Title: Evaluation of ecosystem-based management strategies based on risk assessment

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Abstract

This study presents a comprehensive and generic framework that provides a typology for the identification and selection of consistently defined ecosystem-based management measures and allows a coherent evaluation of these measures based on their performance to achieve policy objectives. The performance is expressed in terms of their reduction of risk of an adverse impact on the marine ecosystem. This typology consists of two interlinked aspects of a measure, i.e. the "Focus" and the "Type". The "Focus" is determined by the part of the impact chain (Driver-Pressure-State) the measure is supposed to mitigate or counteract. The "Type" represents the physical measure itself in terms of how it affects the impact chain directly; we distinguish Spatio-temporal distribution controls, Input and Output controls, Remediation and Restoration measures. The performance of these measures in terms of their reduction in risk of adverse impacts was assessed based on an explicit consideration of three time horizons: past, present and future. Application of the framework in an integrated management strategy evaluation of a suite of measures, shows that depending on the time horizon, different measures perform best. "Past" points to measures targeting persistent pressures (e.g. marine litter) from past activities. "Present" favours measures targeting a driver (e.g. fisheries) that has a high likelihood of causing adverse impacts. "Future" involves impacts that both have a high likelihood of an adverse impact, as well as a long time to return to pre-impacted condition after the implementation of appropriate management, e.g. those caused by permanent infrastructure or persistent pressures such as marine litter or specific types of pollution.

Key words

DPSIR; Ecosystem-based management; Spatio-temporal distribution controls; Remediation; Restoration; Marine Strategy Framework Directive

1 Introduction

All marine ecosystems are impacted by human activities (e.g. Glover and Smith 2003; Halpern *et al.* 2007) and in many cases, the exploitation of resources is occurring at an unsustainable rate resulting in a deteriorated ecosystem. Impacts are caused by the multitude of sectors in operation to exploit a wide range of habitats and species (ecosystem components), thereby forming a complex network of interactions (Leslie and McLeod, 2007; Liu *et al.*, 2007; Knights *et al.*, 2013) that may cause harm to the environment (Levin *et al.*, 2009; Goodsir, submitted). This has left current sectoral approaches to the management of marine and coastal resources apparently incapable of conserving the marine ecosystem and exploitation rates remaining unsustainable (Smith *et al.*, 2007). A widely promoted solution is an ecosystem approach to management also known as ecosystem-based management (EBM) (Airoldi & Beck, 2007; EC, 2008; Halpern *et al.* 2007); a concept in which the network of impacts is identified and managed. However, the number of impacts can make the identification and management of detrimental pathways difficult (Bottrill *et al.*, 2008; but see Knights *et al.*, 2013) and presents a major challenge to resource managers in transforming the ecosystem approach from a concept into an operational framework (Leslie and McLeod, 2007). This challenge can be addressed by the development of a comprehensive generic framework for integrated decision-making on the exploitation of marine resources.

The effective management of human impacts requires that the pathways through which activities cause harm are identified (Fletcher *et al.*, 2010; Leslie and McLeod, 2007). Linkage-based frameworks (e.g. DPSIR) have been developed for marine and terrestrial environments (Elliott, 2002; Holman *et al.*, 2005; La Jeunesse *et al.*, 2003; Odermatt, 2004; Scheren *et al.*, 2004), adopting a causal-chain approach to infer pressure-state relationships between human activities and ecosystem state (Rounsevell *et al.* 2010). The number of potential links between sectors and the state of the ecosystem (Airoldi and Beck, 2007; Knights *et al.*, 2013) can increase the difficulty of decision-making, especially when time is limited (Haynes, 2009). In support, several frameworks for formal decision-making are available (Jeffrey, 1983; Jeffrey, 1992; Resnik, 1987) with risk assessment in particular providing a flexible, problem-solving approach that is capable of linking the relationship between human activities and the environment supporting the decision-making needs of environmental managers (Hope, 2006). Risk assessment in general describes the likelihood and consequences of an event. In the context of EBM, it evaluates the degree to which human activities interfere with the achievement of management objectives that are related to particular ecological characteristics (Samhouri and Levin, 2012) and is increasingly seen as a way to integrate science, policy and management (CENR, 1999).

To date, risk assessment has been used to assess a wide range of environmental issues. Early efforts addressed a single ecosystem component and considered few threats (e.g. Francis, 1992), followed by more comprehensive frameworks that were developed for species (e.g. Kappel, 2005; Samhouri and Levin, 2012) or features (e.g. Zacharias and Gregr, 2005; Halpern *et al.*, 2007). In none of these cases was a specific link to existing environmental policy made. But in perhaps the most extensive framework to date, Driver-Pressure-State combinations for entire ecosystems were developed (Robinson *et al.* 2013; Knights *et al.* in press) and these combinations (which were referred to as "impact chains") were explicitly linked to existing policy objectives, namely the Marine Strategy Framework Directive (MSFD) and its qualitative descriptors of good environmental status (GES) (EC, 2008a). Assessing the risk to an ecosystem from a particular impact chain can be done using quantitative approaches (e.g. Francis, 1992; Samhouri and Levin, 2012) or qualitative approaches (e.g. Breen *et al.*, 2012; Fletcher, 2005; Fletcher *et al.*, 2010). Ecological risk assessments (e.g. Fletcher, 2005; Campbell and Gallagher, 2007; Astles *et al.*, 2006) tend to be based on a likelihood-consequence approach for estimating the risk of a rare or unpredictable event (i.e. calamities) (Williams *et al.*, 2011). However, when an assessment of on-going (current) pressure is needed (i.e., normal operations, where the likelihood equals 100%), then an exposure-effect analysis is more suitable (Smith *et al.*, 2007) using qualitative descriptors such as habitat resistance and resilience to assess the vulnerability of habitats (Bax and Williams, 2001) and more recently, assess the potential for EBM at a sub-regional scale (Samhouri and Levin, 2012).

Building on the vulnerability measures of Halpern et al (2007), Robinson *et al.* (2013) conducted a qualitative pressure assessment that assesses the threat from different driver-pressure combinations to the state of the ecosystem components (thus making up impact chains) for all European regional seas. From this, Knights *et al*. (in press) used an exposure-effect analysis with five criteria to assess risk for each impact chain which can be interpreted as the likelihood or degree to which human activities interfere with the achievement of policy objectives. Risk can then be assessed for each Driver, Pressure or State component through aggregation across those impact chains that include that particular Driver, Pressure or State component. This, in turn, allows for an evaluation of how risk will decrease over time once management on one or more of these components or combinations of components is implemented.

The logical next step towards achieving policy objectives is the choice of appropriate ecosystem-based management (EBM) measures to mitigate those risks affecting these objectives (Samhouri and Levin, 2012). To that end we developed a comprehensive framework for integrated Management Strategy Evaluations (iMSE) framework that links directly to the risk assessment approach described (e.g.

Halpern *et al.*, 2007; Knights *et al.*, in press), providing guidance for the identification and selection of consistently defined measures, and also allowing an evaluation of the effectiveness of these measures through their reduction of risk. For this, the effectiveness of a management measure depends on both (a) the number of impact chain(s) it targets; (b) the weighting of the chains based on the five risk criteria; and (c) the likelihood the measure can reduce the impact of these chains. Measures that target a selection of impact chains that together contribute a high proportion of the risk to the ecosystem being assessed are likely to be most effective.

2 Material and methods

2.1 Summary of risk assessment approach

This framework for the identification, selection and evaluation of management measures (MMs) is based on the most extensive risk assessment approach to date consisting of Driver-Pressure-State combinations (so-called "impact chains") that each contribute to the risk of not achieving policy objectives (Knights *et al.*, in press). Risk is determined based on scores given to five criteria. These are: (1) the spatial (Extent), and (2) temporal (Frequency) overlap of a sector-pressure and ecological characteristic, which together describe the exposure of the ecological component to a sector-pressure combination in terms of their spatio-temporal overlap; (3) the Degree of Impact (DoI) of the sector-pressure on that characteristic describing the severity of the impact where interactions occur; whilst the potential for recovery after the impact has occurred is described by (4) the Persistence of the pressure (the number of years before the pressure impact ceases following cessation of the activity introducing it), and (5) the Resilience of the ecological characteristic (recovery time in years) (see full details of criteria in Robinson *et al.*, 2013). Based on these criteria, Knights *et al.* (in press) allocated scores and considered two aspects of risk:

- Impact Risk (IR) = the likelihood of an adverse ecological impact following a sector-pressure introduction = Extent * Frequency * DoI
- Recovery Lag (RL) = the time it takes for an impacted ecological component to return to pre-impacted condition after the implementation of a measure = Persistence * Resilience.

2.2 Selection of MMs

As MMs tend to either reduce the exposure to a pressure, the severity of impacts where there are interactions, or actively promote recovery, it is possible to select measures using the five criteria described above, and thus to target particular aspects of risk in the ecosystem (Table 1). Linked to these risk assessment criteria, the selection of MMs can then also be guided by two distinct aspects of a MM: the "Focus" and the "Type" of measure. The "Focus" is determined by the element(s) of the impact chain (i.e. Driver-Pressure-State) that the measure targets. A measure may involve only one single element in the impact chain (i.e. Driver, Pressure or State), the combination of two (i.e. Driver-Pressure or Pressure-State), or all three making the measure more specific as more elements are combined (see first column in Table 1 and examples in Table 2). The "Type" distinguishes six categories, loosely based on the measures distinguished in (EC, 2008b), that mitigate or counteract the impact of the human activity on the ecosystem directly. Each category links specifically to one of the risk criteria (Table 1).

Table 1. A typology for ecosystem-based management measures based on the impact-chain "Focus" and control "Type" of a measure distinguishing three groups of generic measures: affecting several impact chains and either exclusively reduce impact risk (red); reduce recovery lag (green); or reduce both impact risk and recovery lag (yellow). White cells indicate no possible combination of "Focus" and "Type". The numbers in the cells correspond to the management measures in Table 2.

Focus	Type					
	Spatial distribution controls	**Temporal distribution controls**	**Input control**	**Output control**	**Remediation**	**Restoration**
D	1,2		6			
D-P	3			7,8	13	
P	4			9	14	
P-S	4			10	15	
S	5					17,18,19
D-P-S				11,12	16	20
Risk assessment criteria	Extent	Frequency	Degree of Impact		Persistence	Resilience
Aspects of risk	Impact Risk				Recovery Lag	
Time horizon	Present				Past	
	Future					

The measure types “Spatial distribution controls”, “Temporal distribution controls”, “Input control” and “Output control” each (or in combination) mitigate or counteract aspects of Impact Risk. The first two involve a reduction of the extent in space and time of the activity and are further considered as a single type, i.e. Spatio-temporal distribution controls, because in addition to spatially closed areas, e.g. Marine Protected Areas (MPAs) (Browman and Stergiou, 2004), or seasonal closures (Dinmore *et al.*, 2003) there are Real Time Closures (RTCs) (Bailey *et al.*, 2010) which are essentially a combination of both. The latter two come originally from fisheries management and affect the DoI where “input control” applies to capacity (size of the fleet) or effort (fishing activity), and “output control” applies to the reduction of the catch itself (FAO, 2003). In this integrated framework, i.e. beyond fisheries management, we interpreted input controls as only mitigating the Driver while output controls mitigate the Pressure, possibly in combination with either some Driver or some State component. While the four types of controls (i.e. spatial distribution, temporal distribution, and input/ output control) mitigate the risk of potential impact (respectively linked to assessment criteria: Extent, Frequency and DoI), the mitigation of any already existing impacts occurs through the reduction of the Recovery Lag, for which we distinguish between the reduction of pressure persistence through “Remediation” measures, and the increase of the resilience of the state component(s) through “Restoration” measures.

2.3 Evaluating effectiveness of MMs

For the evaluation of the effectiveness of MMs, a non-exhaustive list of examples of MMs was compiled (Table 2) that could reduce risk through the various pathways indicated in Table 1. The process of identification and selection of possible MMs was based on three groupings of measures (see colours in Table 1) distinguishing between fairly generic measures (several impact chains) and very specific measures (involving few impact chains), and either aimed at the reduction of Impact Risk or Recovery Lag. The aim was to select examples that together covered most of the boxes shown in Table 1, so that the utility of the approach in evaluating effectiveness could be explored fully.

For the evaluation of the effectiveness of measures we assumed a full implementation of the measure (i.e. a 100% reduction of the risk criteria linked to the type of measure). For example, if the MM covered a ban on littering (not specified to any sector), then any impact chain that contained Marine Litter as pressure would be removed and the reduction in risk (across the whole ecosystem) associated with this is calculated to express the effectiveness of the MM. Using the two different risk aspects mentioned earlier, i.e. Impact Risk and Recovery Lag, we considered it relevant to assess the effectiveness of MMs against three time horizons:

- “Past” - aimed at recovery of already affected ecosystems as reflected by the Recovery Lag (RL) score,

- "Present" – aimed at reducing the likelihood of an adverse ecological impact from current activities as reflected by the Impact Risk (IR) score, while
- "Future" – aimed at reducing the likelihood of impacts, specifically those that require a long time to recover from. This is reflected by Total Risk (TR) which is the product of RL and IR.

These "Time Horizon" perspectives were used in the process of identification and selection of possible management measures, as well as the subsequent evaluation of these measures.

3 Results

The results show (1) the application of our framework incorporating the European risk assessment data to guide the identification and selection of MMs for the North East Atlantic (NEA) region, followed by (2) an evaluation of the effectiveness of measures in reducing risk to the ecosystem across three management time horizons.

3.1 Identification and selection of MMs

The identification and selection of MMs was approached differently for each of the three (color coded) groups of generic measures identified using the typology in Table 1. As the type of measures intended to mitigate the IR mostly involve a focus on Driver and/or Pressure, the selection of these measures can be guided by information such as represented in Figure 1. This shows that for the NEA, fishing is by far the most important driver (37% across all pressures), and selective extraction of species (33% across all drivers) the main pressure, the combination contributing 26% to IR, making these the most likely candidates (separately or in combination) for MMs aimed at mitigating IR. Other important drivers are shipping (11%) and tourism/recreation (9%) while marine litter and the introduction of synthetics are the next important pressures each contributing 11% to IR.

The type of measures intended to reduce the RL mostly involve a focus on Pressure and/or State (see Table 1, Figure 2). The four least resilient ecosystem components, i.e. both demersal and pelagic fish, marine mammals, and seabirds contribute to 88% (across all pressures) of the RL while the five most persistent pressures, i.e. sealing, marine litter, introduction of synthetics, introduction of non-synthetics, introduction of radionuclides, contribute to 81% (across all components) of the RL. For more specific measures (i.e. focus on P-S rather than P or S) any combination of these pressures and ecosystem components can be considered. Each combination contributes to approximately 3-4% of the RL.

The third group to guide the identification and selection of measures involves very specific measures (i.e. focus on specific D-P-S combination), which depending on the choice of the type of management measures, may reduce the IR (i.e. any of the control types), RL (i.e. Remediation, Restoration) or TR (all control types). When individual impact chains are ordered according to their contribution to the overall IR, RL or TR (Figure 3) we find that notably for IR and TR there are a few, but different, individual impact chains that contribute disproportionately (i.e. furthest to the left with a relative contribution to risk > 1), and thus should be targeted by specific management measures. For IR, it is fishing affecting demersal, pelagic and deep sea fish as well as the sublittoral sediment habitat through the pressure biological extraction. These four individual chains together contribute more than 22% to the total IR. In contrast, for TR marine litter from shipping affecting the least resilient ecosystem components (i.e. seabirds, marine mammals and fish) emerges as the main contributors causing close to 10% of the TR. The driver coastal infrastructure is affecting the littoral habitats (both sediment and rock) through sealing as well as some other pressures. The pressure marine litter is caused mainly by shipping and fisheries and affects all ecosystem components.

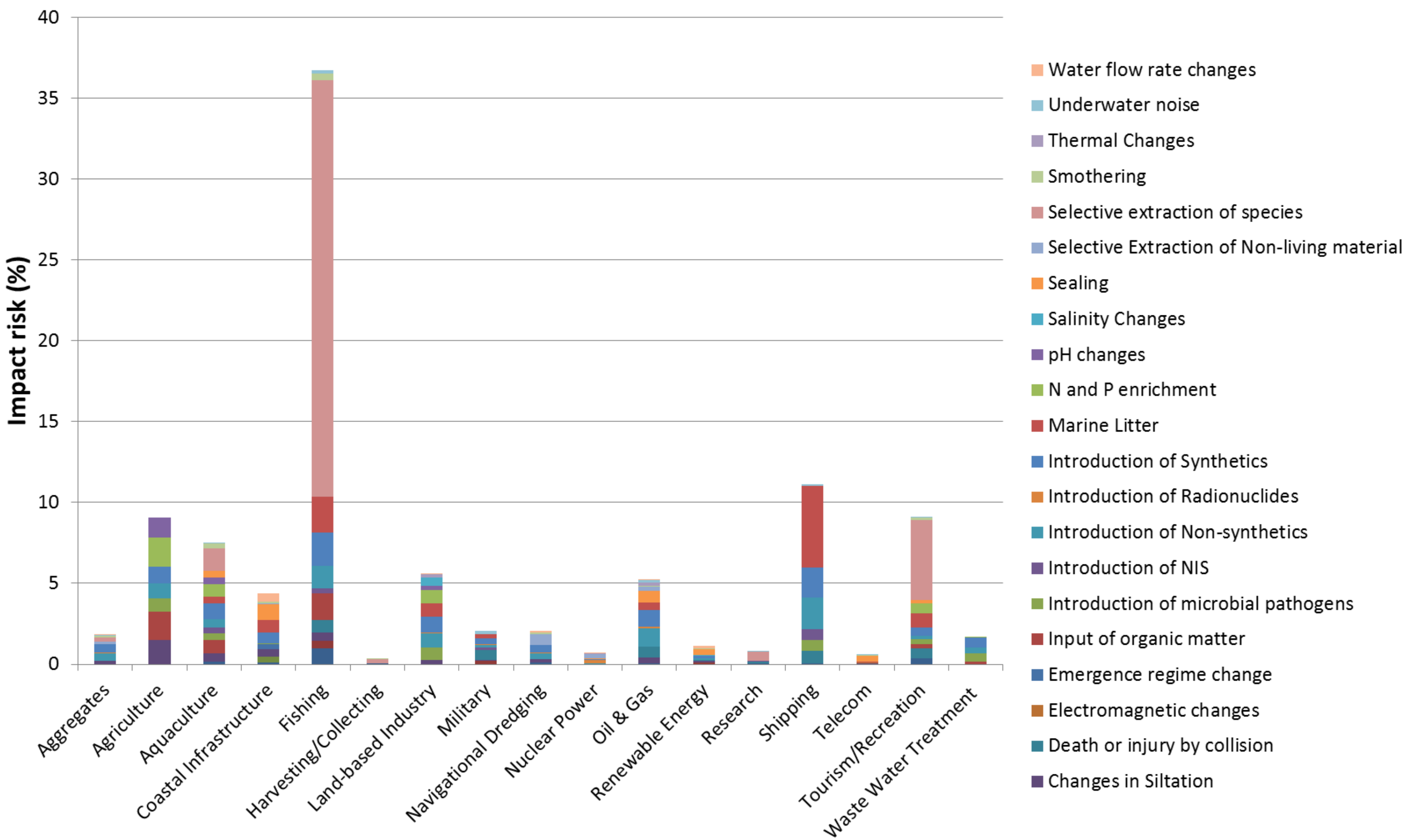

Figure 1. Impact Risk per Driver-Pressure combination expressed as the % contribution to the total risk of an adverse impact.

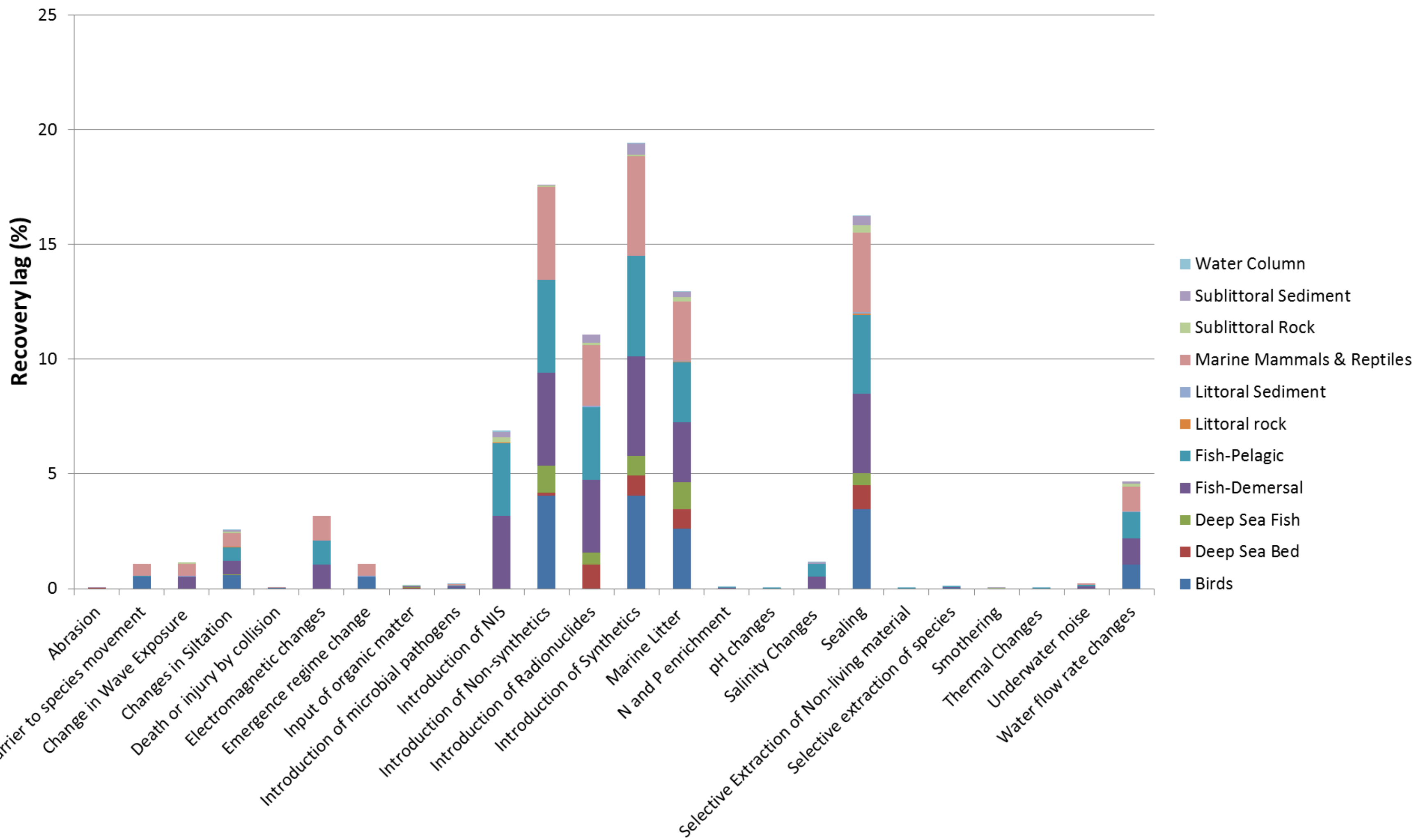

Figure 2. Recovery Lag per Pressure – State combination expressed as the % contribution to the total time it takes for the impacted ecological components to return to pre-impacted condition after the introduction of the pressures has stopped.

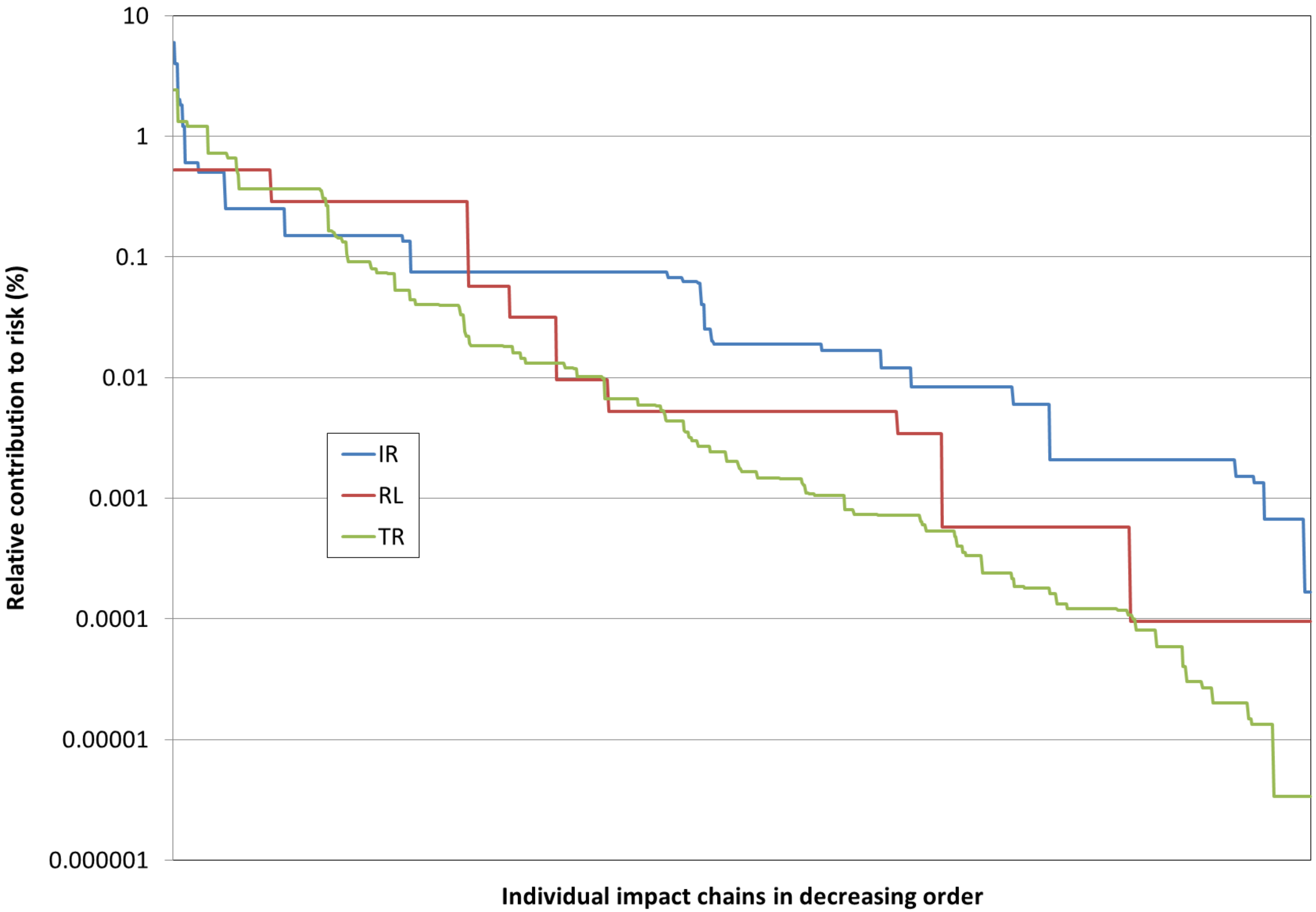

Figure 3. Relative contribution to Total Risk (TR) and the two aspects (IR=Impact Risk, RP=Recovery Potential) that determine TR by each individual impact chain arranged in decreasing order. Note the logarithmic scale of the y-axis.

3.2 Effectiveness of MMs at reducing risk over three time horizons

Guided by the above results, we selected a non-exhaustive suite of 20 potential management measures (Table 2) and calculated the reduction in IR, RL and TR the full implementation of these measures would achieve. We phrased the measures 1-3 as “Spatio-temporal closures/restrictions....” in line with our assertion that often measures contain both spatial and temporal dimensions. In this assessment MMs 1 and 2 are conventional fisheries management measures but here considered in an EBM context where not only more pressures are considered than the commonly used “biological extraction of species” (i.e. catch) but also other components of ecosystem state than fish. The distinction between MMs 1 and 2 lies not only in the subset of fish they target (i.e. respectively pelagic versus demersal) but also in that the demersal fishery impacts the seafloor habitats through physical disturbance (i.e. abrasion, smothering and changes in siltation). Other pressures, such as marine litter and underwater noise apply to both fisheries. Because the MMs 1 and 2 are assumed to involve a spatio-temporal closure for the fishing vessels belonging to a specific metier (i.e. demersal or pelagic), we consider these MMs as focussed on the Driver only. However, in Table 2 we used the selection of the State components, pelagic fish and demersal fish, to focus on the appropriate fishing metiers.

MMs 4 and 5 are explicitly spatial but this should not imply that measures with also a temporal component can be conceived for those cells in table 1. No Take zones, or totally closed areas (Horwood *et al.*, 1998), can be defined as marine areas in which the extraction of living and non-living resources is permanently prohibited, except as necessary for monitoring or research to evaluate effectiveness (NRC, 2001, cited by Jones, 2006). Although this measure can be introduced to reduce the risk for a specific ecosystem component (Focus = P-S), it could also be introduced to protect all components in that area (Focus = P). Based on this definition, the measure affects all impact chains that include the pressures ‘selective extraction of non-living resources’ or ‘selective extraction of species’; and are not related to the driver ‘research’. Although in some cases the focus could include specific components of State, all ecosystem components were included in this assessment.

MMs 8, 9 and 13-15 all involve marine litter but the % risk reduction achieved varies considerably because of the difference in focus of the measures. MM 9 is the least specific and therefore results in the largest potential reduction. Even though MM 8 and MM 13 both involve the mitigation of effects of marine litter from fisheries we distinguished between MM 8 which involves all litter and MM 13 mitigating only the effects of “ghost-fishing”, here assumed to affect fish only. MM 14 will only remove marine litter from fishable habitats while MM 15 was assumed to affect only the littoral habitats and the ecosystem components that inhabit the intertidal zone.

Table 2 shows that management measures cause different reductions in the three aspects of risk which correspond to the three time horizons for management we considered. From a “Present” perspective,

Table 2. Non-exhaustive list of potential management measures, how these were interpreted in terms of “Focus”, the number of impact chains affected based on this “Focus” and the maximum potential reduction that can be achieved if the measures are fully implemented and effective. The numbers correspond to those in Table 1. RL=Recovery Lag, IR=Impact Risk and TR=Total Risk.

Nr.	Management measure	Focus	Number Impact Chains	Potential reduction (%)		
				RL	IR	TR
1	Spatio-temporal closures of the pelagic fishery	D (Fisheries) P (All pressures except those disturbing the seabed) S (Excluding demersal and deep sea fish and all seafloor habitats)	27	0	11	9
2	Spatio-temporal closures of the demersal fishery	D (Fisheries) P (All pressures specifically related to this type of fishery) S (Excluding pelagic and deep sea fish but including all habitats)	52	0	25	9
3	Spatio-temporal restrictions to the discharge of ballast water	D (Shipping, Military) P (Non-indigenous species)	4	0	1	3
4	No take zone(s)	P (Selective extraction of species and	46	0	34	2

		non-living resources) S (may be applied, e.g. a specific seafloor habitat but was not in this assessment)				
5	Closed areas for deepwater coral or seamounts	S (Deep sea bed)	28	0	3	6
6	Decommissioning fishing vessels	D (Fisheries)	76	0	37	18
7	System for identification of oil spills from offshore installations	D (Oil & Gas) P (Non-synthetic compounds)	10	0	1	2
8	Biodegradable fishing gear	D (Fisheries) P (Marine Litter)	11	0	2	6
9	Ban on littering	P (Marine Litter)	76	0	11	27
10	Fish guide	P (Selective extraction of species) S (Fish)	11	0	19	2
11	MSC	D (Fisheries) P (Selective extraction of species)	10	0	26	2
12	TAC/Quota	D (Fisheries) P (Selective extraction of species) S (Fish)	3	0	14	1
13	Retrieval of lost or abandoned fishing gear	D (Fisheries) P (Marine Litter) S (Fish)	3	1	0	4
14	Collection of fished litter (fishing for litter scheme)	P (Marine Litter) S (Sub-littoral habitats and water column)	21	0	0	1
15	Additional beach cleaning	P (Marine Litter) S (Seabirds, Mammals, Littoral habitats)	30	5	0	9
16	Cleaning pollution from offshore drilling operations, e.g. drilling muds and cuttings	D (Oil & Gas) P (Synthetic and Non-synthetic compounds) S (Excluding deep sea)	17	2	0	3
17	Breeding program Seabirds	S (Seabirds)	79	17	0	12
18	Breeding program Fish	S (Demersal fish)	130	25	0	29
19	Breeding program Marine mammals	S (Marine mammals)	110	22	0	16
20	Optimise shape burrow pits for ecological development	D (Aggregates) P (Abrasion, Selective extraction of non-living resources) S (Sediment habitats but not deep sea)	4	0	0	0

we only consider measures that affect the likelihood of current activities to cause an adverse impact (MMs 1-12 where RL is not affected) and do not consider the remaining management measures (MMs 13-20 where IR is not affected), which are specifically intended to reduce existing adverse impacts and hence only relevant for the "Past" perspective. All management measures are relevant for the "Future" perspective for which TR applies.

The "Past" perspective (RL column in Table 2) shows that the most effective (and very generic) Restoration measure (MM 18) targeting the most impacted ecosystem component (i.e. demersal fish) performs better in terms of a reduction of the RL than the best (and relatively specific) Remediation measure (MM 15) targeting the 4th important pressure (i.e. Marine litter).

The "Present" perspective (IR column in Table 2) shows that measures targeting what is currently the main driver causing adverse impacts (i.e. fisheries) either through a Spatio-temporal closure (MM 2), Input control (MM 6) or Output Control (MM11) cause the largest reductions in IR and that there is only a weak relationship between the performance of the measures and the number of impact chains targeted by the measure.

The "Future" perspective (TR column in Table 2) shows that an Output control (MM 9) on a relatively persistent pressure (i.e. marine litter) performs almost equally well as a very extensive Restoration measure (MM 18) on a fairly resilient ecosystem component affected by many different drivers.

4 Discussion

This framework shows how EBM can be developed for the NEA based on the type of risk assessments available for this region as well as the other European MSFD regions. The results illustrate two phases in the EBM process: 1) identification/selection and 2) evaluation of management measures.

Table 1 combined with Figures 1-3 are mostly relevant for the first phase where the table helps to identify the measures while the figures are examples of how the information from the risk assessment can be used to select potential measures. Following the three "Time Horizon" perspectives, the figures revealed that the main adverse impacts from "Past" activities come from persistent pressures such as the introduction of (non-)synthetics, radionuclides or non-indigenous species, marine litter and sealing. A "Present" management perspective would focus on the potentially large adverse impacts of current fishing practices which, however, can be mitigated in the relatively short term. A "Future" perspective could focus the decision-makers on a few impact chains involving widespread activities such as shipping or fishing causing persistent pressures (e.g. marine litter or non-indigenous species) that affect ecosystem components that require long recovery times (e.g. marine mammals, birds) which are likely to cause persistent adverse impacts with high likelihood.

For the second phase where the management measures were evaluated, we assumed the measure to be 100% effective (i.e. full implementation and compliance) of each measure, e.g. spatial distribution control aimed at a specific driver effectively results in a closure of 100% of the area covered by that driver thereby effectively reducing the likelihood of any impact through all relevant impact chains of that driver to 0. Similarly we assumed that restoration of a specific ecosystem component resulted in the complete recovery to pre-impact levels of that ecosystem component. While we acknowledge that in reality it is probably not feasible to ever achieve such goals, it is considered appropriate for the purpose of this exercise because 100% effectiveness results in higher reductions (i.e. ten-fold compared to a more realistic 10% effectiveness) while giving the same relative performance of the measures, both qualitatively (i.e. the same measure will always come out best) as well as quantitatively (i.e. the degree to which one measure outperforms the other).

The evaluation of the management measures can be based on both a qualitative (i.e. based on ranked order) and quantitative (based on % potential reduction of risk) perspective of the relative performance of the measures but there are several reasons why this framework should only be used for a qualitative evaluation. Firstly, even though TR and its two aspects (IR and RL) are based on criteria that represent real-world characteristics, the way these characteristics are assessed (Robinson *et al*., 2013) and how subsequently the achieved reduction in the criteria and thus (aspects of) risk are calculated prevent any simple (i.e. linear) relationship to real-world characteristics of anthropogenic pressure (e.g. fishing intensity, or quantity of some contaminant) or ecosystem state (e.g. the abundance of a species or quality of a habitat) that would determine the true relative performance of these measures. Secondly, ultimately the selection of management measures is not only based on their performance to improve ecosystem state but also on various socio-economic considerations. These determine the potential reduction the measure can achieve as well as the likelihood this is actually achieved. In this framework, a reduction in any of the criteria that determine IR, RL and thus TR would give the same reduction in that aspect of risk and can therefore be implemented interchangeably. In this framework it makes no difference if a Temporal distribution- (Reducing Extent), Spatial distribution- (Reducing Frequency), Input- or Output control (Reducing DoI) is implemented as they all reduce IR (of those impact chains targeted by the Focus-part of the measure) with the same level of effectiveness. Similarly for Remediation and Restoration in relation to RL. In reality, however, the selection of a measure, determined by "Type" and "Focus", will be mostly decided based on socio-economic and institutional considerations (Knights *et al.* 2014) resulting in a very different level of effectiveness for each of those criteria (linked to "Type") and thus different reductions of IR, RL or TR.

In this framework the "Type" only determines which aspect of TR (i.e. IR or RL) is reduced and the choice is largely determined by the "Time horizon" perspective, while the "Focus" is strongly linked to (aspects of) risk through the observed relationship between the number of impact chains targeted and the reduction of (those aspects of) risk.

While each measure "Type" is directly linked to a risk assessment criterion such that it is obvious how the implementation of the measure reduces the criterion (e.g. Spatial distribution controls reduce the Extent of the overlap), this is less clear for the Input/Output control measures linked to the DoI. While in reality the Input/Output control directly relates to the intensity or amount of the activity causing the pressure, this is not the case in our framework because intensity is not considered in the definition of DoI (i.e. severity of a single interaction event between the pressure and an ecosystem component, Robinson *et al*., 2013). In fisheries management, for example, this implies some output control, e.g. technical measure, could reduce the DoI (e.g. from acute to chronic, see Robinson *et al*., 2013) but others, e.g. Total Allowable Catch (TAC), cannot as it only affects the intensity of the pressure. For this evaluation we assumed any output control would reduce the DoI but the suitability of this framework to evaluate input/output control measures would improve if the intensity or amount of (the activity causing the) pressure was explicitly included in the assessment of severity.

The "Type" of measures in this paper include several measures that occur in the MSFD Annex VI Programmes of Measures, namely "Input controls", "Output controls", "Spatial and temporal distribution controls" and "Mitigation and remediation tools", where the latter MSFD measure includes both our restoration and remediation measures. The other potential MSFD measures, i.e. "Management coordination measures", "Measures to improve the traceability", "Economic incentives", "Communication, stakeholder involvement and raising public awareness", are essentially indirect measures that affect our proposed, direct, measures through some (implementation) mechanism and are therefore not explicitly considered in this framework.

In order to include all the measures occurring in the MSFD Annex VI Programmes of Measures, we can expand our framework into a hierarchy based on existing typologies of measures (ARCADIS, 2012; van Vliet, 1999) that distinguishes between physical measures (identical to our five "Types"), which may be carried out by any stakeholder (i.e. industry, NGO, policy) and three types of instruments that are implemented at a governmental level and may initiate these physical measures.
These three types of instruments, i.e. regulatory, economic and social, thus have an indirect effect on the impact chain insofar as respectively institutional, market-based, or participatory aspects are involved.

Regulatory instruments emerge from the principle that human nature is self-centered/egoistic and should be controlled by the government (van Vliet, 1999). These instruments directly influence the behavior of actors by imposing rules that limit or prescribe the actions of the target group (ARCADIS, 2012). Irrespective of the management mechanism employed, all instruments are built on a common legal basis and require enforcement and control if they are to be successful.
Economic instruments may also be used. Their effectiveness is based on the principle that the pursuit of individual economic self-interest will lead to the optimal benefit for everyone (van Vliet, 1999). These instruments are defined by the OECD as "fiscal and other economic incentives and disincentives to incorporate environmental costs and benefits into the budgets of households and enterprises" (UN, 1997). The common underlying rationale is inspired by the polluter-pays principle (UN, 1997) and involves a modification of the actors' behavior through the price of a commodity in the market such that acceptable levels of pollution, optimum rates of resource use or depletion are achieved and thus the protection of the environment is ensured. Examples of such instruments are fee-based systems, subsidies, liability and compensation regimes and trading systems (ARCADIS, 2012).
A key feature of social instruments is the participatory nature and the essence of legitimacy lies in the involvement of stakeholders in decision-making, thereby improving the knowledge system on which policy making is based and possibly leading to higher compliance rates (van Vliet, 1999). Sectors are stimulated to take actions based upon their own motivation, often through information (education, training) or awareness raising campaigns. Good or bad image building and associated perception from

society (e.g. through communication or certification) can provide important incentives to adapt behavior.

Some of the measures considered in our framework do not require the implementation of any instrument by regional managers to initiate change. For example, many sectors are often in the process of continuous development and application of new technologies (i.e. technical measures for output control). In addition there are voluntary initiatives of private stakeholders, which can initiate community action (i.e. remediation measures).

This typology of MMs was developed to help implement the MSFD (EC, 2008a) and together with our framework could contribute to EBM as it merges the three pillars of sustainability, i.e. environmental, economic and social (UN, 2005) with the institutional context. While the framework developed in this study assesses the performance of the potential MMs in terms of their reduction of the risk of an adverse ecological impact, and the time it takes to return to pre-impacted conditions after the implementation of the MM, the final choice of the actual MMs requires an interpretation of the feasibility of the guidance coming from this type of framework in a real-world context. The instruments to initiate them should be based on the outcome of this process considered in the appropriate institutional and socio-economic context.

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