evaluating gaps and deficits in the ecosystems' structures and functions* as well as in social institutions and capacities that need to be bridged in order to make reaching the management objectives feasible.
- *Assessing available alternatives to cope with management challenges* in terms of cost-effectiveness, cost-benefit analysis, multi-criteria decision and other relevant methodologies to assess policy alternatives with effectiveness, efficiency, fairness, legitimacy and other socially and environmentally relevant criteria.
- *Developing management-oriented indicators to support the assessment of challenges, objectives, policy options*, etc., and guaranteeing the standardisation of definitions and metrics to make assessment and comparisons relevant for management.
- *Conveying evidence-based information relevant to policy-making* in a way that can be understood and used by stakeholders to screen out policy alternatives and understand the foreseeable consequences of the different courses of action (including business as usual and management scenarios).
- *Supporting the construction of a shared understanding of foreseeable consequences,* as well as the uncertainties linked to the different management alternatives and reinforcing collective decision-making in the face of uncertain outcomes.
- *Favouring learning by doing*, development of individual and institutional capacities to EBM, fostering cooperation and agreement and unveiling other social adaptation processes oriented towards the development of robust institutions and governance setups.

Meeting these ambitious objectives implies a series of methodological challenges and, therefore, requires a comprehensive analytical framework able to inform on the multiple interactions between system components and, in particular, on the two-way links and the feedback loops between its social and ecological components. It also entails the need to highlight and prioritise critical information gaps and to integrate current and new knowledge into a new research programme, purposely designed to understand the complexities of SES and to inform decision-making processes.

The AQUACROSS architecture is the first step in the research project strategy designed to develop this far-reaching analytical framework.[10]

These methodological challenges are vast and, perhaps, not within the reach of existing knowledge. The diversity of scientific perspectives involved has led to fragmented and scattered pieces of knowledge that limit our ability to understand the relevant social-ecological linkages.

Yet, the right methodological approach to improve current and future decisions does not consist of waiting until a better knowledge base is available, but rather of conveying the best available knowledge into the policy arena to generate the positive feedback loops that may improve current environmental responses and drive a new research agenda.

The focus of the AQUACROSS architecture is, therefore, on providing a basis for the operational framework to put the diverse and scattered pieces of knowledge into value to inform policy-relevant decisions and to improve human well-being through enhancing resilience and long-term sustainability of SES.

3.1 Choosing the right foundations

The integration of ecosystems and social information in a way that is familiar to stakeholders and managers is an integral part of strategies intended to remediate negative environmental impacts and to realise environmental policy goals, such as those defined in the EU WFD, the MSFD and the EU Biodiversity Strategy to 2020. Such strategies are also shown in different conceptual models that have been developed to support the implementation of EBM (Ogden et al., 2005 and Kelble et al., 2013).

The first conceptual models developed for this purpose followed the pressure-state-impact pathway to conceptualise baseline management. Subsequently, the response dimension was added to mainstream policy responses (as in the canon PSR model, Gentile et al., 2001). In these first approaches, the whole social system was embedded in the "pressure" dimension and the ecological one under "state". These models offered few insights to understand social processes leading to multiple

[10] The AQUACROSS Assessment Framework (Deliverable 3.2) will make the project concept operational by mobilising existing data, analytical models and assessment tools and by bridging identified knowledge gaps. All this according to the concepts, the structure and the roadmap provided in this document (Deliverable 3.1).

pressures. Additionally, their consideration of the ecological systems was limited to the affected structural parameters, rather than considering a comprehensive analysis of ecological processes and functions.

The first basic models rapidly evolved into the DPSIR (**D**riving forces, **P**ressures, **S**tates, **I**mpacts, **R**esponses). Advances resulted from adding the anthropogenic "drivers" of ecosystem change, to provide a better understanding of the functioning of the social system, and, also from including the "impact" dimension to understand the deeper consequences of socially-driven pressures over ecosystems (Sekowski et al., 2012). These models contributed to enhance the science-policy interface and have been extensively applied to the assessment of terrestrial, freshwater and marine ecosystems (Kristensen, 2004; Atkins et al., 2011; Tscherning, 2012; Kelble et al., 2013).

Whereas the family of such conceptual models have supported outstanding progress in the understanding of impact pathways through which human action affects nature, in both negative and positive ways, the main shortcoming is that DPSIR application mostly focuses on single, respectively most relevant pressures in ecosystems and neglects simultaneously-acting pressures. Furthermore, these models are of limited use to convey information on the importance of nature for human welfare, i.e. integrating the linkage between ecosystem functions and ecosystem services. DPSIR models have rather favoured impact mitigation strategies and might fail to initiate structural responses such as those implied by EBM.

For instance, approaches based on the DPSIR logical sequence:

- Mostly focus on top-down analysis and are not fitted to inform about feedback loops and cumulative forward and backward processes, hence favouring responses that are reactive and remedial rather than proactive and pre-emptive.
- Are better suited to assess responses that reduce or modify pressures, regardless of how the socio-economic system and stakeholders adapt their decisions and behaviour and the drivers themselves of ecosystem change.
- Neither do they explicitly take ecosystem services into account nor their impact on human welfare. They are, therefore, unable to accommodate the rationale of EBM that balances the costs and benefits of enhancing natural assets or ecosystems to improve resilience and adaptability.

However, the solution to integrate ecosystem services, nevertheless, should not only rely on adding one more clog within impact pathway analysis. From our viewpoint, the goal of the conceptual model should be to represent how ecosystems function in connection with the socio-economic system, delivering ecosystem goods and services and contributing to social welfare.

When the ecosystem approach came into play in the early 2000s, the analysis of ecosystem services and their importance for human welfare shifted the focus from a "what shall we do to nature?" towards a "what does nature do for us?" perspective. The impact dimension became relevant as it could inform about the negative consequences of nature degradation over people, rather than only over nature itself. Additionally, economic progress and human well-being were added to the criteria to favour nature preservation that was previously dominated by conservationist approaches.

The ecosystem services approach led to a more comprehensive frame including economic perspectives and served to call for social action more effectively. This new approach has led to new perspectives based upon the potential of ecosystems to provide society with the valuable services they demand and to new conceptual frameworks to integrate these new concepts on the previous DPSIR (Turner, 2000; Cheong, 2008; Weinstein, 2009).

Ecosystem services provided the missing analytical block to proceed from the biophysical to the human dimensions of science. As above, Ecosystem services are the main and most welfare-relevant outcome from the interaction of social and ecological systems. Therefore, they can serve as the missing analytical block to proceed from the biophysical to the human dimensions of science. In order to ensure the policy relevance of the conceptual model, endpoints are to be (mainly) placed in those ecosystem functions and services people do care about (Kelble et al., 2013).

The integration of both traditions, the impact pathway analysis on the one hand and the ecosystem services approach on the other, has fostered the emergence of a growing number of alternative SES analytical frameworks (Binder et al., 2013). Nevertheless, their success and their capacity for a smooth integration of knowledge may have been impaired by the mismatch resulting from mixing pieces built in different "factories" and for diverging purposes.

Indeed, analytical models and indicators have notably improved our understanding of two important links between social and ecological systems (Niemeijer and de Groot, 2008). Nevertheless, to some extent, both approaches share the drawbacks of common practice and may only offer a partial view of the complex links between social and ecological systems that are actually relevant. To our understanding, the integration between both traditions is still partial.

Posing the two basic questions these two traditions have tried to solve is especially clarifying. On one side, it is now possible to build operational models to understand how social outcomes (pressures and responses) affect ecosystems' conditions; it is also possible to get a good grasp of how ecosystems' outcomes (or services) affect human welfare.

It is not yet clear, though, how both pathways can be linked in a meaningful way. In other words, the main research gaps to overcome on both ends are:

- First, there are important knowledge gaps to be filled on the ecological side, so as to improve our understanding of how an impaired or recovered ecosystem structure, including its self-adaptive processes, ends up with a given potential to sustainably provide more or less valuable ecosystem services of any kind. Similarly, understanding how biodiversity and ecosystem processes are linked to each other and to the delivery of ecosystem services is an important element for the assessment of EBM responses (e.g. Cardinale et al., 2012).
- Second, on the social side, it is still unclear how individual and collective decisions are affected by environmental changes and how the improved or degraded supply of ecosystem services affect human-driven pressures and responses over the environment. Both links are required to transfer the social-ecological linkages into real feedback loops (e.g. Dolbeth et al., 2016) and to help us assess the positive and negative impacts of ecosystem degradation and EBM.
- Third, ecosystem services have complex links amongst themselves and with biodiversity levels that must be properly understood to get a deeper insight on how socio-economic processes affect the structure and function of ecosystems, let alone their resilience and the provision of ecosystems services (e.g. Bennett et al., 2009).

Therefore, albeit useful to provide more comprehensive sets of data and indicators (Cooper, 2013), assembling well-established but partial frameworks may be of limited use to support the analytical elements required to understand meaningful social-ecological interactions and feedback loops (Binder et al., 2013; Box 7).

Box 7: Failed interventions and the missing links of conceptual models

A comprehensive approach should go beyond adding bottom-up and top-down approaches and should also be able to ascertain feedback loops and two-way interactions that are relevant to understand the status and dynamics of the whole SES and to identify and assess potentially more effective pathways towards sustainability.

Actually, most of the uncontrolled factors that hinder the achievement of biodiversity policy objectives (such as the Aichi 2020 targets), may lie in those interstices of the SES that are still poorly analysed by specialists and/or not yet streamed into policy-making (see: Tittensor et al., 2014; Hill et al., 2015). For instance, effectiveness of biosecurity measures to eradicate invasive species may be undermined by global trade and tourism (Koblentz, 2010; Rodríguez-Labajos et al., 2009). The lack of effective mechanisms that enforce compliance may render fishing regulations dysfunctional (Laxe, 2010). Additionally, many effective and efficient actions to prevent the extinction of threatened species may become unfeasible, if they challenge existing demands of ecosystems services and usual land use patterns (Schneider et al., 2012).

Under this basis, our strategy to build the AQUACROSS architecture suggests to take stock of the better of the two traditions. Subsequently, we make them fit into the analysis of complex adaptive systems to build a comprehensive framework. The project's conceptual model consists of three building blocks: the impact pathway analysis (or the DPSIR in its different alternatives), the ecosystem services approach, and the interplay of both through the processes that take place in the social and the ecological systems.

3.2 The AQUACROSS Architecture I: setting the structural components

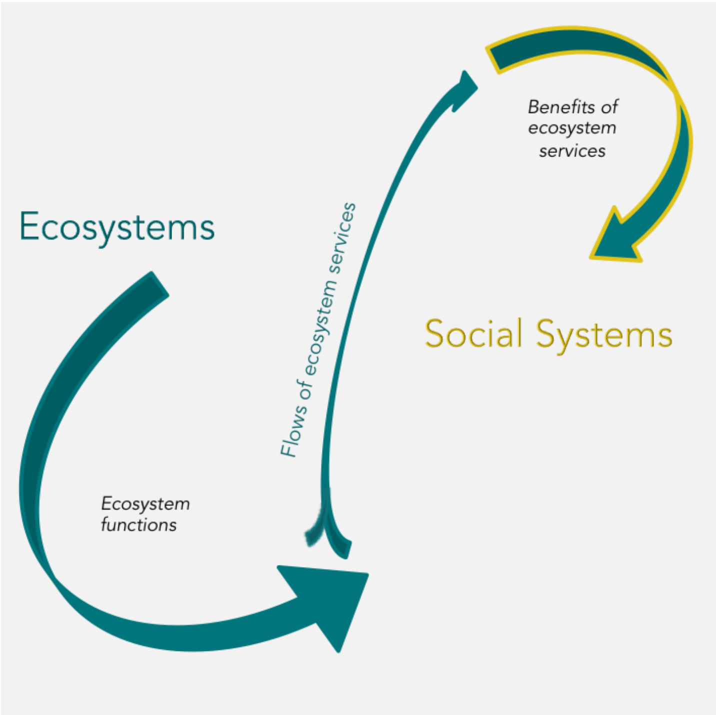
The analysis of the relationship between social and ecological interactions can be based on the distinction between two closely interrelated sets of links. The first refers to how ecosystems are linked to human welfare; the second to how social systems shape and change ecosystems. Both links are connected to each other through the complex adaptive processes taking place in ecological and social systems. These two sets of links, from ecosystems to society ('supply-side') and the other way around ('demand-side'), can be interpreted as two complementary ways to analyse environmental services.

- The *supply-side relationship* goes from the ecological to the social system. It represents and elucidates the potential of ecosystems to supply and effectively deliver ecosystem services to the social system. It includes the capacity of the social system to transform those services delivered into benefits for people and society. This is all contingent on the state of the ecosystems' structure and on those processes taking place in the biophysical system from which ecosystem services are the most socially relevant outcomes.
- The *demand-side relationship* goes from the social to the ecological system. It represents and explains the demand and the effective use of ecosystem services

and the impacts on ecosystems. The demand of ecosystem services depends on income, tastes, technology, institutions, and other social and economic factors. Beyond pressures on ecosystems, this demand-side relationship also considers social and individual decisions towards protecting and restoring ecosystems in order to preserve their benefits depending on the governance institutions in place. Both detrimental pressures and incremental responses are the most ecologically relevant outcomes of the social system.

3.2.1 The supply-side relationship (from ecosystems to human welfare)

Figure 2: AQUACROSS Architecture. Supply-side relationship.



PURPOSE

The analysis and assessment of ecosystems and their link to human welfare through the supply and use of ecosystem services

Sources of Inspiration

- Millennium Ecosystem Assessment.
- MAES
- TEEB

Source: Own elaboration

The link between ecosystems and human welfare can be built through analysing **the status and the processes** that take part in an ecosystem. This effort seems meaningful to ascertain the actual potential of the ecosystem to deliver a bundle of services (or the **functions** performed by the ecosystem in connection to human welfare),[11] to identify each of the **services** actually provided and the **benefits** stemming from these services and their **value**[12] **(Figure 2).** Sometimes this analytical pathway is dubbed as a supply-side approach to the analysis and assessment of ecosystems (see Maes et al., 2015 and 2016, and Figure 2).[13]

Ecosystems and their services: concepts and methodological challenges

By definition, all human activities are (directly or indirectly) dependent on ecosystems. They are important for individuals (that enjoy access to multiple services including essential ones, such as drinking water), for the performance of all economic activities (that allow transforming natural resources into valuable goods and services to meet human needs and aspirations). Therefore, linking ecological and social systems to human welfare through the notion of ecosystem services is essential to understand and assess the multiple trade-offs involved in individual and collective decisions in a clear and consistent manner.

The supply of ecosystem services depends on the capacity of the ecosystem (i.e. its physical properties, ecological structure and/or functions) but also on social values, available infrastructures, human capital and institutions in place to put them into value for human well-being (Ernstson, 2013). As above, ecosystem services are the key emerging outcome of the interaction between ecological and socio-economic systems (Biggs et al., 2012). These services are certainly 'produced' and delivered by ecosystems. However, these ecosystems are continually shaped by their interaction

[11] Reports on status or ecosystems' condition under EU water (Water Framework Directive/WFD), nature (Habitats Directive/HD) and marine (MSFD) directives provide an information basis on on-going efforts to assess ecosystems potential, such as for instance in Culhane, et al. (2014). These are insightful efforts to assess critical knowledge gaps (see State of Europe's Seas report (EEA, 2015) for an application to marine ecosystems).

[12] To see how this sequence would be integrated into the AQUACROSS assessment framework, please see next section. Following TEEB (TEEB, 2010): "Clearly delineating between functions, services and benefits is important to make ecosystem assessments more accessible to economic valuation, although no consensus has yet been reached on the classification".

[13] Maes et al. (2015) is based on Maes et al. (2012) conceptual framework, which in turn is rooted in the ecosystem service cascade. It represents how ecosystem functions define a (potential) supply of ecosystem services which, depending on the demand, results in a realised use (effective supply) of services. A wealth of literature does not use the term supply but a set of synonyms such as stock, potential services or capacity of ecosystems to deliver services (see Maes et al., 2015; Baró et al., 2015; Culhane et al., 2014).

with socio-economic systems and these may favour detrimental, transformative or restorative processes (Biggs et al., 2015b).[14]

Within the contemporary interface of social and ecological systems, ecosystem services should not be considered as "gifts from nature" but rather, to a large extent, as co-produced by humans and nature. Human actions and institutions shape ecosystem services in landscapes or seascapes by management and uses, which in turn shape human behaviour and institutional settings. For example, the time, quantity and quality of freshwater flows provided by ecosystems at any specific place depend on rainfall, which is affected by anthropogenic changes in weather and climate, and runoff, which in turn is increasingly shaped by land use (see Box 8). Freshwater flows are subject to hydrological risks which depend on past water uses and current water demands (Bunn and Arthington, 2002; Vörösmarty et al., 2010). This all has an impact on human welfare that depends on the social capabilities to match water supply and demand through building water storage facilities and water governance institutions.

Box 8: Aquatic ecosystems and their services: are these clear-cut concepts?

Water realms are the source of valuable ecosystem services (Maes et al., 2014). Nevertheless, the same notion of "aquatic ecosystem" is particularly elusive. For instance, if water processes are in the interface of virtually all of the Earth's ecosystems, what are the boundaries of an "aquatic ecosystem"? Moreover, this has not prevented the extensive use of the concept of water ecosystem services.

Actually, the different versions of "water ecosystem services" derive from their practical use and are not necessarily compatible with each other. For instance, "water ecosystem services" are defined as those "delivered by water bodies" (allowing for the distinction between

[14] Disentangling interlinkages and contributing to disambiguation between ecological and social systems that are relevant to manage ecosystems require distinguishing the driver of ecosystems' change and the pressures and responses from the social system, as well as to understand how these outcomes impact over ecosystems' structures. After all, once considered the ecological processes of adaptation, these results in changes in the functions performed by the ecosystem in general and in the ability to provide ecosystems services in particular. While terms such as functions, processes, structure, driver, pressure, responses, benefits and values have become common in this specific literature their definitions, meanings and differences are still far from being consensual (see below for an attempt to define these concepts in an unambiguous manner).

freshwater ecosystems and marine ecosystems)[15] "or by water dependent habitats" (such as riparian zones or floodplains: Grizzeti et al., 2015). Although convenient for policy implementation in specific domains, the exclusion of other water related services (such as runoff regulation, soil formation, water provision for rainfed agriculture, etc.) have led to, for example, the definition of "hydrological ecosystem services" as those provided in the "conjunction of water ecosystems services and some terrestrial ones" (Brauman et al., 2007; Grizzeti et al., 2015). AQUACROSS will take stocks of these discussions to produce a consistent definition of the ecosystems services across the water realms relevant throughout the whole project.

The notion of ecosystem services as "the benefits people obtain from ecosystems" (MEA, 2005) encompasses all possible ways in which ecological systems are important for human welfare. It includes the direct provision of valuable goods and services, such as water, food or clean air, whose link to human well-being is straightforward. This also holds true for other ecosystem services such as soil and water regulation. Their importance must be traced through complex ecological and social processes, such as soil formation, water retention and land use in order to understand how they contribute to social welfare. Examples of this are reduced flood and drought risks, improvements in human health or water quality and supporting biodiversity. The variety of all the potential services provided by ecosystems and the multiple ecological processes and structures that may produce them, challenges the possibility of making a comprehensive as well as a precise classification (see Box 9).[16]

Ecosystem services are valued by their contribution to human welfare. Some contributions to economic welfare may be represented by their market value (like fossil fuel prices and water productivity in agriculture), but this value does not reflect their full contribution to human well-being (for example the external effects of fossil

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[15] For Maes et al. (2014) freshwater ecosystems include: "Lakes, rivers, wetlands and groundwater that deliver clean water for multiple purposes and are thus vital to human well-being". Marine ecosystems are: "Oceans, seas and especially coastal zones". The report recognises the difficulties involved in applying the CICES classification to marine and freshwater ecosystems (Grizzetti et al., 2015).

[16] The Millennium Ecosystem Assessment MEA (2005) distinguishes between support, provisioning, regulating and cultural services. To avoid double counting in assessing ecosystems structure, function and services, The Economics of Ecosystems and Biodiversity (TEEB), suggest distinguishing between habitat services and ecosystems functions instead of supporting services (See e.g.TEEB, 2010). Further discussions around the classification of ecosystems services can also be found in: Daily 1997; Boyd and Banzhaf, 2007; Wallace, 2007; Costanza, 2008; Costanza et al., 2014; Fisher and Turner, 2008; Fisher et al., 2009; Granek et al., 2010; Haines-Young and Potschin, 2013; Robinson et al., 2013, among others.

fuel consumption or the environmental impact of water abstractions are not factored in in market prices). Some others may be valued in monetary units (such as water purification services in streams, or the security added by the flood regulation of a river basin or a flood defence for coastal areas). However, many relevant ecosystem services cannot be measured in monetary terms, e.g. the option value of biodiversity (e.g. uses of biodiversity potentially be discovered in the future) and cultural identity values.

Box 9: Ecosystems services: alternative classifications

Ecosystem services were first defined as "the benefits people obtain from nature" (MEA, 2005; Ernstson, 2013). According to that, they include (i) provisioning services (e.g. biomass, energy flows and water), (ii) the self-regulating and supporting services of the ecosystem (including climate, biodiversity support, pollution control and soil formation), and (iii) cultural services (e.g. aesthetic, spiritual and recreational services).

The Common International Classification of Ecosystem Services (CICES) was developed from the work on environmental accounting undertaken by the European Environment Agency (EEA). It supports their contribution to the revision of the System of Environmental-Economic Accounting (SEEA), which is currently being led by the United Nations Statistical Division (UNSD).

Due to the need to shed light on the distinction between services, benefits and the values associated to them, ecosystem services can be more precisely defined as "the direct and indirect contributions of ecosystems to human wellbeing". This concept builds upon the MEA (2005) definition and makes a distinction between services provided by nature and the benefits to human well-being so that a given ecosystem service may lead to different benefits depending on the way they are used and appropriated within the social system; these benefits affect welfare of different people in multiple direct and indirect ways (TEEB, 2010). TEEB classifies ecosystem services in 4 main categories: (i) provisioning, (ii) regulating, (iii) habitat and (iv) cultural & amenity services. As compared to the MEA (2005), TEEB (2010) does not consider supporting services such as nutrient cycling and food-chain dynamics, as proper ecosystems services but as ecological processes.

Ecosystem services are the outcome of complex ecosystems. Their **benefits** go far beyond their individual use and too often spread out over the socio-economic and the ecological systems. For instance, the provision of water for irrigation is the critical input that allows farmers in semi-arid areas to benefit from their comparative advantages and to build up a wealthy economy based upon irrigated agriculture with benefits that spill over complementary industries such as food processing, transport and input production. Some relevant contributions of ecosystem services to human welfare are indirect. This is, for example, the case of wider macroeconomic impacts (through multiplier effects) over economic growth and employment derived from primary sectors heavily dependent on the provision of ecosystems services (namely commercial fisheries, offshore and onshore aquaculture or irrigated agriculture) that extend over local economies and regional and global markets.

The ability to manage ecosystems depends on the perception of their importance for human well-being. Decisions over ecosystem management, both private and public, are affected by the external benefits and costs associated to the provision and use of ecosystems services, as well as to the public good character of these services.

Due to their own nature, the provision of ecosystem services is linked to significant externalities, such as the degradation of the structure of ecosystems as a result of the way water provisioning services are delivered or to the reduction in future water availability when water services are supplied in excess of freshwater ecosystem capacities at a local level. Benefits of water provision in the short term, such as measurable benefits for crop production, households or manufacturing, are perceived in a clearer way than all the uncertain foregone ecosystem services. This asymmetric or unbalanced perception leads to management options that give priority to use over conservation, and then to short-sighted financial profits over broader welfare benefits. In addition, they lead to the relative neglect of co-benefits (or positive externalities) associated to ecosystem restoration.

Ecosystem goods and services are strictly different from private commodities and services. For the latter, production and use decisions can be left to the spontaneous and decentralised decisions that characterise the market economy. Indeed, to some extent, all ecosystem services are non-rival and/or non-excludable goods, so that competitive markets cannot efficiently decide their provision. Hence, their management requires collective decisions and cooperation.

Services such as flood protection, water quality regulation, recreation, biodiversity support or pest control are largely non-excludable. Providing these services to someone implies making it available to anyone else in the area leading to the well-known problems of common access (to fisheries in distant seawaters), or to free riding (the free enjoyment of public goods, such as landscape or security against storm surges, when excluding those who overfish or do not have a license is unfeasible).

Furthermore, many ecosystem goods and services are to some extent non-rival. This means that, unlike private goods, the use of ecosystem services by someone does not necessarily reduce the amount or the quality of the service available to anyone else. This is, for instance, true for natural beauty, flood protection, air quality or to the potential future benefits of biodiversity in contrast to the services of exhaustible resources, such as freshwater, that are rival.

Levels of rivalry and excludability result in a spectrum of features from common pool services, such as high sea fisheries, which are rival but not excludable, to close to public goods, such as the reduced flood risk provided by floodplains at a local scale (which are neither rival nor excludable).[17] This includes, for instance, the information contained in biodiversity (that is non-rival but may be made excludable through patents over seeds or drugs).

The economic features of ecosystem services, such as their degree of excludability and rivalry, are critical in designing institutional structures and mechanisms for their conservation, use and management.

Similarly, the direct or indirect links between ecosystems services and benefits are critical to define the right scale of intervention. In fact, the negative impact of ecosystems' overexploitation and degradation, and the external effects associated to their use have detrimental impacts. These are more likely to be ignored when their contribution to human welfare is indirect (as in the case of regulation and support services provided by ecosystems: TEEB, 2010), or when the connections between the production of the service and the enjoyment of their benefits are distant in time and space (such as the global climate control and air quality regulation services). These circumstances explain why many ecosystem services remain undervalued, particularly when they are produced in distant places (the so-called distance decay of value or the spatial discounting of ecosystems services, as in TEEB, 2011).

3.2.2 The demand-side relationship (from social systems to ecosystem condition)

This approach focuses on understanding ecosystem degradation and restoration as processes triggered by the demand of ecosystem services arising in the social systems and by the particular way these demands are met [18] (see Figure 3 below).

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[17] See e.g. Fisher et al. (2009) for an account on how gradients of rivalry and excludability can be applied to position ecosystems services in a spectrum from pure private (excludable and rival) to pure public goods (non excludable and non rival).

[18] Unlike the supply-side analysis, the term demand of ecosystem services is less common in the literature. This might be explained by the many ways the demand for ecosystem services is defined and used. In a recent survey, Baró et al. (2015) show that Burkhard et al. (2014) define it as "services currently consumed or used in a particular area over a given time period, not considering where ecosystem services actually are provided". Alternatively, for economists, ecosystem services demand is defined as "the amount of a service required or desired by society" (Villamagna et al., 2013) depending

It takes stock of the DPSIR framework, which represents the best known and most relevant approach to address the impacts of drivers and pressures on ecosystem states and to establish management responses. The evaluation, how drivers and pressures act on ecosystems, is directly linked to adequate metrics (see below).

Under the demand-side analysis, the link between society and ecosystems starts by analysing social processes and identifying all the social, policy and economic processes which outcomes might result in a relevant change in the structure of ecosystems. These social outcomes constitute the human **drivers** of ecosystems change.

Therefore, a useful distinction can be made between the two kinds of consequences these drivers might have for ecological systems: detrimental (pressures) and incremental (responses).

- Detrimental pressures over ecosystems are spontaneous results of the way the economy works and of how social issues are managed.
- Incremental responses are the result of collective decisions that arise as **response**s to ecosystem challenges and that are expected to have a positive impact over ecosystems' structure.

Finally, the negative and positive **impacts** of both pressures and responses must be assessed in terms of changes over the **structure and function** (or the status) of ecosystems.

This analytical approach can be integrated into the AQUACROSS architecture by bringing in the abundant research on impact pathway analyses and, more recently, on their use for the design and implementation of policy responses to environmental degradation.

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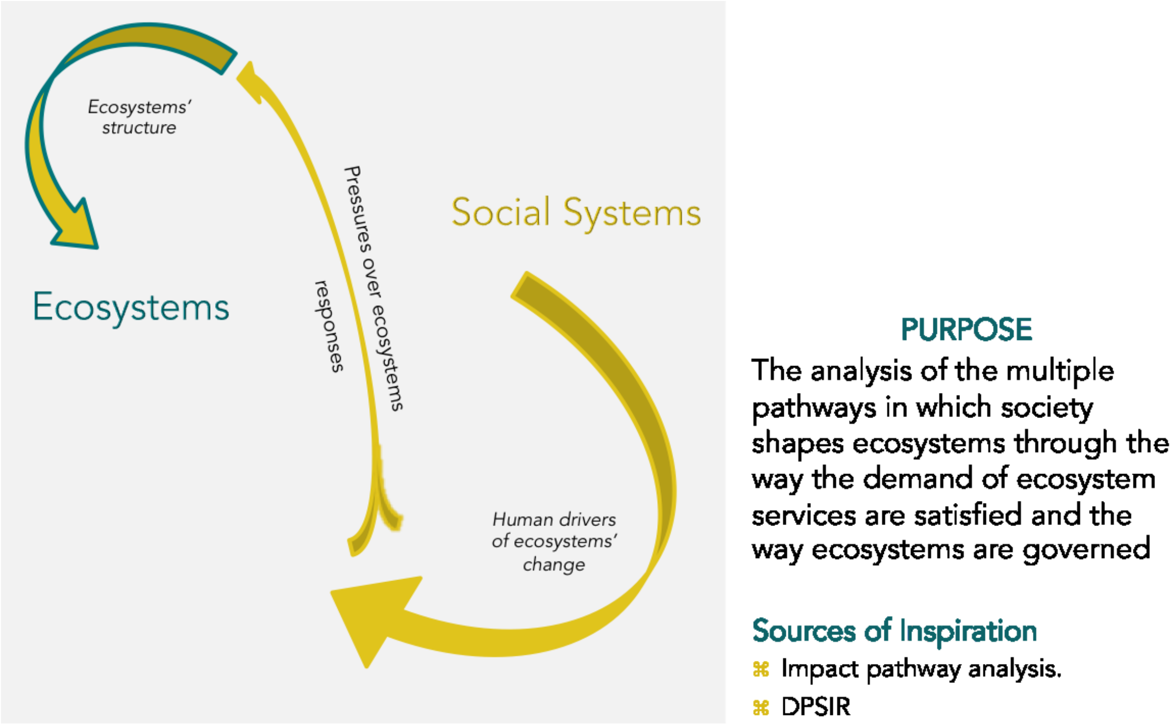
on "the individual agents' preferences for specific attributes of the service" (Schröter et al., 2014) as well as on their incomes, the incentives in place, regulations and other demand driving factors".

Figure 3: AQUACROSS Architecture. Demand-side relationship.



Source: Own elaboration

There is an evident need to understand how social-ecological systems evolve over time and respond to policy interventions. For that purpose, conceptual models valid for large scales can provide synthetic pictures addressing linkages between single agents.

The **causes of ecosystem change** may be found in any natural or human-induced factor that directly or indirectly triggers a change in an ecosystem. Accordingly, the comprehensive explanation of ecosystem changes involves all parts of the social and ecological systems. Consequently, this is the main purpose of building the AQUACROSS architecture and the heuristics on information flows and analytical models that in common allow for a holistic understanding of ecosystem change. Within this structure, the notion of **drivers of ecosystem chang**e must be bounded to a precise definition that is instrumental to the analysis of how social systems shape ecological systems (see Box 10). Otherwise, it might be impossible to make a clear distinction between important notions such as drivers, pressures, processes, ecosystem functioning, services and benefits.[19] For the sake of accuracy, the notion

[19] It has become increasingly frequent to make a distinction between direct and indirect drivers (Alcamo et al., 2005; Nelson et al., 2005; MEA, 2005). In such a way, we avoid mixing up pressures, which are

of drivers will be limited to the outcomes of the social system that are at the origin of ecosystem change. They can be summarised and categorised in the following five groups, which can be further sub-classified into several sectors: (i) demography, (ii) economy, (iii) socio-politics, (iv) science and technology, and (v) culture and religion.

Pressures, sometimes referred as direct drivers of ecosystem change, are changes in an ecosystem's status or structure that result from (social) drivers. They represent physical, biological or chemical changes that directly influence ecosystem processes and then trigger shifts in ecosystem functions and over the actual provision of ecosystems goods and services (Alcamo et al., 2005; Nelson et al., 2005; MEA, 2005). Important pressures include habitat changes due to land cover change, shifts in thermal regimes due to climate change, eutrophication due to plant nutrient availability, or invasive species and diseases in all water realms. In marine ecosystems, fishing represents the most overwhelming pressure.

Freshwater ecosystems have been directly impacted by water abstractions or pollution (particularly high organic and nutrient load and toxic substances). The excessive loads of nutrients also represent a pressure that acts across the freshwater-marine continuum. Furthermore, the pressure of invasive species affects the different aquatic realms.

Changes in ecosystem services are almost always caused by multiple, interacting drivers that work throughout time (such as population and income growth interacting with technological advances that lead to climate change) and over different levels of organisation (such as local zoning laws versus international environmental treaties), and are triggered by extreme events (such as droughts, wars, and economic crises).

Box 10: Causes and drivers of ecosystems change

The underlying causes of change in ecosystems pervade all the processes that take part in the complex and adaptive SES. The notion of drivers is more specific, and with conceptual precision and avoiding double counting, results from the basic concept, common to all the frameworks developed in the impact pathway tradition, that environmental status or its change is ultimately driven by humans (see Cooper, 2013, for a review of these frameworks since they were first proposed by the EEA in 1999 up to 2013). These (human induced) drivers result in identifiable pressures over ecosystems.

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the underlying causes of impacts that trigger ecosystems adaptation processes, resulting in changes of ecosystems functions and changes in the supply of ecosystems services, benefits and so forth with the drivers of ecosystems change.

One important methodological challenge that must be addressed in developing the demand-side analysis stems from the need to efficiently link the different sectors for which environmental policies have been designed and implemented. A consequence of that is the asymmetry in concepts and methods that might need to be reconciled to serve the purposes of EBM. One clear example of this can be found in the alternative definitions and reference lists established for concepts such as pressures, drivers and impacts.

In fact, once a particular area of interest is abandoned, it might be impossible to define these common concepts in an unequivocal way. For instance, for water management, it makes sense to classify the significant pressures over water bodies in four categories: point-source pollution, diffuse pollution, water abstractions and water flow regulations and morphological alterations (see for instance the CIS WFD guidance: EC, 2009). However, for the implementation of the Habitats Directive (HD), the relevant pressures are clearly linked to land use practices such as grazing, forest and mining that affect the concerned habitats.[20] None of these purposely built classifications is fully functional and might need to be adapted for the implementation of the MSFD, which classifies pressures as physical (losses, damages and other disturbances) interferences with hydrological processes, contamination by hazardous substances, releases of substances, matter enrichment and biological disturbance (Directive 2008/56/EC; Table 2).[21] A comparison of pressures throughout the freshwater-marine continuum may be facilitated by a sub-set of pressures found on the HD-list, which represents the more comprehensive classification as it targets all realms, at least in a basic manner. In most cases, the nomenclatures classify the pressures on two levels: the upper-level pressure category (e.g. agriculture, climate change), which enable the link to the drivers, and the single-pressure level (e.g. urban wastewater, water flow regulation), which enable the link to the impacted ecosystem processes.

[20] The list of WFD relevant pressures can be found in EC (2009), Table 6.b page 51, and the one of the Habitats Directive can be consulted at the Reference Portal of the European Topic Centre on Biological Biodiversity.

[21] The MFSD list of pressures is closer to AQUACROSS' definition of pressures (as "the primary alterations over the relevant ecosystem resulting from human driver factors") with the advantage that the Directive builds the link between these pressures and their resulting impacts (see the Table 2 in the Annex of the MFSD). The WFD is consistent with our project's definition of pressures but over water bodies and not over proper ecosystems. The Habitats Directive leads to misleadingly mix up pressures with the economic activities from which these pressures result.

Traditional pressure-impact analyses focus on single pressures or on additive impacts of single pressures, respectively. Recently, more attention has been paid on potential synergistic (more than purely additive) and antagonistic (less than purely additive) impacts of the cumulative effects of multiple pressures (Piggott et al., 2015).

3.2.3 Linking the demand and supply side analysis of ecosystem services

The identification of change and responses of both social and ecological systems need to be integrated to effectively design strategies for sustainability (Gual and Norgaard, 2010).

The global SES is changing in diverse dimensions, such as peace and security, urbanisation and migration, affluence and public health, consumption and technology, governance and institutions, and condition of the biophysical environment. Global changes from human activities include overwhelming alterations of ecosystems and the services they provide to humanity.

Drivers of environmental change are likely to intensify as human population grows and per capita consumption increases. Some of the changes to the Earth system have led to substantial gains in human well-being and economic development through improved access to food, water and other basic needs. At the same time, there has been degradation of many ecosystem services, increased risks of abrupt changes such as diseases and pests, and increasingly vulnerable livelihoods.

The process of identifying change entails detecting the rate of occurrence and the relevant spatial and temporal scales, as well as examining changes in quantity and quality of ecosystem functions and services. Minor changes may lead to large-scale impacts and larger changes may induce small-scale impacts, which need to be considered (Costanza et al., 1997). To get to the “root” of change, it is critical to identify the agents or drivers of these changes, which are embedded in the way humans live.

The challenge of sustainable development is to grasp this opportunity and transform SES to provide food, water, energy, health and well-being in a way that is economically, ecologically and socially sustainable, i.e. feasible for many generations into the future and for people in all parts of the world.

Both challenges are linked to each other by complex processes taking place in the ecological system (that link the demand side to the supply side of ecosystems services), and in the social system (that link the supply of ecosystems services with the demand side; see Figure 1).

In other words, assembling all the pieces into a unique structure requires building two important linkages:

- First, it is essential to improve our understanding of ecological processes, not only to account for non-human drivers of ecosystem change but also to link the impacts of human decisions back to human well-being. The only way to progress towards this consists in improving our understanding of how ecological systems work and transform the modifications induced by socially driven pressures and responses into changes in **ecosystems structures** and into a worse or better supply of ecosystem services in particular. Summing up, ecological processes allow us to go from the demand side to the supply side of ecosystem services analysis (see Box 11).

Box 11: Ecological processes to bridge the demand and the supply side of ecosystem services assessment

1 **Ecological processes** are natural transformations resulting from the complex interactions between biotic (living organisms) and abiotic (chemical and physical) components of ecosystems through the universal driving forces of matter and energy.

2 **Structure of an ecosystem** is formed by components and their layout within the ecosystem. It includes biotic (living organisms) and abiotic components.

3 **Ecosystem functioning** is the capacity or potential of ecological processes and components to provide goods and services that satisfy human needs, either directly or indirectly. Ecosystem functions depend on ecological processes taking place within ecosystems structures. They are classified in the following categories:

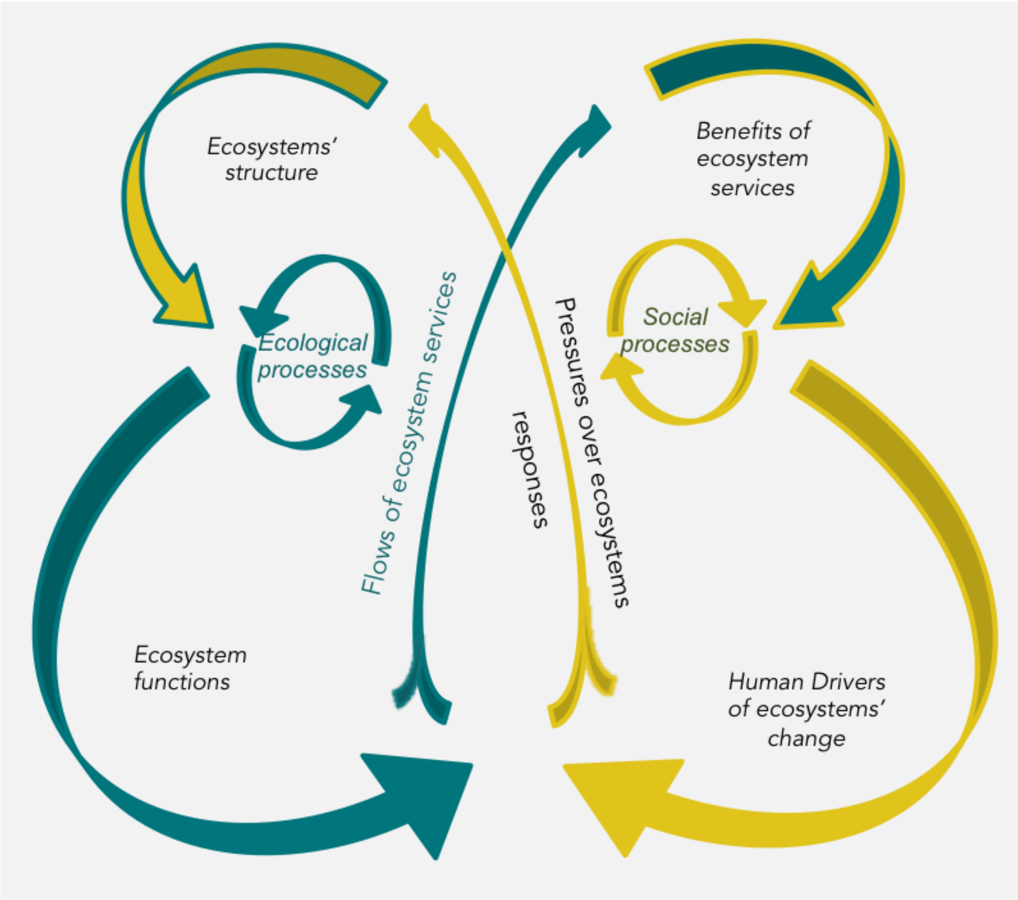
- **Regulatory functions** reflect the capacity of an ecosystem to regulate essential ecological processes that serve (i) to maintain or adapt the structure of the ecological system and (ii) to provide ecosystem services to the social system (i.e., clean air, water and soil, and biological control services).
- **Habitat functions** (sometimes considered as part of regulatory functions), reflect the capacity of ecosystems to provide refuge and to create and maintain a reproduction habitat to wild plants and animals, thereby contributing to the conservation of biological and genetic diversity and the evolutionary process within the ecological system.
- **Production functions** reflect the photosynthesis and nutrient processes that convert energy, carbon dioxide, water and nutrients into a wide variety of carbohydrate structures, which are used by secondary producers to create an even larger variety of living biomass. Besides its intrinsic importance for ecological structure

and processes, this biomass is linked to the provision of a wide array of ecosystem services, including food, production inputs and genetic material.

- **Information functions** reflect the potential of ecosystems to provide opportunities for spiritual enrichment, inspiration and cognitive development, recreation and aesthetic experiences, as well as to develop social values such as identity, cohesion, etc.

- Second, it is important to improve our understanding of social processes, not only to understand the functioning of the economy and governing institutions and the relatively autonomous processes that explain human development, but also to link the provision of ecosystem services back to the drivers of ecosystem transformation, and to the responses to environmental challenges as perceived by individuals and institutions. The only way to progress consists in improving our understanding on (i) how social systems work and transform the provision of ecosystems services in new demand, and (ii) on how societies adapt to ecological changes such as scarcity, drought, floods and other nature-driven risks and climate change. Summing up, social processes allow us to go from the supply to the demand side of ecosystem services analysis.

Figure 4: AQUACROSS Architecture



Source: Own elaboration

All in all, the AQUACROSS architecture as a whole is formed by two analytical pathways linking two complex adaptive systems (see Figure 4).

- One analytical pathway, or the supply-side analysis of ecosystem services, explains how ecosystems services (the main outcome of ecological systems) are connected to human well-being.
- The other analytical pathway, or the demand-side analysis of ecosystems services, explains how the drivers of ecosystems change and the responses to ecosystems challenges (the main outcomes of social systems) are linked to ecosystems structures and conditions.
- One complex system, the ecological one, with its autonomous, complex and adaptive processes, transforms the ecosystem modified by human-driven impacts into new ones with a different ability to provide ecosystem services.
- The other complex system, the social one, with its autonomous, complex and adaptive processes, transforms the actual and perceived capacity of the ecological system into new drivers of ecosystem change and responses to environmental challenges.

A closer look at ecosystems and biodiversity: some methodological challenges

A better understanding of ecological processes is essential to bridge the knowledge gap between the demand-side and the supply-side analysis of ecosystems services. This is of paramount importance to generate the knowledge required to face stakeholders with the consequences of their actions (drivers and responses) in terms of their own welfare. The demand-side analysis informs us on how social outcomes impact the environment, while the supply-side analysis shows how important ecosystem services are for welfare and human development. Yet, substantial knowledge gaps remain in our ability to explain how human drivers affect the potential of ecological systems to continue providing the ecosystem services to support human well-being.

The link between impacts over ecosystems and their potential to sustainably deliver ecosystem services is mediated by ecological processes. Many of them are nonlinear and lead to abrupt changes that are currently neither properly understood nor integrated into policy-making. In addition, the trade-offs amongst ecosystem services are not fully comprehended (Bennett et al., 2009).

Besides their primary impact, the major anthropogenic drivers and pressures trigger adaptive ecological processes in ecosystems that take them to alternative stability domains (resulting, for example, in habitat changes and/or losses); lead to cumulative changes in the structure, abundance and composition of species (leading to extirpation or extinctions as well as to the proliferation of invasive species or pathogens); affecting ecosystems at local, regional and global scales (from single habitats to climate change), and with differentiated effects over time (with threats over future ecosystems' resilience, loss of options, irreversible changes and negative legacy effects).

Within the past 20 years, several studies have started assessing how different components of biodiversity affect ecosystem processes that are related to the sustained provisioning of ecosystem services and services to society (e.g. see: Balvanera et al., 2014; Cardinale et al., 2012; Gamfeldt et al., 2014; Hooper et al., 2005 and 2012; Giller et al., 2004). Through a suit of meta-analyses of published data, Hooper et al. (2012) showed that the ecosystem consequences of local species loss are as quantitatively significant as the direct effects of several global change stressors that have mobilised major international concern and remediation efforts. These authors further stressed the need for more studies to unravel the interactive effects of diversity loss and environmental changes.

The analysis of ecological process in AQUACROSS will shed light on the relationships between biodiversity and ecosystem functions and services and particularly to solve the following research questions:

- To what extent does the protection of ecosystem services also guarantee the protection of biodiversity?
- What are the trade-offs between objectives for ecosystem services and other policy objectives? For example, an increase in nutrients and phytoplankton would represent an increase in waste treatment services, but this would be moving away from policy objectives related to eutrophication; or a decrease in seafloor integrity could increase the potential for seafood from some species, such as plaice, but decrease it for others, like cod.
- What are the synergies and trade-offs between different ecosystem services? In particular, between provisioning services (actually the main driver of biodiversity decline) and regulation and maintenance services (actually those ecosystem services to which biodiversity can contribute the most) and cultural services.
- How does biodiversity affect ecosystem function and services? (Positive and negative links: soil biodiversity and nitrogen cycle, soil retention, pest risks, etc., and how these effects vary as biodiversity increases).

- How does biodiversity affect ecosystem stability and resilience (i.e. functional diversity and redundancy, diversity of crop species and resistance to pests, marine biodiversity)?
- What is the role of water interfaces (ecotones) in relation to ecosystem resilience and ecosystem flows at different levels (community, ecosystem)?

In AQUACROSS, this will be mainly tackled by using existing data from literature and selected case studies to perform a global meta-analysis. Quantifiable measures (metrics) will be used to track and assess the status or summarise the information relevant to the identified indicators. The multidimensional nature of causal relationships will be addressed with multivariate modelling approaches across large regions. This will aid in:

- Identifying environmental issues linked to resilience, namely how different types of biodiversity affect resilience;
- Identifying biodiversity indicators and metrics suitable to forecast resilience;
- Identifying biodiversity aspects (through expert judgment) that might promote resilience of ecotones at the following interfaces: land-freshwater, land-costal, freshwater-marine; and
- Integrating resilience aspects in biodiversity causal links between biodiversity and ecosystem functions and services.

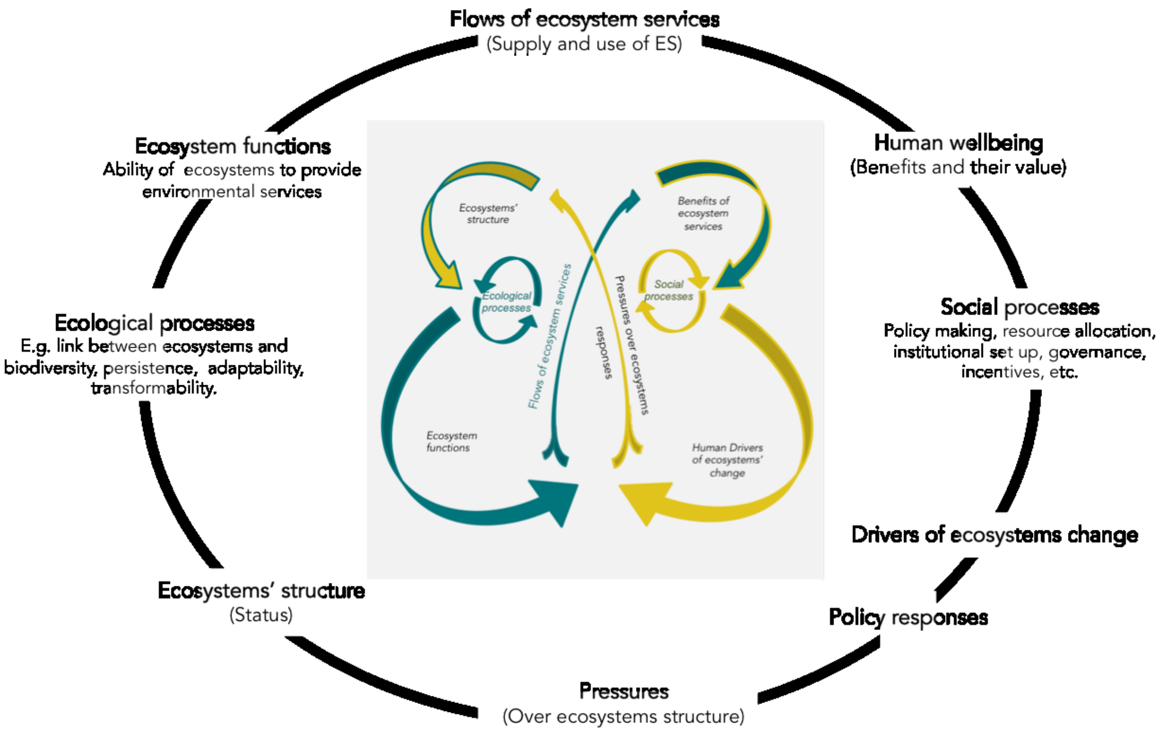
3.3 The AQUACROSS architecture II: Heuristics

AQUACROSS heuristics is defined as the accounting frameworks and analytical models and their display over the AQUACROSS architecture that is expected to support and inform the objectives of this research project as presented in the introduction. It is important to make a clear distinction between accounting for information frameworks on one side and for analytical frameworks on the other. The first group helps to organise information and to conduct assessments to each of the information layers or building blocks within the overall project architecture. The second one is formed by the models and tools that allow navigating through the project architecture, as its main purpose consists in providing the understanding of how one thing leads to another across the different information layers.

3.3.1 A closer look to the information layers and flows within the AQUACROSS architecture

The project information system consists of a coherent system including data and indicators organised around precisely defined concepts and coherent metrics that allow for the integration of different disciplines in the AQUACROSS architecture at the spatial and temporal scales required in the analysis. The information layers are the building blocks of the conceptual model behind the AQUACROSS architecture and can be represented as a circular information flow to inform the relevant linkages explained above. This circular information flow, represented in Figure 5 as a grey circle around the AQUACROSS architecture, can be dubbed as the AQUACROSS heuristics or strategy to speed up the process of analysing the complex interaction between social and ecological systems and find effective, efficient and socially acceptable EBM responses.

Figure 5: AQUACROSS Heuristic I: information layers and flow



***Heuristic** (from Eureka): Any approach to problem solving, learning, or discovery that employs a practical method not guaranteed to be optimal or perfect, but sufficient for the immediate goals. Where finding an optimal solution is impossible or impractical, heuristic methods can be used to speed up the process of finding a satisfactory solution*

Source: Own elaboration

What follows is a basic description of the different layers that should be developed to build the AQUACROSS information flow. AQUACROSS will take stock of all the assessment exercises developed so far to evaluate each one of these information layers.[22]

- **Ecosystem services**: contains maps of the relevant biophysical flows of ecosystem services provided by particular ecosystems. They include regulation and self-supporting services that maintain the structure and function of ecosystems and flows to the socio-economic system through the provision of goods and services as well as cultural and aesthetic values.
- **Human well-being (or human welfare)**: it contains a map of the *benefits* for human welfare obtained from ecosystem services and the way they are used by the economy depending on the technology and institutions in place. It may include information about the *value* of these benefits in monetary terms.
- **Social processes**: it gathers relevant concepts and methods to understand the demand of ecosystems services as well as the governance institutions in place. It includes the social impacts and responses to environmental challenges such as resource scarcity, pollution, water-borne hazards, and climate change, and the analysis of adaptive responses to these changes.
- **Drivers of ecosystem change**: they refer to the decisions taken by social and economic agents both individually and in a coordinated way, to meet their demands and to satisfy the needs and demands of ecosystem services whilst putting them into value for the market economy and the overall socio-economic system. These drivers must be understood as the main outcome of social and economic interactions and are mediated by policy institutions, technology and social values.
- **Pressures over ecosystems**: this information layer maps the relevant qualitative and quantitative information about how the socio-economic system affects and directly transforms the biophysical one. It includes, for instance, water

[22] Social-ecological accounting frameworks, such as DPSIR, have been primarily concerned with the definition of relevant types of information. "Their further development requires consideration of how to incorporate information on the temporal lags between measures of different categories and the degree of uncertainty in the relationship between information categories, as well as how these relationships may be affected by other changes in future" (Cooper, 2013).

abstractions, diversions, impoundments, pollution, land use, soil transformation, alterations of nutrient and sediment balances.

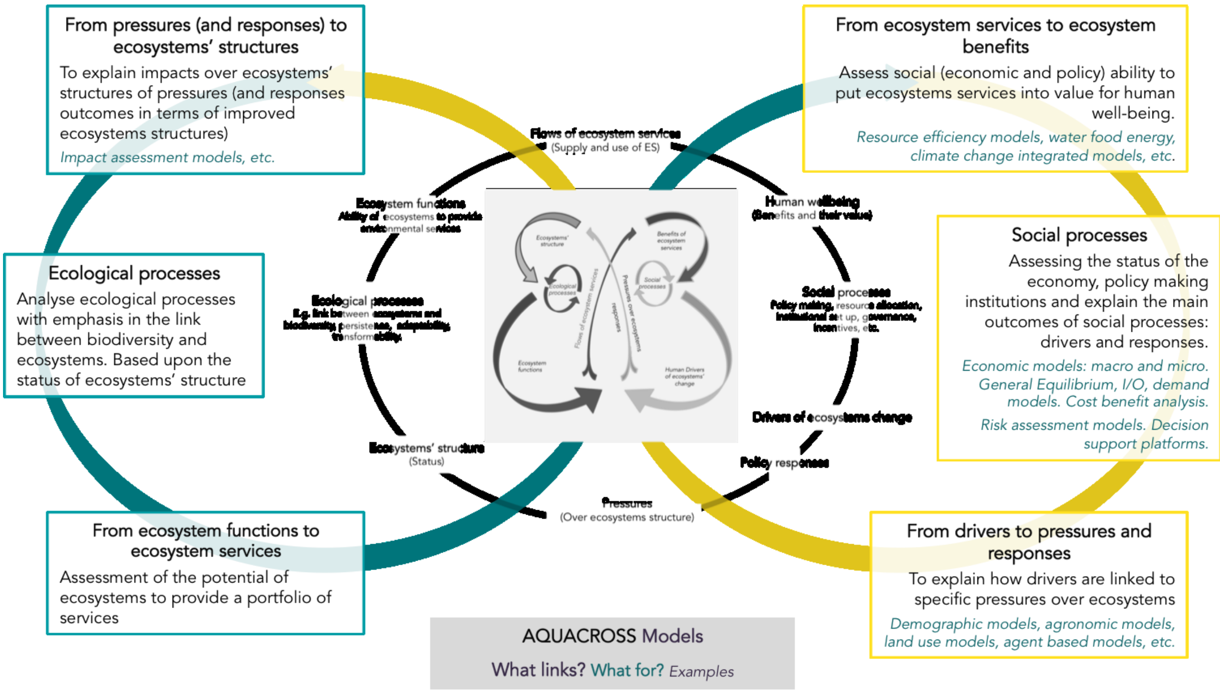
- **Responses to ecosystem's challenges**: it maps all the primary changes in the ecosystems structure (or its components) resulting from policies and management options intended to generate a positive impact on the ecosystem. While pressures are measured over existing structures, responses are measured as changes with respect to a baseline or no action scenario.
- **The structure**: it maps information representing the biophysical status of the relevant elements of the ecosystem (i.e. their state). This information covering quantity, quality, morphology, biodiversity and other indicators of the ecosystem has a proven potential to improve communication between scientists, policy-makers and stakeholders, as well as to help develop collaborative research and build shared understanding on the importance of preserving critical ecosystem functions.
- **Ecological processes**: it maps the natural transformations resulting from complex interactions between biotic (living organisms) and abiotic (chemical and physical) components of ecosystems through the universal driving forces of matter and energy. Special attention is paid to the links between ecosystem structure and function and biodiversity as an integral component of the ecosystem, as well as to the link between biodiversity, the delivery of ecosystems services, and their resilience.
- **Ecosystem functions**: it maps the potential of ecosystems to provide a flow of ecosystems services, depending on the structure (condition or status) and the ecological processes taking place in the ecosystem.

3.3.2 The analytical models: how does one thing lead to another within the AQUACROSS architecture?

The information layers described in the previous section, and the standardised and consistent information systems they conform, facilitate the description and the assessment of each one of the building blocks of the AQUACROSS architecture.

Going one step further requires being able to build upon the causal links between one layer and the other, as well as within the social and ecological systems themselves through analytical models. Beyond description and assessment, the distinctive character of analytical models relies on the fact that they allow navigating through different information layers and building comprehensive scenarios, storylines, assessments of the overall SES and the development of comprehensive decision tools and platforms to support the identification, design, implementation and assessment of EBM options.

Figure 6: AQUACROSS Heuristics II: Analytical models and tools, how one thing leads to another



Source: Own elaboration

More specifically, models involved in the AQUACROSS architecture (see Figure 4) are purposely designed to explain specific critical links and can be classified accordingly as follows (see Figure 6):

1 **Analytical models that explain the drivers of ecosystem change as outcomes of economic and social processes.** They include:

- Behavioural models at different temporal and spatial scales that contribute to explain the complex dynamics of socio-economic systems but may also try to factor in how these dynamics are affected by ecosystem services and by trends in the function and the structure of critical ecosystems.
- Behavioural models based on specific ecosystem services (such as water, energy, fish demand models) towards models able to account for interlinkages between different drivers (from energy, water, food, climate change, input-output models to general equilibrium models).
- Rather than solely explaining pressures through economic drivers, these behavioural models also have the ambition to inform how the economic and

social systems respond to environmental challenges such as water scarcity, exposure to droughts and floods, biodiversity losses, marine resource depletion and climate change.

- Institutional models that explain policy outcomes in the relevant areas (water, energy, land planning, etc.) and that may explain institutional failures and success of existing policy setups, as well as opportunities for cooperation, synergies and trade-offs linked to the design and implementation of EBM.
- These models provide the causal relationships required to link the supply to the demand-side analysis of ecosystem services. They explain how social decisions are shaped by the provision of ecosystem services, their transformation into benefits and welfare as well as by the perception of how changes in the supply of ecosystems services drive social responses.

2 **Analytical models that explain the pressures resulting from the drivers of ecosystem change** (and the effectiveness of policy measures) and enable to shed light on land use patterns.

- They include, for example, agronomic models explaining the pressures resulting from irrigated and rainfed agriculture. These models are intended to show how changes in the economy and social behaviour would result in direct changes in pressures and to analyse how the pressures might change according to different economic and social behaviours to better understand the pressures exerted on ecosystem services. For example, scenarios of future land use depending on changes in energy demand, food diets or changes in productivity. Other models focus on policy-driven changes that may result in changes in land use (e.g. Common Agricultural Policy) or the prevention of the conversion of land into artificial use (e.g. development of urban areas Natura 2000, Less Favoured Area, Birds and Habitats Directives).

3 **Analytical models that explain how the state of ecosystem components are impacted by pressures.** This covers a wide array of environmental impact assessment models that enable the transformation of pressures into a representation of the status (or the structure) of the affected ecosystem. They include hydrological models, biological models and pollution dispersion and transformation models.

4 **Ecological models that explain the adaptive processes taking place in the ecological system.** These models go one step further to explain how the direct impact of existing pressures and responses over the ecosystem condition (structure) trigger different adaptive processes and may result in major ulterior changes in the structure and the resilience of the ecosystem. A particular set of models within this class is designed to analyse the multiple causal links between

ecosystems and, particularly, the complex connection between biodiversity and the supply (potential and effective) of ecosystems services. This group of analytical models link the demand- to the supply-side analysis by analysing how the demand of ecosystems services is met shapes the ecological system and has ulterior effects in the capacity of the affected ecosystems to supply ecosystems services to the social system.

5 **Ecosystem models that assess the functions performed by ecosystems.** These models are intended to assess the potential of particular ecosystems to provide specific services on a regular basis. They include, for instance, the supply-side analysis to assess the potential of marine ecosystems (Culhane et al., 2014), the assessment of the long-term water resources available or the water retention potential depending on soil conditions and the rainfall runoff models, as well as different partial analysis models intended to measure the potential of particular places for development, such as irrigation, electricity, fishing and recreation.

6 **Economic models that explain how ecosystem services are transformed into benefits.** They include resource efficiency models that assess the potential to obtain welfare gains, production and employment opportunities by the allocation of critical resources, such as water, energy or land, as well as models that assess the allocation of these resources in the economy. A variety of models serve to measure the potential benefits of ecosystem services for recreation, tourism, R&D, etc. Models also consider negative contributions to human well-being (disservices) resulting from nature driven risks (as risk assessment models) or environmental degradation trends (the welfare losses derived from water scarcity or climate change, etc.)

This rather ambitious architecture should not be seen as a straightjacket, but as an adaptable framework to represent knowledge and knowledge gaps, to favour communication and cooperative research, to help build a common understanding over relevant problems and to inform decision-making processes about relevant environmental issues people care about.

As part of the AQUACROSS architecture, an intensive modelling exercise will be made. Please refer to Annex 2 for a table with some of the most relevant models and tools to be used.

A final note on building baseline and alternative policy scenarios

Scenarios are critical in order to evaluate the likely outcome of ecosystem management and conservation measures against a business-as-usual or baseline scenario and to assess their potential outcome in terms of the delivery of ecosystem services and human welfare.

The project heuristic will support the precise identification of information and knowledge gaps for building scenarios in AQUACROSS. Scenarios may go from representations based on detailed information and models to storylines based on stylised data, qualitative information, and general models). Different scenarios need to be considered: business-as-usual, counterfactual, policy, no-action scenarios and their link to EBM approaches.

Building scenarios will mobilise existing knowledge within AQUACROSS. For instance, trends in the wide range of drivers/pressures of aquatic ecosystems will allow building scenarios to test the predictive power of the models used within the AQUACROSS project, allowing the application of different types of models and possibly the comparison of the outputs of different modelling approaches.

This is an aspect in which model robustness and detailed information trade-off, with relevance and the need to make the overall AQUACROSS architecture operational. For this purpose, it is worth taking stock of the following ideas about scenarios:

- Scenarios are based upon existing knowledge and bridge critical knowledge gaps. They recognise what is available but focus on relevant information and models.
- Scenarios are not precise and detailed explanations of what is actually happening or of what will happen in the future, but explorations on what we know and what will happen. They are structured narratives.
- In policy-making contexts, scenarios are not the end of something, but the start of a social dialogue and an instrument to build a common understanding about the challenges ahead and the options to cope with them.
- Scenarios foster discussions and trigger stakeholder engagement and interactions.
- Scenarios do not represent the future, but serve as instruments to consider possible futures and to think of the robustness of alternative courses of action, which will make system regimes more resilient.

4 Conclusions and road ahead

According to the objectives of Work Package 3, Deliverable 3.1 develops the AQUACROSS project conceptual foundations on the basis of existing ecosystem and SES assessment frameworks. A review of available concepts and approaches was required not only to ensure internal consistency amongst consortium partners, but mostly to jointly examine as a multidisciplinary group key concepts and knowledge gaps aimed at improving EBM schemes, to identify key research questions, and to provide the necessary (conceptual) architecture for the remainder of the work to be developed in the project.

This concept will thus be used as the foundations for the practical development of the AF, which will ultimately present the scientific consensus on the AQUACROSS concept, but also on the methods and tools to be developed in the different project work packages and implemented in the different case studies.

Accordingly, this concept aimed at building (scientific) consensus and common ground for concepts, methods and approaches for facilitating collaborative model development, identifying opportunities linked to biodiversity, ecosystem services, and human welfare, and for assessing barriers, trade-offs, synergies, and drawbacks of traditional approaches.

This deliverable already highlights some of the innovative aspects of AQUACROSS, such as the ecosystem services-based MAES (Mapping and Assessment of Ecosystems and their Services) conceptual framework as the basis for developing an assessment framework routed in existing policy initiatives, the policy-relevant principles for enhancing the resilience of SES as the basis for integrating operational resilience thinking in EBM, or the determined attempt to generate a higher degree of consistency of analysis across all aquatic realms.

The AQUACROSS concept also serves to make the advantages of holistic approaches more visible, to represent and analyse uncertainty about scientific outcomes, to develop methods to assess the robustness of alternative paths of action, and to support the development of articulated targets in terms of managing ecosystems and the services they deliver, as well as to manage risks in the long-term.

<u>Three central concepts can be said to be the pillars of this document:</u>

- Complex adaptive systems, as self-organising entities (such as an economy or an ecological system), consisting of many local or micro-level adaptive agents making predictions of one another's behaviour and responding to information and signals from their neighbouring environment.

- Resilience thinking as the backbone to build up sustainability. It provides a framework to support policy decision-making processes aimed at overcoming the vulnerability and the long-term negative consequences of current practices of human development. It allows mobilising existing knowledge and to identify the critical knowledge gaps and stresses upon the importance of governance and institutions as the keystone that explains the adaptive capacity of socio-economic systems.
- The AQUACROSS Architecture, as outlined in Chapter 3, is a methodological approach to integrate scientific knowledge in a fashion that is familiar to stakeholders and managers, suitable to inform EBM approaches to manage SES. The concept and the AF are policy- and management-driven; thus, EBM is not only the third critical concept but also actually the cornerstone of the project.

Deliverable 3.1 has provided the interdisciplinary project consortium with an opportunity for disambiguation of concepts. In addition, the authors of the document have agreed on the fact that some issues or notions "set in stone upstream" in the assessment of the interactions between social and ecological systems (i.e. the characterisation of linkages between drivers and pressures or the relationships between biodiversity and ecosystem services) pose a number of difficulties "downstream" for science and policy purposes.

As per the way forward, project partners have already identified some critical issues:

- There is no need to go for radical change, in the sense that transitional approaches are more realistic (i.e. sequencing reforms, making the best out of available knowledge and management practices, etc.). Therefore, although very ambitious, the scope of the project's concept and AF will also be realistic (including leeway for unknown drivers and pressures, recognition that EBM does not necessarily require changing everything, etc.);
- AQUACROSS will be (partially) building on MAES, for policy relevance, but also recognises the constraints of that process;
- AQUACROSS will bear in mind the difference between datasets, data flows, and information layers on one side, and information that is actually needed for analytical or assessment purposes on the other side. This stems from the belief that even in the presence of data, sometimes there is lack of understanding;
- There are clear opportunities to add value from AQUACROSS, as part of this conceptual exercise: shedding additional light on the DPSIR logical chain (and moving beyond); contributing to the discussion of links among ecosystem structure, processes, functions, functioning, and services to ascertain relationships between biodiversity and ecosystem services; etc.;

- The challenge may be not so much to yield new indicators or metrics, but rather to use insightful ones that are not part of common practice; and
- Further attention is needed for trade-offs, uncertainties, and critical thresholds.

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5 Annex 1 – Glossary (abridged version)

Term	Definition (as in the Concept note)
Adaptability	A defining component of resilience. It refers to the capacity of a social-ecological system (SES) to adjust its responses to changing external drivers and internal processes and thereby allow for development within the current stability domain and/or along the current trajectory.
Adaptation	It is the "adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities" (IPCC, 2007). According to Lukasiewicz et al. (2015), in terms of land and water management, adaptation actions involve reducing non-climate threats that increase the resilience of populations to a changing environment in situ as well as enabling the species concerned to migrate to a more suitable habitat under a changing climate (CBD, 2010).
Complex adaptive system	Complex adaptive systems (such as an economy or an ecological system) consist of many local or micro-level adaptive agents The structure, the functions and the dynamics of the system at the macro-level are not planned by a central control but emerge from the interaction and interconnectedness of their constituent parts and of the system with other complex adaptive systems. Complex adaptive systems are self-organising entities.
Driver	The main outcome of social and economic interactions and are mediated by policy institutions, technology, and social values.
Ecosystem based management (EBM) approach	EBM "is an interdisciplinary approach that balances ecological, social and governance principles at appropriate temporal and spatial scales in a distinct geographical area to achieve sustainable resource use. Scientific knowledge and effective monitoring are used to acknowledge the connections, integrity and biodiversity within an ecosystem along with its dynamic nature and associated uncertainties. EBM recognises coupled SES with stakeholders involved in an integrated and adaptive management process where decisions reflect societal choice" (Long et al., 2015 p. 59).
Ecological process	They are the natural transformations resulting from the complex interactions between biotic (living organisms) and abiotic (chemical and physical) components of ecosystems through the universal driving forces of matter and energy.
Ecosystem service	Those benefits humans get from ecosystems.

Ecosystem structure	Components and their layout within the ecosystem. It includes the biotic (living organisms) and the abiotic components.
Persistence	Persistence is the tendency of a SES subject to change to remain within a stability domain, continually changing and adapting yet remaining within critical thresholds.
Pressure	Direct and indirect transformation over the ecosystems structure. It includes, for instance, water abstractions, diversion, impoundment, pollution, land use, soil transformation, alterations of nutrient and sediment balances.
Resilience (ecological /social /economic/ socio-ecological)	A general characteristic of a system that results from its ability to respond to change, perturbations and perturbation regimes (adaptability), and transform when necessary. It is closely connected with the diversity of ecosystems and species (heterogeneity), the capacity of a system to contain or spread a perturbation along its constituent parts (which depends on the system modularity), and the capacity of a particular part or population to recover after a shock has taken place (which is linked to the system connectivity). **Adaptability** – a component of resilience defined as the capacity of a SES to adjust its responses to changing external drivers and internal processes and thereby allow for development within the current stability domain, along the current trajectory. **Transformability** – a component or resilience reflecting the capacity of a SES to create new stability domains for development, a new stability landscape, and cross thresholds into a new development trajectory.
Resilience thinking	It is a framework approach to sustainability that emphasises that humans and ecosystems are interdependent, that SES are complex adaptive systems and that cross-scale dynamics matter to support the deliberate transformation of SES. Resilience thinking aims at: 1) assessing firstly the relative merits of the current versus alternative, potentially more favourable stability domains, and, 2) fostering resilience of the new development trajectory, the new basin of attraction. It focuses on the three aspects of SES: resilience as persistence, adaptability and transformability (Folke et al., 2010).
Transformability	The capacity to create new stability domains for development and a new stability landscape, and to cross thresholds into a new development trajectory.

6 Annex 2 – Models and tools

Aquatic system	Emphasized system	Tool name	What is it (for)?	Why is it useful for AQUACROSS? *Some features and examples*
All aquatic realms	Social-ecological	ARIES (ARtificial Intelligence for Ecosystem Services)	Models integration software platform for rapid ecosystem service assessment and valuation (ESAV). It encodes (maps) relevant ecological and socioeconomic knowledge to map ESS delivery, use, and benefit flows. ARIES carries out an automated data integration process by using an extensive database featuring global through local scale GIS data and ecosystem service models.	• Open-source modelling framework to map ecosystem services flows. • Generalisable. • Applicable at land-scale – extensions to marine ecosystems being explored. • Independently applicable. • Examples of applications: data and models available for several countries (BC3).
	Social-ecological	Marxan (Conservation planning tool)	A software-based planning tool aimed to provide decision support to conservation planning problems, such as the design of new reserve systems, performance of existing reserve systems reporting and multiple-use zoning plans for natural resource management development. Applicable to terrestrial, freshwater and marine systems. It can be used to manage natural resources by prioritising management and the definition of areas for biodiversity conservation and ecosystem services delivery.	• For biodiversity conservation and ecosystem service delivery assessment. • Flexible. • Entailing stakeholder involvement. • Examples of applications: Swiss Plateau (FVB-IGB, EAWAG) and North Sea (IMARES, ULIV)

Aquatic system	Emphasized system	Tool name	What is it (for)?	Why is it useful for AQUACROSS? *Some features and examples*
Marine	Ecological	EcRiAss (Ecological Risk Assessment)	It seeks to estimate the effects of environmental contamination on the growth, reproduction, and survival of a variety of ecological receptors (e.g. birds, mammals, fish, plants) that may be exposed to chemicals in contaminated environmental media, either now or in the future.	• Oriented to possible pathways that affect ecosystem status and assess the risk. • Considers different drivers and their pressures, human activities, management objectives. • Entails stakeholder involvement. • Examples of applications: European regional seas (IMARES, ULIV).
River, lake, coastal	Ecological	WASP7 (Water Quality Analysis Simulation Programme)	A model to interpret and predict water quality responses to natural phenomena and anthropogenic pollution for various pollution management decisions.	• Oriented to phytoplankton and nutrients in rivers, lakes and coastal waters. • Considers environmental conditions (climate change), management measures, etc. • Examples of applications: Danube (BOKU, local and ecosystem level (floodplain, river stretch).

Aquatic system	Emphasized system	Tool name	What is it (for)?	Why is it useful for AQUACROSS? *Some features and examples*
River catchment	Social-ecological	Probability network model	The model is used for the prediction of the consequences of river rehabilitation options by taking into account the knowledge from available sources (e.g. basic scientific knowledge, specialised literature, other models, data, and expert knowledge). It takes into account causal relationships between the main variables of the rehabilitation project and some relevant decision-making attributes. This approach divides the model into sub-models (e.g. (hydraulics, benthos, vegetation, fish, other fauna, economics…) and considers prediction uncertainty.	• For risk and uncertainty analysis of restoration measures. • Takes into account biodiversity of invertebrates and fish climate, land use, and population growth scenarios and suggested management strategies. • Examples of applications: Swiss Plateau (EAWAG), multiple river catchments.
		Social-ecological modelling	To assess the dynamic interrelations among human and environmental factors, and the capacity of a social-ecological system in a catchment to adapt to change, and to study the key structural elements and processes in social and ecological subsystems.	• Oriented to the capacity of a social-ecological system in a catchment to adapt to change. • Considers key structural elements and processes in the social and ecological subsystems, their interactions and management strategies. • Flexible. • Entails stakeholder involvement. • Example of applications: Ringström (SRC)

Aquatic system	Emphasized system	Tool name	What is it (for)?	Why is it useful for AQUACROSS? *Some features and examples*
	Ecological	BIOMOD & BIOMOD2(R) Package	An ensemble platform for species distribution modelling (SDM). BIOMOD (and its new version biomod2) is a computer platform for ensemble forecasting of species distributions, enabling the treatment of a range of methodological uncertainties in models and the examination of species-environment relationships. This tool models species distributions by using different techniques, tests models with a wide range of approaches, projects species distributions into different environmental conditions and dispersal functions.	• For distribution patterns (niche) of invertebrates and fish. • Considers major drivers/pressures (temperature, precipitation, hydrology, nutrients, land use…) and management options. • Potential of making future projections under climate and land-use change scenarios. • Flexible. • Examples of applications: Danube catchment (FVB-IGB, BOKU).
		MONERIS (MOdelling Nutrient Emissions in RIver systems)	A semi-static emission model to estimate the emissions of nitrogen and phosphorus (adaptable to include heavy metals and certain priority substances as lindane) to surface water, by different independent pathways for separate catchments and the in-stream retention in the surface water network (i.e. for agricultural and urban management options).	• For total nitrogen, total phosphorus and dissolved silicium. • Considers agricultural and urban management options. • Examples of applications: Danube catchment (FVB-IGB).

Aquatic system	Emphasized system	Tool name	What is it (for)?	Why is it useful for AQUACROSS? *Some features and examples*
Rivers	Ecological	FATs (Fish Assemblage Types)	Spatially-based method (developed by Schmutz et al. (2007b) and Melcher et al. (2007)) to assess the ecological status of European fish assemblage types in European running waters (responding to multiple human pressures). It entails the description of a river and fish assemblage typology based on minimally impacted sites and also the analysis of impacted conditions for each type.	• For fish assemblage types in European running waters. • Takes into account multiple human pressures. • Flexible. • Examples of applications: European running waters (BOKU).
		Meta-community approach	Theoretical and conceptual tool to understand feedbacks and impacts across multiple scales and the emergent properties that arise from spatial coupling of local ecosystems.	• For species assemblages. • Contemplates different environmental factors and pressures. • Examples of applications: Danube (BOKU), local to regional.
Lakes	Socio-ecological	FCM (Fuzzy Cognitive Mapping)	Originally a semi quantitative and dynamic method to structure expert knowledge based on cognitive mapping. It is a graphical representation of the knowledge about or the perception of a given system (illustrating the relationships between its concepts, nodes and relationships).	• For the assessment of protocols in place for invasive species. • Considers management in transboundary context. • Flexible. • Entails stakeholder involvement (UCC). • Examples of applications: Lough Erne, UK/ROI.

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