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Title: Spatially explicit risk approach for multi-hazard assessment and management in marine environment: the case study of the Adriatic sea

Article Type: Research Paper

Keywords: Marine Strategy Framework Directive, multi-hazard assessment, endogenic and exogenic pressures, Multi-Criteria Decision Analysis, Adriatic sea, Geographic Information Systems.

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First Author: Elisa Furlan, PhD

Order of Authors: Elisa Furlan, PhD; Silvia Torresan, PhD; Andrea Critto, PhD; Antonio Marcomini, Professor

Abstract: In the last few decades the health of marine ecosystems has been progressively endangered by the anthropogenic presence. Natural and human-made pressures, as well as climate change effects, are posing increasing threats on marine areas, triggering alteration of biological, chemical and physical processes. Planning of marine areas has become a challenge for decision makers involved in the design of sustainable management options. In order to address threats posed by climate drivers in combination with local to regional anthropogenic pressures affecting marine ecosystems and activities, a multi-hazard assessment methodology was developed and applied to the Adriatic sea for the reference scenario 2000-2015. Through a four-stages process based on the consecutive analysis of hazard, exposure, vulnerability and risk the methodology allows a semi-quantitative evaluation of the relative risk from anthropogenic and natural sources to multiple endpoints, thus supporting the identification and ranking of areas and targets more likely to be at risk . Resulting output showed that the higher relative hazard scores are linked to exogenic pressures (e.g. sea surface temperature variation) while the lower ones resulted from endogenic and more localized stressors (e.g. abrasion, nutrient input). Relatively very high scores were observed for vulnerability over the whole case study for almost all the considered pressures, showing seagrasses meadows, maërl and coral beds as the most susceptible targets. The approach outlined in this study provides planners and decision makers a quick-screening tool to evaluate progress toward attaining a good environmental status and to identify marine areas where management actions and adaptation strategies would be best targeted. Moreover, by focusing on risks induced by land-based drivers, resulting output can support the design of infrastructures for reducing pressures on the sea, contributing to improve the land-sea interface management.

Response to Reviewers: Response to Reviewers

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[Comment 4] Reply-8. Bathymetry and currents are included in figure 1; alas, neither the scale of blue is indicated as a legend, nor the length of the arrows according to the representative speed.
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Editorial office, *Science of the Total Environment*

September 8th, 2017

Dear Editorial Office,

here enclosed you will find a new revised version of the manuscript STOTEN-D-17-03133 entitled:

SPATIALLY EXPLICIT RISK APPROACH FOR MULTI-HAZARD ASSESSMENT AND MANAGEMENT IN MARINE ENVIRONMENT: THE CASE STUDY OF THE ADRIATIC SEA

which we would like to resubmit for publication in the Science of the Total Environment Journal.

The manuscript describes a spatially resolved risk-based methodology aimed at evaluating multiple threats posed by climate drivers in combination with local to regional anthropogenic pressures on marine ecosystems and related activities. By integrating a wide array of indicators concerning human-made and natural hazards (e.g. bottom stress due to sealing and abrasion of seabed, temperature and salinity variation) and vulnerability (e.g. sensitive habitat extent and typology, biodiversity indexes) with Multi Criteria Decision Analysis (MCDA) and Geographic Information Systems (GIS), the methodology allows to produce a range of spatial maps and tabular results summarizing key relative risk metrics to identify and rank hot-spot areas and vulnerable targets that are more likely to be at risk of not achieving the Good Environmental Status (GES) by 2020 (as required by the Marine Strategy Framework Directive –MSFD-) in the Adriatic sea case study.

The manuscript was entirely revised according to the Reviewer' suggestions and recommendations. A reply to each specific comment is presented in the 'Response to Reviewers' attached to the updated version of the manuscript. A new revised version of the manuscript, including all the performed amendments in review mode, is also provided.

We hope that the revisions and responses will be sufficient to make our manuscript suitable for publication in the Science of the Total Environment Journal.

Sincerely yours,

Prof. Andrea Critto

Response to Reviewers

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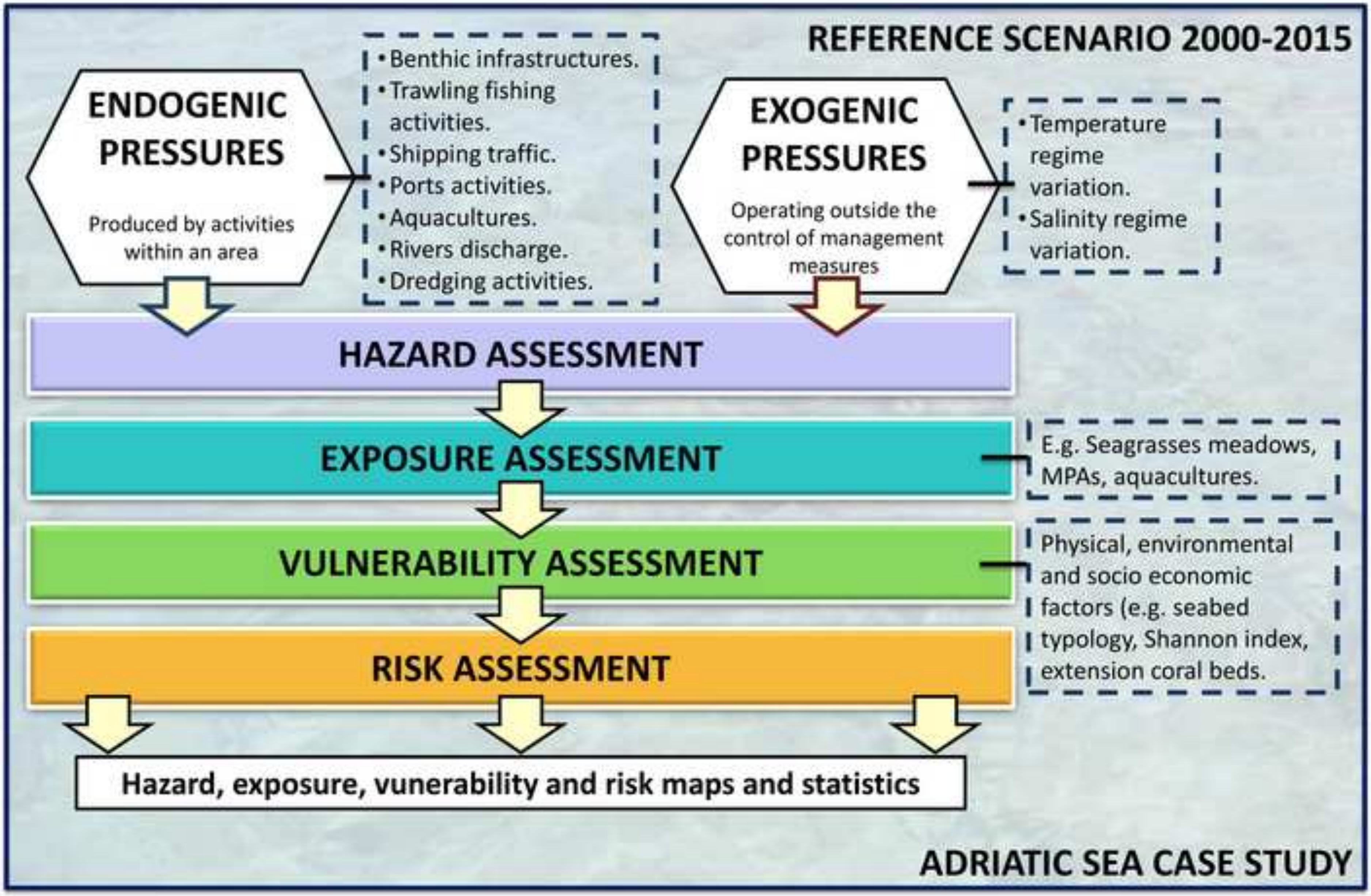
***Graphical Abstract**



REFERENCE SCENARIO 2000-2015

ENDOGENIC PRESSURES

Produced by activities within an area

- Benthic infrastructures.
- Trawling fishing activities.
- Shipping traffic.
- Ports activities.
- Aquacultures.
- Rivers discharge.
- Dredging activities.

EXOGENIC PRESSURES

Operating outside the control of management measures

- Temperature regime variation.
- Salinity regime variation.

HAZARD ASSESSMENT

EXPOSURE ASSESSMENT

E.g. Seagrasses meadows, MPAs, aquacultures.

VULNERABILITY ASSESSMENT

Physical, environmental and socio economic factors (e.g. seabed typology, Shannon index, extension coral beds.

RISK ASSESSMENT

Hazard, exposure, vunerability and risk maps and statistics

ADRIATIC SEA CASE STUDY

Highlights:

- A risk-based method for the evaluation of pressures in marine areas is presented.
- It integrates Multi-Criteria Decision Analysis and Geographic Information Systems.
- It is flexible to be applied in different marine regions and scenarios.
- Results can be used to inform maritime spatial planning and risk management.

Spatially explicit risk approach for multi-hazard assessment and management in marine environment: the case study of the Adriatic sea

Elisa Furlan (1, 2), Silvia Torresan (1, 2), Andrea Critto (1,2),
Antonio Marcomini (1,2)

(1) Department of Environmental Sciences, Informatics and Statistics, University Ca' Foscari Venice, Via Torino 155, 30170 Venezia-Mestre, Italy.

(2) Fondazione Centro Euro-Mediterraneo sui Cambiamenti Climatici (Fondazione CMCC), c/o via Augusto Imperatore 16, 73100 Lecce, Italy.

Abstract

In the last few decades the health of marine ecosystems has been progressively endangered by the anthropogenic presence. Natural and human-made pressures, as well as climate change effects, are posing increasing threats on marine areas, triggering alteration of biological, chemical and physical processes. Planning of marine areas has become a challenge for decision makers involved in the design of sustainable management options. In order to address threats posed by climate drivers in combination with local to regional anthropogenic pressures affecting marine ecosystems and activities, a multi-hazard assessment methodology was developed and applied to the Adriatic sea for the reference scenario 2000-2015. Through a four-stages process based on the consecutive analysis of hazard, exposure, vulnerability and risk the methodology allows a semi-quantitative evaluation of the relative risk from anthropogenic and natural sources to multiple endpoints, thus supporting the identification and ranking of areas and targets more likely to be at risk~~ of not achieving the Good Environmental Status by 2020, as required by the Marine Strategy Framework Directive~~. Resulting output showed that the higher relative hazard scores are linked to exogenic pressures (e.g. sea surface temperature variation) while the lower ones resulted from endogenic and more localized stressors (e.g. abrasion, nutrient input). Relatively very high scores were observed for vulnerability over the whole case study for almost all the considered pressures, showing seagrasses meadows, maërl and coral beds as the most susceptible targets. The approach outlined in this study provides planners and decision makers a quick-screening tool to evaluate progress toward attaining ~~the~~ a g~~G~~ood e~~E~~nvironmental s~~S~~tatus and to identify marine areas where management actions and adaptation strategies would be best targeted. Moreover, by focusing on risks induced by land-based drivers, resulting output can support the design of infrastructures for reducing pressures on the sea, contributing to improve the land-sea interface management.

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Keywords: Marine Strategy Framework Directive, multi-hazard assessment, endogenic and exogenic pressures, Multi-Criteria Decision Analysis, Adriatic sea, Geographic Information Systems.

1. INTRODUCTION

According to the recent ~~integrated~~ assessment of the European environment's state (EEA, 2015), Europe's seas are facing increasing threats and degradation due to a wide range of human activities, impairing marine ecosystems and their goods and services for human wellbeing. The growth of maritime activities is taking place without the full understanding of the complex interactions between natural and human-induced changes (Ehler & Douvere, 2009). Due to this overexploitation, happening across all of Europe's regional seas, marine biodiversity is declining, jeopardizing the conservation status of ecosystems and compromising the achievement of the Good Environmental Status (GES) by 2020, as required by MSFD (EC, 2008). A further complication is determined by climate change which is posing additional pressures on marine ecosystems through rising sea levels, increased sea temperatures and ocean acidification. Climate change is already affecting the marine environment and will continue triggering changes on biological, chemical and physical processes (IPCC, 2014) with stronger and more numerous impacts projected for the future, leading to exacerbate others existing anthropogenic pressures (e.g. temperature-induced changes are expected to interact with existing nutrient inputs) (Brown et al., 2014). Accordingly, the provision of ecosystem services is expected to decline across all European seas in response to climate change, thus reducing the ecosystem resilience to other anthropogenic pressures taking place in marine areas (IPCC, 2014).

Over the course of the last 30 years several directives, laws and agreements were approved by the International and European organizations for ensuring the sustainable growth of our oceans and seas, by allocating marine space, rights and responsibilities of sovereign nations (United Nations Convention on the Law of the Sea -UNCLOS III) (UN, 1982), ~~and~~ regulating use and exploitation of marine and coastal areas which inevitably lead to the deterioration of marine ecosystems' environmental status (Maritime Spatial Planning Directive -MSP-) (EC, 2014), as well as posing specific requirements and procedures for the assessment of the environmental state and quality of marine areas (Marine Strategy Framework Directive 2008/56/EC) (EC, 2008). Within these regulatory frameworks the Ecosystem Based Approach (EBA) is widely recognized as the strategic tool to be integrated with planning and management processes in order to preserve marine biodiversity (Convention of Biological Diversity -CBD-) (UN, 1992). Within the European context, the growing interest on the development and protection of marine ecosystems is highlighted by the Marine Strategy Framework Directive 2008/56/EC (EC, 2008) providing a legislative framework aimed at preserving the marine environment, preventing its deterioration and, where feasible, restoring ecosystems in adversely affected areas (Long, 2011). ~~The Directive requires an integrated approach to the management and governance of oceans, seas and coasts, allowing to move forward~~

~~the traditional sectorial one, towards a more holistic and coordinated development and organization of marine spaces and related natural resources. This kind of approach will be able to strengthen sustainable economic and environmental development, achieving at the same time the GES of the EU's marine waters by 2020. The assessment of pressures and impacts in marine areas is one of the key features of the MSFD, requiring member states to implement assessment procedures aimed at analyzing the environmental state, pressures and impacts to the marine environment by means of a well-defined set of indicators (EC, 2010) and to take appropriate and effective measures towards achieving the GES.~~

According to several scientific studies (Elliott, 2013~~); (~~Borja et al., 2010; Douvere & Ehler, 2009; Kenny et al., 2009) ~~these complex environmental evaluations~~the assessment of pressures and impacts in marine areas requires new methodological approaches able to move forward the traditional sectorial management and analysis of marine spaces and related issues, towards a more holistic and coordinated development of marine areas, and the assessment of the relative significance of environmental and anthropogenic forcing on the marine ecological status.~~The Directive requires an integrated approach to the management and governance of oceans, seas and coasts, allowing to move forward the traditional sectorial one, towards a more holistic and coordinated development and organization of marine spaces and related natural resources.~~ These~~is~~ kind of approaches will be able to strengthen sustainable economic and environmental development, achieving at the same time a higher environmental quality of ~~the GES of the EU's marine waters by 2020~~marine areas.

In this context, an environmental risk-based approach should be applied in order to support the identification of hot-spot areas and vulnerable targets that are more likely to be at risk ~~of not achieving the GES by 2020 (EC, 2008)~~ due to multiple threats posed by climate drivers in combination with local to regional anthropogenic pressures. Spatial risk assessment, performed by means of Geographical Information Systems (GIS), is an effective approach allowing a quick scan and spatial visualization of risks produced by multiple sources of various stressors, considering the presence of multiple marine habitats at broad spatial scales (Hayes & Landis 2004; Grech et al. 2011). It supports the integration of spatial models on species and habitat distribution with qualitative and quantitative information on the relative impact produced by multiple endogenic (i.e. from anthropogenic activities within an area) and exogenic pressures (i.e. induced by natural drivers operating outside the control of management measures employed in a regional sea and where the management measures can only address the consequences rather than the cause) (Elliott et al., 2015; Halpern et al., 2008; Andersen et al. 2004; Andersen et al. 2013; Crain et al. 2009; Micheli et al. 2013; Kappel et al. 2012; Korpinen et al. 2012; Ban et al. 2010; Stelzenmüller et al. 2009),

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Formatted: Font: Times New Roman, English (United States) providing a structure and analysis' output able to facilitate and inform maritime spatial planning and management and aids science-based decision-making (Cormier et al., 2010).

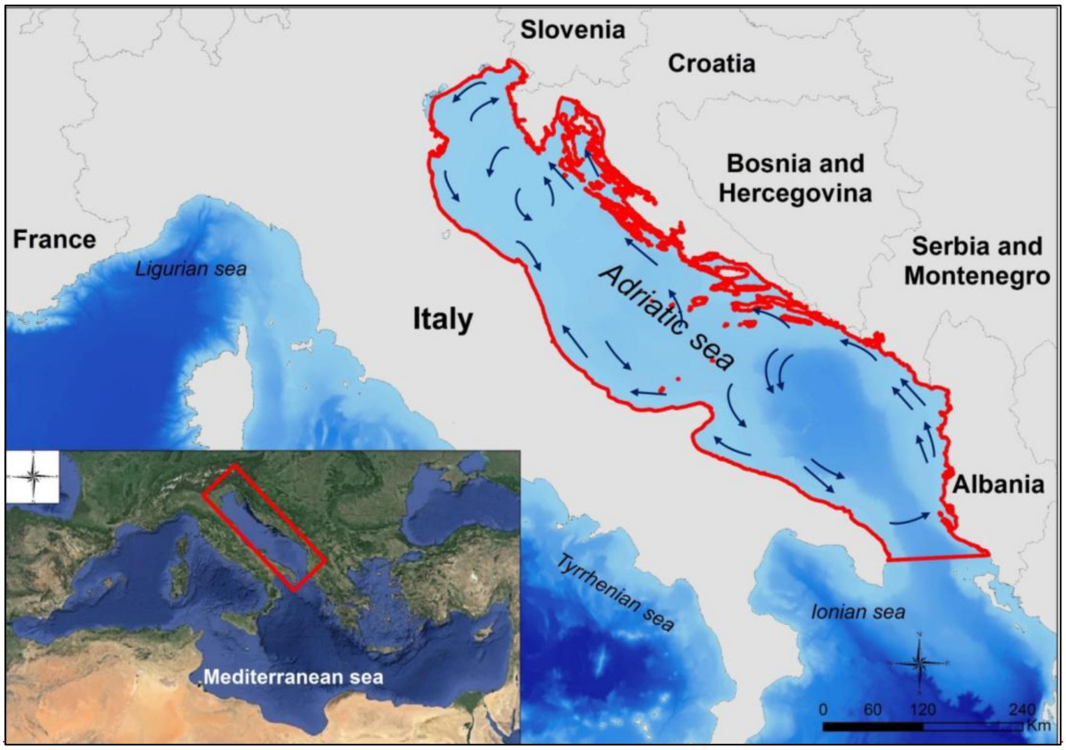
In this setting, this paper aims at developing and applying in the Adriatic sea case study a risk-based methodology allowing to evaluate relative risk scenarios induced by endogenic and exogenic pressures over vulnerable marine targets. Based on recognized methodologies in scientific literature for regional scale comparative assessment (Rizzi et al., 2017 and 2015; Sperotto et al., 2016; Ronco et al., 2015; Lamon et al., 2014; Torresan et al., 2012; Hayes & Landis, 2004; Landis, 2004) it will attempts to produce, for the considered reference scenario (i.e. 2000-2015), a suite of spatial maps and statistics representing key risk metrics, useful to public authorities to identify and relative ranking areas and targets mostly at risk ~~of not achieving GES by 2020~~ and requiring effective strategies for risks mitigation and priority actions for environmental restoration and conservation. Following a brief introduction to the case study area and the available dataset for the methodology implementation (Section 2), this paper describes in detail the developed multi-hazard approach, with its conceptual framework and operative steps (Section 3) and, finally, presents the resulting output from its application in the selected case study, including GIS-based maps and statistics obtained for the marine region of the Adriatic sea (Section 4).

2. Description and characterization of the case study area

This section introduces the case study area of the Adriatic sea marine sub-region (Section 2.1) focusing on its administrative, environmental and socio-economic aspects. Moreover, available input dataset retrieved for for the case study are described, including GIS-based data (i.e. vector and raster maps) and climate model outputs (Section 2.2). The supporting dataset has played an important role in the definition of the methodology since it is closely linked to the availability of consistent and homogeneous data covering the whole case study.

2.1 The Adriatic sea: main features and environmental issues

The case study area selected for the implementation of the multi-hazard assessment methodology is represented by the marine sub-region of the Adriatic sea located in the wider Mediterranean sea (Figure 1).



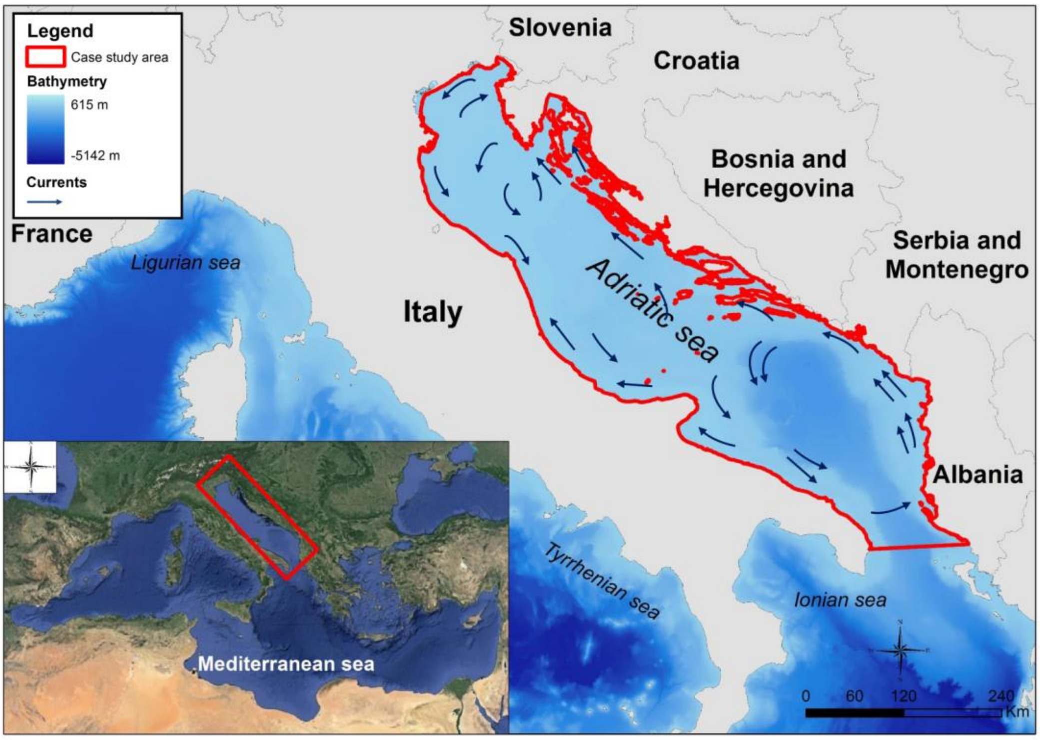


Figure 1 The Adriatic sea case study area (general circulation of the water masses adapted from Millot and Taupier-Letage, 2005)

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The Adriatic Sea is a semi-enclosed basin with a total surface of about 138,600 km2 and a volume of 33,000 km3; Its shape can be approximated to a rectangle extending north-southwest, about 800 km long and 200 km wide (EC, 2011) (Ramieri E., 2014), bounded by the Italian peninsula at west, the Balkan peninsula at east and communicating with the Ionian Sea in the south through the Otranto Strait which is the narrowest part (75 Km wide). It is surrounded by six coastal states: Albania, Bosnia and Herzegovina, Croatia, Italy, Slovenia and Serbia-Montenegro. The basin is divided into three major geographical parts: Northern, Central and Southern, where the coastal areas correspond to three continental shelves. Overall, the Adriatic sea is featured as a shallow enclosed sea area; however, the southern part of the region is far deeper than the northern one in the areas of the Pomo depression (-260 m) and the Pelagosa sill (-170 m) in the middle Adriatic, the wide abyssal depression (-1200 m) and the Otranto sill (-800 m) in the South Adriatic. The northern and northwestern coastlines are featured by shallow waters and sandy beaches whereas the eastern part of the basin is deeper, rocky and comprises many islands and islets. The beauty and the high environmental value of the Adriatic Sea makes this region an attractive place to live and work: each year, more tourists spend holidays in the countries surrounding the Adriatic sea where important tourist destinations are located. However, this massive coastal and marine tourism, as well as multiple economic activities located along the coastline, are leading to increase sea pollution by marine litters, one of the major concern for the global oceans. Indeed, land-based drivers (including land-based activities and coastal tourism), rather than ocean-based ones (e.g. shipping transport), result as the main sources of anthropogenic debris in the Mediterranean Seas (Suaria & Aliani, 2014; Galgani et al., 2013; UNEP, 2009), representing a relevant environmental and economic threat for the biodiversity of marine ecosystems and the goods and services they provide (Sutherland et al., 2011).

As far as the economic side is concerned, the Adriatic sea is also an important maritime transport route, used by tourist and merchant ships in international and national trade, by yachts, fishing vessels and other non-merchant ships. A significant number of important industrial centers are located along the western Adriatic coasts and several mid-European countries highly depend on the Northern Adriatic ports (e.g. the port of Trieste, Venice, Koper and Rijeka) for importing energy. Moreover, apart from being an important maritime transport route, the Adriatic sea basin is among others a productive area for fishing (including aquaculture). Fishing has traditionally been an important sector for most the Adriatic countries and Italy is by far the largest fishing fleet in the Adriatic (EC, 2011). However, the share of the fisheries sector in the national economies is decreasing. Fish stocks have suffered from overfishing and pollution caused by water discharges of industrial activities, agriculture and urbanized areas, especially in the Italian part of the Northern Adriatic Sea.

In this context of multiple human-made pressures a further complication is determined by climate change which poses additional exogenic pressures on this environment through rising sea levels, increased sea temperatures and ocean acidification (IPCC, 2014). Climate change is a prominent issue for the Adriatic sea both considering the vulnerability of important ecosystems such as wetlands and seagrasses, and the concentration of cultural and socio-economic values. The basin is known to have a large spatial and temporal variability (both seasonal and interannual) depending on its driving forcing (atmospheric and land-based). In this setting, is therefore quite important to evaluate, at the regional scale, the localization and extent of changes in the Adriatic sea case study, according to both endogenic and exogenic forcing, also considering potentially affected sensitive targets and their vulnerability to multiple pressures.

Drawing on this, by considering the multiple anthropogenic activities taking place in its marine space (e.g. fisheries and aquacultures, commercial and touristic shipping traffic), the large spatial and temporal variability of temperature (both seasonal and interannual) depending on its driving forcing (atmospheric and land-based) (IPCC, 2014), and its great morphological diversity resulting in a high diversity in terms of productivity and biodiversity, the Adriatic sea represents a relevant case study where analyzing potential risks arising from multiple and overlapping endogenic and exogenic hazards, potentially affecting vulnerable environmental and socio-economic targets. Most of these environmental features and issues can be observed, with site-specific traits and combinations of human-made and natural pressures, in other marine areas worldwide (e.g. Bosphorus strait, Mediterranean and Black sea), thus making the proposed case study a reference area for the implementation of similar risk-based approach in others geographical contexts.

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2.2 Available dataset for the case study area

Acquiring the necessary data to inform risk assessment approaches in marine areas is a difficult task, mainly because detailed data for coastal and marine habitats are far less organized and available than for terrestrial environments (Grech et al., 2011). Accordingly, with the main aim of evaluating the effect of multiple threats on relevant marine habitat in the Adriatic sea case study, an in-depth research and collection of GIS-based dataset was performed, paying specific attention to their spatial resolution and homogeneous coverage for the whole basin. A variety of physical and environmental data, as well as data on main endogenic (i.e. from anthropogenic activities) and exogenic pressures (i.e. related to natural drivers) acting on the Adriatic sea, were retrieved in order to characterise the spatial pattern and distribution of targets (e.g. seagrasses, marine protected areas), as well as to define appropriate indicators for spatially modelling hazards and vulnerabilities in the considered area. The available dataset for the Adriatic sea are summarized in Table 1 highlighting their spatial domain and resolution, data source and update. Most of dataset concerning the spatial distribution of human activities located in the Adriatic sea (i.e. ports, aquaculture facilities, shipping routes, offshore installations) were retrieved by the web data portals of the SHAPE project '*Shaping an Holistic Approach to Protect the Adriatic Environment between coast and sea*' (http://www.shape-ipaproject.eu) and the Adriplan project '*ADRiatic Ionian maritime spatial PLANning'* (http://adriplan.eu). As far as climate-related drivers are concerned (i.e. sea temperature and salinity), data for the reference scenario 2000-2015 were provided by the Euro Mediterranean center on Climate Change (CMCC, www.cmcc.it) within the climate simulation developed in the frame of the PERSEUS project '*Policy-oriented marine Environmental Research in the Southern EUropean Seas*' (http://www.perseus-net.eu) (Lovato et al., 2013; Oddo et al., 2014). More specifically, since the assessment of potential impacts from temperature and salinity change was focused on selected shallow benthic habitats (e.g. seagrasses meadows and coral beds), sea surface temperature and salinity data were used to represent water variations at the top layer of the Adriatic sea (Okey et al., 2015).

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DATASET	SPATIAL DOMAIN AND RESOLUTION	UPDATE DATA	SOURCE
PHYSICAL AND ENVIRONMENTAL DATA			
Adriatic basin boundary	Adriatic sea, 1:50000	2013	http://atlas.shape-ipaproject.eu
Marine administrative zones	Adriatic sea, 1:50000	2013	http://atlas.shape-ipaproject.eu
Marine Protected areas	Global ocean 1: 1.000.000	2014	www.protectedplanet.net
	Adriatic sea, 1:50000	2013	http://atlas.shape-ipaproject.eu
Sites of Community Importance (SCI), Zone of Special Protection (ZSP)	Adriatic sea, 1:50000	2013	http://atlas.shape-ipaproject.eu
Nationally designated areas	Adriatic sea, 1:25000	2013	http://atlas.shape-ipaproject.eu
Biologic protection zones (BPZ)	Adriatic sea, 1:10000	2013	http://atlas.shape-ipaproject.eu
Fishing regulated areas	Adriatic sea, 1:1000000	2013	http://atlas.shape-ipaproject.eu
EUSeaMap -seabed habitat map-	Adriatic sea, 1: 1.000.000	2014	http://www.emodnet.eu/seabed-habitats
Biodiversity Shannon's Index	Global scale, hex grid	2014	http://www.iobis.org/mapper
Seagrass species richness	Global ocean 1: 1.000.000	2003	http://data.unep-wcmc.org
ENDOGENIC AND EXOGENIC DRIVERS			
Ports and harbours	Adriatic sea, 1:50000	2014	http://atlas.shape-ipaproject.eu
Platform and wells for hydrocarbon extraction	Adriatic sea, 1:50000	2014	http://atlas.shape-ipaproject.eu
	European seas, 1:100000		http://www.emodnet.eu/human-activities
Regasification terminals	Adriatic sea, 1:500000	2014	http://atlas.shape-ipaproject.eu
Underwater pipelines and cables	Adriatic sea, 1:50000	2014	http://atlas.shape-ipaproject.eu
Foul areas	Adriatic sea, 1:50000	2014	http://atlas.shape-ipaproject.eu
Wrecks	Adriatic sea, 1:50000	2014	http://atlas.shape-ipaproject.eu
Dumping disposal sites	Adriatic sea, 1:100000	2014	http://atlas.shape-ipaproject.eu
Dumped munitions sites	European seas, 1:100000	2014	http://www.emodnet.eu/human-activities

Dredge spoil dumping	European seas, 1:100000	2015	http://www.emodnet.eu/human-activities
Offshore dredged areas	Adriatic sea, 1:100000	2014	http://atlas.shape-ipaproject.eu
Offshore sand deposits	Adriatic sea, 1:100000	2015	http://adriplan.eu
Map of spatio-temporal distribution of trawling fishing pressure based on Vessel Monitoring System data (2007-2010)	Adriatic sea, 3x3Km grid	2010	http://adriplan.eu
Mineral titles	Adriatic sea, 1:50000	2015	http://adriplan.eu
Shipping traffic	Global ocean 1:1.000.000	2008	https://www.nceas.ucsb.edu/globalmarine
Distributional map of alien species	Mediterranena sea, 10x10Km grid	2015	http://easin.jrc.ec.europa.eu
Ship accidents points - oil spills (1977-2014)	Mediterranena sea, 1:100000	2014	http://accidents.rempec.org
Coastal artificial protection	Adriatic sea, 1:25000	2014	http://atlas.shape-ipaproject.eu
Military practice areas	Adriatic sea, 1:50000	2014	http://atlas.shape-ipaproject.eu
Sea surface temperature (SST)	Mediterranena sea, 1/7 degree	2015	http://www.perseus-net.eu
Sea surface salinity (SSS)	Mediterranena sea, 1/7 degree	2015	http://www.perseus-net.eu
Chlorophyll ‘a’	Mediterranena sea, 1/7 degree	2015	http://adriplan.eu

Table 1 Available dataset for the application of the multi-hazard methodological approach in the Adriatic sea case study area

Finally, also the environmental dataset, supporting the identification of sensitive marine targets and the characterization of their vulnerability to the considered pressures, were mainly acquired by the web data portal of the SHAPE project (e.g. fishing regulated areas, marine protected areas, biological protection zones), with the exception of the seabed habitat map retrieved from the web-GIS of the European Marine Observation and Data Network (http://www.emodnet.eu). Moreover, by means of the Ocean Biogeographic Information System (http://www.iobis.org/), a comprehensive open-access database of marine species datasets from all of the world's oceans, map representing the Shannon Diversity Index for the Adriatic sea, was retrieved with a hexagonal grid resolution (UNESCO, 2015).

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All collected data were pre-processed in order to homogenize data format and their geographical reference system, as well as clip all layers on the Adriatic sea administrative boundaries for removing data outside the investigated area. As already mentioned, the process of data selection was focused on the availability of updated, homogenous and detailed (i.e. with high spatial resolution) data for the whole case study, in order to feature, as much as possible, marine targets and their vulnerability to the considered pressures in the area of concern. As a consequence, the accessible supporting dataset, including data measured (or modelled and validated for what concern the sea surface temperature and salinity) for the whole Adriatic sea, has played an important role in the definition of the multi-hazard methodology, leading to focus the analysis on environmental features and pressures that could be modelled with the available data.

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3. The multi-hazard assessment methodology applied to marine areas

The multi-hazard assessment methodology proposed in this paper aims to evaluate multiple risks posed by natural and anthropogenic threats as well as climate-driven pressures in the Adriatic sea case study. More specifically, according to Landis et al. (2004) the methodology supports the identification and relative ranking of the sources of hazard, habitats and sensitive marine targets potentially exposed and, finally, the environmental impacts in the considered marine region (Hayes & Landis, 2004).

The following sections describe the conceptual framework (section 3.1) and the step-by-step procedure applied in the selected case study, highlighting, for each of them, input parameters and applied mathematical equations for the spatial modelling and data integration (section 3.1.1-3.1.4).

3.1 Methodological framework.

In order to evaluate the environmental impacts produced by human-made pressures in combination with climate-related hazards in marine areas, a risk-based approach was developed and applied in the Adriatic Sea. According to the IPCC (2014) and UNISDR (UN, 2009) conceptual frameworks, risk has been considered as result of the integration between hazard, exposure and vulnerability. As a consequence, the proposed approach is composed of four consecutive steps (highlighted in Figure 2 by different colored boxes) allowing a gradual analysis of all components contributing to risk increasing in a specific area.

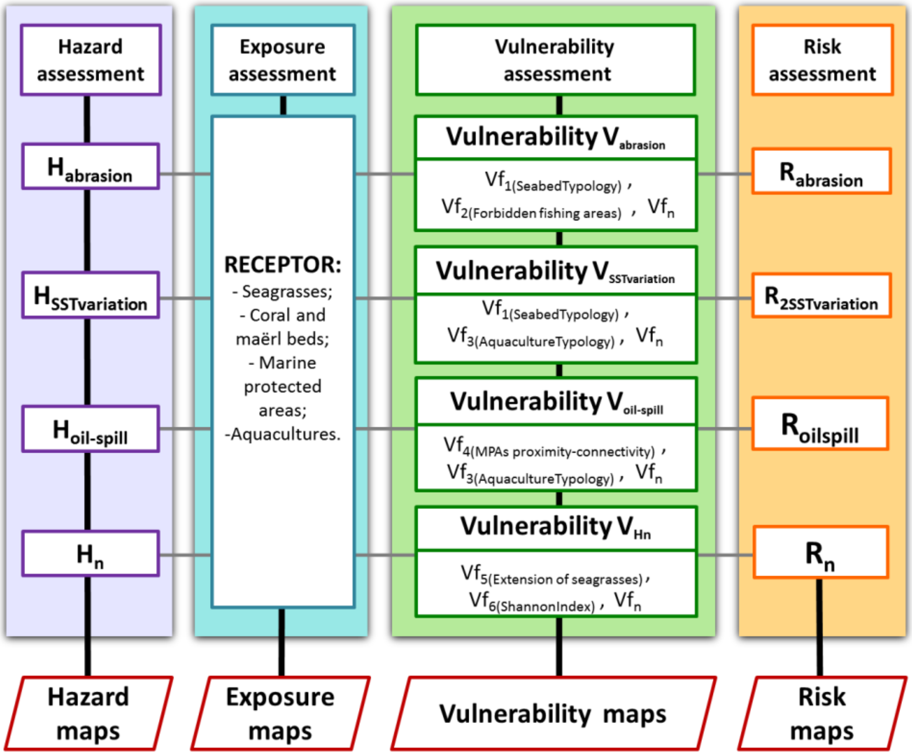

Figure 2 The multi-hazard assessment conceptual framework, where 'H' stands for Hazard; 'Vf' stands for Vulnerability factor; 'R' stands for Risk.

The first phase consists in the hazard assessment which aggregates metrics and scenarios of climate, ocean, bio-geochemical and anthropogenic pressures (e.g. temperature and salinity variation, bottom stress by abrasion and sealing of seabed) for determining potentially affected areas. The exposure assessment identifies and localizes key receptors that could be subject to potential losses in marine areas (e.g. seagrasses and coral and maërl beds). Subsequently, the vulnerability assessment is aimed at evaluating the degree to which receptors could be adversely affected by the considered hazards, based on their specific physical and environmental features (e.g. habitat extent and typology, biodiversity indexes). Finally, the relative risk assessment phase combines all the information about the considered hazards, exposure and vulnerabilities, in order to identify marine areas and targets at higher risk from multiple pressures. The application of each step of this methodology requires the management of a huge amount of heterogeneous input data (Table 1, Section 2.2) that are normalized and aggregated through Multi-Criteria Decision Analysis (MCDA), in order to provide spatial information useful for planners and decision makers involved in management and setting of marine areas (e.g. National Institutes for Environmental Protection and

Research, Civil Protection, Water and port authorities, Regional agencies for the protection of the environment, Municipalities).

Following sections describe step by step the developed methodology explaining main aims, the specific equation applied for data integration and the resulting output, including GIS-based maps and related statistics.

3.1.1 Hazard assessment

The first step of the proposed methodology is the hazard assessment which allows to aggregate scenarios from ocean, climate, biogeochemical models with anthropogenic pressures, in order to identify and prioritize areas that could be affected by multiple and overlapping pressures, according to the considered timeframe scenario (i.e. reference scenario 2000-2015). For this purpose it is firstly required to identify the hazard stressors (e.g. installations for hydrocarbon extraction, maritime traffic, ports and harbours) and metrics (e.g. intensity of maritime traffic, goods and people per ports, sea surface temperature regime variation) for characterizing each pressures considered in the assessment procedure. Indeed, each hazard can be triggered by one or more stressors defined as the cause of environmental hazard impacting large geographic areas (Hunsaker et al., 1990). Accordingly, the hazard assessment is performed through the more specific following steps:

1. Identification of hazards' drivers and related metrics for the considered pressures.
2. Development of an ad-hoc spatial model and related equation for characterizing hazards' spatial distribution in the case study area;
3. Normalization of the hazard scores for all the considered pressures.

For the application of the hazard assessment phase we defined a set of hazards as human-derived stress factor causing either temporary or permanent physical disturbance, loss or damage for one or several components of an ecosystems. They were selected based on emerging methodologies for cumulative impact assessment in marine areas (Halpern et al., 2008; Andersen et al., 2013; Micheli et al., 2013; Kappel et al., 2012; Korpinen et al., 2012; Ban et al., 2010)~~, They were selected according to the Annex 3, Table 2 of the MSFD (e.g. smothering and sealing of seabed, abrasion and extraction of seabed, underwater noise, introduction of non-indigenous species; EC, 2008) whereas their driving forces, and part of the set of indicators and metrics for spatially modelling them, were identified according to the Italian Initial Assessment Reports of the marine environmental state (http://www.strategiamarina.isprambiente.it/consultazioni/consultazione-2012),~~

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Formatted: No underline, Font color: Auto, French (France), Not Highlight pointing out, for almost all the considered ~~pressures~~hazards, their drivers, indicators and metrics for their evaluation in the ~~different Italian marine assessment areas (ISPRA, 2012a and b)~~Adriatic sea. However, has to be underlined that their assessment was performed by using input data measured or modelled for the whole case study.

~~Even though the MSFD doesn't explicitly account for climate pressures, although it was given greater prominence in the proposed Directive (EC, 2005),~~Moreover, we expanded the analysis by including exogenic pressures such as the variation in temperature and salinity regime, in order to analyse how climate drivers can ~~influences or inhibits the MSFD implementation and its repercussions on the ability to meet GES~~threaten the environmental status of the analysed area. Indeed, it is well-known how climate change is triggering and will continue affecting the structure, function and processes of marine ecosystems (EEA, 2015) and, as such, will result in 'shifting baselines' which need to be accommodated in monitoring, and 'unbounded boundaries' (i.e. climate change-induced migrations and dispersal of highly-mobile, nekton and plankton specie) compromising the use of static reference conditions or targets in the evaluation of thee environmental status of marine areas~~GES~~ (Elliott et al., 2015; Patrício et al., 2014).

Hazards' selection was highly conditioned by the availability of homogeneous and high resolution data (Section 2.2) for the whole case study. ~~As a consequence, not all pressures listed in the MSFD (Annex 3, Table 2) (EC, 2008) were included in this study.~~ The results of this process are summarized in Table 2 providing, for each selected hazard, main drivers, hazard metrics and equations applied for hazards' spatial modelling in the Adriatic sea (i.e. Equations 1-8). More specifically, based on literature review (Andersen et al., 2013; Micheli et al., 2013; Kappel et al., 2012; Korpinen et al., 2012; Ban et al., 2010; Halpern et al., 2008) the spatial modelling has followed specific procedures (reported in the Supplementary Material, SM1) aimed at developing credible hazard scenarios. In some cases, the retrieved data were directly used to represent hazards' intensity or their mere presence/absence in the case study area (e.g. artificial benthic infrastructures leading to smothering and sealing of seabed). In other ones, when data on their intensity and propagation were not available, different spatial modelling approaches were used as proxies to derive hazards spatial distribution and intensity (e.g. trawling fishing areas as a proxy for the seabed abrasion). In a nutshell, since there are no direct measurement for some of the considered hazards, they were estimated based of the causative human activities, thus providing a 'proxy spatial modelling' of their distribution in the case study (Andersen et al., 2013). They allow to represent potential circumstances where accidental emissions and pressures to the environment could more likely occur, based on the supporting dataset and at locations where higher potential damage might happen in the considered scenario (i.e. 2000-2015).

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In order to maintain the highest spatial resolution and fit with methods pointed out in the Italian Initial Assessment Reports ~~related to the MSFD~~ (ISPRA, 2012a and b), implementation of the hazard assessment phase was based on a spatial unit (i.e. grid cell) of 100m.

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Hazards	Drivers	Hazard metrics	Equation
Smothering and sealing of seabed	- Platforms and wells for hydrocarbons' extraction. - Regasification terminal. - Coastal artificial protections. - Ports and harbors. - Cables and pipelines. - Areas for unexploded ordinances' sinking. - Area of military practice. - Wrecks.	Presence/absence of benthic anthropogenic infrastructures.	**<u>Equation 1:</u>** $Hs_{smoth} = \begin{cases} 0 & \text{if no benthic structures are present in the investigated cell} \\ 1 & \text{else} \end{cases}$ <u>Where:</u> Hs_{smoth}= hazard score related to the smothering and sealing of the seabed.
Abrasion and extraction of seabed	- Trawling fishing area. - Dredging and extraction areas.	- Trawling fishing efforts expressed in hours of fishing activities. - Intensity of dredging activities expressed in m3 of dredged material.	**<u>Equation 2:</u>** $Hs_{abr} = \frac{(I_{traw}+I_{dredg})_i}{\text{maxItot}}$ <u>Where:</u> Hs_{abr}= abrasion and extraction hazard score. $(I_{traw} + I_{dredg})_i$ = sum of the intensities related to sand dredging and trawling fishing for the cell i, in 2013. max$Itot$ = maximum intensity of sand dredging and trawling fishing in the case study area for 2013.
Underwater noise	- Maritime traffic. - Platforms and wells.	- Intensity of maritime traffic. - Presence/absence of platforms and wells.	**<u>Equation 3:</u>** $Hs_{noise} = \frac{(I_{traff}+I_{hyd})_i}{\text{maxItot}}$ <u>Where:</u> Hs_{noise}= underwater noise hazard score; $(I_{traff} + I_{hyd})_i$ = sum of the intensities linked with the maritime traffic and platform for hydrocarbon extraction for the cell i. max$Itot$ = maximum intensity linked with the maritime traffic and platform for hydrocarbon extraction in the case study area.
Introduction of non-indigenous species	- Maritime traffic. - Ports and harbors. - Aquacultures.	Number of detected non-indigenous species.	**<u>Equation 4:</u>** $Hs_{NIS} = \frac{\text{TotNIS}_i}{\text{maxTotNIS}}$ <u>Where:</u> Hs_{NIS}= introduction of non-indigenous species hazard score. TotNIS_i = total number of indigenous species detected in the cell i until 2015. maxTotNIS = maximum number of potential ordinary emergencies in the case study area until 2015.
Inputs of organic matter	- Rivers discharge; - Urban waste water.	Chlorophyll concentration (Chl 'a').	**<u>Equation 5:</u>** $Hs_{OrgMat} = \frac{[Chl\ 'a']_i}{\max\,[Chl\ 'a']}$ <u>Where:</u> Hs_{OrgMat}= organic matter input hazard score; $[Chl\ 'a']_i$ = sea surface chlorophyll 'a' mean concentration in the cell i for the timeframe window 2006-2012; max $[Chl\ 'a']$ = maximum sea surface chlorophyll 'a' mean concentration in the case study area for the timeframe 2006-2012.
Introduction of hazardous substances by oil-spills	- Maritime accidents.	Occurrence of shipping accidents resulting in oil spills between 1977- 2014.	**<u>Equation 6:</u>** $Hs_{oilspill} = \frac{\sum_{p \in P} \max\left(0,1-\frac{d(p)}{k}\right)}{\text{maxOilSpill}}$ <u>Where:</u> $Hs_{oilspill}$= introduction of hazardous substances hazard score.

			P = overall of oil-spill points detected in the Adriatic sea. k = constant spatial threshold defined for the case study of 25 km (Micheli et al., 2013). $d(p)$= distance function that returns the points' distance p from th cell (pixel) of concern. maxOilSpill= maximum density of shipping accidents resulting in oil-spills within 25km radius from an accident source, calculated in the case study between 1977-2014.
Sea surface temperature regime variation	- Climate drivers.	Sea surface temperature anomalies in the reference scenario 2000-2015.	**<u>Equation 7:</u>** $Hs_{SST} = \frac{\text{TotSSTanom}_c}{\text{maxSSTanom}}$ <u>Where:</u> Hs_{SST}= sea surface temperature variation hazard score; TotSSTanom_c= total number of sea surface temperature positive anomalies calculated in the cell i for the case study area and considered timeframe scenario 2000-2015; maxSSTanom = maximum number of Sea Surface Temperature positive anomalies calculated in the case study area and considered timeframe scenario 2000-2015.
Sea surface salinity regime variation	- Climate drivers.	Sea surface salinity anomalies in the reference scenario 2000-2015.	**<u>Equation 8:</u>** $Hs_{SSS} = \frac{\text{TotSSSanom}_c}{\text{maxSSSanom}}$ <u>Where:</u> Hs_{SSS}= sea surface salinity variation hazard score; TotSSSanom_c= total number of sea surface salinity anomalies calculated in the cell i for the case study area and considered timeframe scenario 2000-2015; maxSSSanom = maximum number of Sea Surface Salinity anomalies calculated in the case study area and considered timeframe scenario 2000-2015.

🟩 Biological impacts 🟥 Physical impacts 🟦 Chemical impacts 🟨 Climatic impacts

Table 2 Selected hazards for the case study area with related driving forces, metrics and applied hazard equations for spatial modelling. Procedures applied for the spatial modelling are reported in the Supplementary Material, SM1

3.1.2 Exposure assessment

The exposure assessment phase aims to identify, select and localize key receptors (i.e. elements potentially at risk) and hot-spot areas characterized by high environmental and socio-economic value that could potentially be in contact with the considered hazard and, therefore, exposed to losses in affected marine areas. More specifically, this step allows the identification of all the receptors (i.e. r1, r2, r3,…, rn) to be considered in the geographic marine sub-region and for the selected timeframe; they can be chosen according to the objectives of the study, the spatial scale of the analysis and the available dataset. In this study, receptors were selected according to the availability of homogeneous GIS-based dataset for the area of concern ~~as well as to the requirements of the MSFD thus focusing on relevant~~and their~~-~~ environmental and socio-economic ~~targets~~ relevance ~~for the evaluation of the marine environmental state (i.e. environmental state's indicators) (EC, 2008; EC, 2010)~~ for the selected case study. As a consequence the assessment was focused on valuable habitats such as seagrasses meadows and coral and maërl beds, both playing an important role as nursery areas for several species as well as for carbon regulation and fisheries (Salomidi et al., 2012; Savini et al., 2012). Moreover, according to their relevance in maintaining biodiversity in marine regions and support, in a well-connected network of multiple sites, functional ecological linkages such as larval and/or species exchanges (Gabrié C. et al., 2012; Agardy, 1994), protected areas located in the case study area, including marine protected areas, Site of Community Importance (CEC, 1992), zone of biological protection and nursery habitat, were included in the analysis. Finally, even though they represent a driver of pressure in marine areas, we also considered as target of the analysis the aquacultures (i.e. including mussel and fish farms), due to their high economic relevance in the Adriatic sea as a significant sources of income (Allison et al., 2009). However other relevant receptors could be considered in the assessment process (e.g. marine relevant mammals and fish species), but homogenous dataset were not available for the case study. Table reported in the Supplementary Material SM2 summarizes receptors considered in the analysis, also providing a brief description of their main environmental features and value in the area of concern.

In order to keep the highest feasible detail, according to the available dataset (Section 2.2), the exposure assessment was based on a spatial unit (i.e. grid cells) of 100m as applied in the hazard assessment phase (Section 3.1.1). An exposure score equal to 1 was assigned to cells where the receptor is located and equal to 0 in case of absence.

The exposure score is, therefore, evaluated as follows:

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$$E = \begin{cases} 0 & \text{if no receptor is present in the investigated cell} \\ 1 & \text{else} \end{cases} \qquad \text{Equation 9}$$

Where:

E = represents the exposure score related to the geographical area covered by the investigated marine receptors.

Equation 9 returns a value of 0 in the cell where no receptors are located whereas 1 where there is the presence of one or more overlapping receptors. The main output of this step is the exposure map showing the localization and geographic extent of all the investigated elements potentially at risk from multiple endogenic and exogenic pressures in the case study.

3.1.3 Vulnerability assessment

The third phase of the developed methodology is the vulnerability assessment aimed at evaluating the degree to which receptors could be adversely affected by the considered hazards, based on site-specific physical and environmental information (e.g. seabed typology, species diversity index, habitat extension, protection level, habitat connectivity). The choice of relevant vulnerability factors was performed based on scientific literature applying similar methodological approaches (Halpern et al., 2008; Rizzi et al., 2015~~)~~; ~~(~~Micheli et al., 2013), also taking into account ~~some of the environmental state indicators pointed out by the MSFD (EC, 2008; EC, 2010) and the~~ data constraints posed by the available dataset for the Adriatic sea case study (Section 2.2). For each considered hazard a set of vulnerability factors was selected in order to characterize environmental vulnerability of the area of concern to the analyzed pressures (Table 3).

	VULNERABILITY FACTORS							
HAZARDS	Seabed typology	Marine Protected Areas proximity-connectivity	Extension of coral and maërl beds	Extension of seagrasses	Seagrasses species richness	Shannon index	Aquaculture typology	Forbidden fishing areas
Smothering and sealing		▨	▨	▨				
Abrasion and extraction	▨	▨	▨	▨	▨			▨
Underwater noise		▨				▨		▨
SST variation	▨	▨	▨	▨		▨	▨	
SSS variation	▨	▨	▨	▨		▨	▨	
Input of organic matter	▨	▨	▨	▨	▨	▨		
Introduction of hazardous substances	▨	▨	▨	▨	▨	▨	▨	
Introduction of NIS	▨	▨	▨	▨	▨	▨	▨	

Table 3 Vulnerability factors VS hazards matrix
(SST: Sea Surface Temperature; SSS: Sea Surface Salinity; NIS: Non-indigenous species)

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For instance, by considering the physical hazards (i.e. anthropogenic smothering and sealing and extractive technological hazards), vulnerability factors more related to the seabed features (where these kind of hazards mainly threaten) were selected (e.g. seabed typology extension of coral and maërl beds, extension of seagrasses). On the other side, vulnerability factors such as the ‘forbidding fishing areas’ were associated to the physical hazards induced by underwater noise and extractive activities (including trawling fishing), since the presence or absence of specific regulations, can limit or not the shipping traffic (one of the main source of noise in marine areas) and extraction of resources on a marine areas.

Once vulnerability factors were selected for each hazard, they were then classified and scored, in a 0 to 1 range, following the qualitative linguistic evaluations reported in the Supplementary Material SM3. Scores were assigned at the case study level, according to expert judgement and literature review (Micheli et al., 2013; Salomidi et al., 2012; Astles et al., 2009; Halpern et al., 2008), in order to allow the process of integration of vulnerability scores, by the application of MCDA functions, in the relative risk estimate and provide a ranking of more vulnerable areas. However, they are flexible to be applied to other case studies characterized by similar physical and environmental features.

The results of this process are summarized in Table 4 reporting, for each selected factors, classes and scores considered during the application of the methodology in the Adriatic sea.

VULNERABILITY FACTORS	CLASS	SCORE	DESCRIPTION
Marine Protected Areas proximity-connectivity (km)	0 - 25.63	0,2	Spatial proximity was used as a proxy representing the connectivity within the Marine Protected Areas’ network, which allows for linkages whereby protected sites benefit from larval and/or species exchanges, and functional linkages from other network sites. In a connected network individual sites benefit for one another (Gabrié C. et al., 2012).
	25.64 - 48.33	0,4	
	48.34 - 70.58	0,6	
	70.59 - 95.54	0,8	
	95.55 - 137.55	1	
Extension of seagrasses (Km²)	0.02 - 6.01	1	Small seagrasses were considered to have higher vulnerability as they could be more vulnerable to natural and anthropogenic pressures than wider ones. Habitats have to be sufficiently large lo maintain their population, taking into account any threats of deterioration or loss of such habitats (Rizzi et al., 2015; EC 2008).
	6.02 - 27.37	0,6	
	27.38 - 103.75	0,2	
Shannon Index	1.39 - 2.62	1	Ecosystems with high Shannon index (high number of species) were considered to have lower vulnerability since they are characterized by a greater variety of interactions between species and, as a consequence, they are able to better maintain or restore its own balance (Gabrié C. et al., 2012).
	2.63 - 3.65	0,8	
	3.66 - 4.34	0,6	
	4.35 - 4.80	0,4	
	4.81 - 5.55	0,2	
Extension of coral and maërl beds habitats (Km²)	0.07 - 17.79	1	As applied for seagrasses meadows, to smaller coral and maërl beds higher vulnerability score was assigned since habitats have to be sufficiently large lo maintain their population, taking into
	17.80 - 53.45	0,6	
	53.46 - 2014.49	0,2	

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			account any threats of deterioration or loss of such habitats. (EC, 2008).
Aquaculture typology	Fish farms	0,6	Mussels were considered to be more vulnerable to changes in water biogeochemical and physical parameters as they act as filter feeders both on the water column and water sediments and, therefore, they are more vulnerable compared with fish (Rizzi et al., 2015).
	Mussel farms	1	
Forbidden fishing areas	Forbidden areas	0,2	Areas closed to fishing were considered with a moderate vulnerability since they result 'protected' by the presence of specific fishing regulation limiting, in some cases, the shipping traffic linked with this kind of activity as well as the resulting hazards (e.g. underwater noise, seabed abrasion).
	Not forbidden areas	0,5	
Seagrasses Species Richness	Very low richness (n° 1 of species)	1	Different seagrasses species vary in their tolerance and resilience to the changing of environmental conditions caused by both natural and anthropogenic pressures. As a consequence, to areas with higher seagrasses species richness a lower vulnerability score was associated due to the greater probability of finding an appropriate number of species able to withstand to adverse environmental conditions (Gabrié et al., 2012; Waycott et al., 2007).
	Low richness (n° 2 of species)	0,8	
	Medium richness (n° 3 of species)	0,6	
	High richness (n° 4 of species)	0,4	
	Very high richness (n° 5 of species)	0,2	

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Table 4 Classes and scores associated to the vulnerability factors identified for the considered hazards in the Adriatic sea case study

Almost all the selected vulnerability factors were evaluated as hazard-independent (e.g. extension of seagrasses, Shannon Index) and, as a consequence, score associates to each class doesn't change depending on the considered hazard. Differently, concerning the factor related to the 'seabed typology' a specific vulnerability score was assigned to each typology according to the different hazards, as reported and explained in the Supplementary Material SM4 (Halpern et al., 2008; Micheli et al., 2013). After the normalization, vulnerability factors were then aggregated by applying the "probabilistic or" function (Kalbfleisch J. G, 1985), aimed at providing a single normalized score of physical and environmental vulnerability for each cell (i.e. pixel of raster map) and considered hazard in the area of concern, following the Equation 10:

$$V_h = \otimes_i^n [vf_i] \qquad \text{Equation 10}$$

Where:

V_h= physical and environmental vulnerability score, representing the predisposition of the marine environment to be affected by the considered hazard h;

$\otimes$= "probabilistic or" function (see Supplementary Material SM5);

vf_i = i^{th} physical and environmental vulnerability factor.

Resulting score ranges from 0 (i.e. no vulnerability) to 1 (i.e. higher vulnerability in the case study area) and is calculated cell by cell aggregating information from overlaid vulnerability factors for each selected hazard.

3.1.4 Relative risk assessment

The final step of the developed methodological approach is the relative risk assessment which allows to integrate information about the hazard with the receptors' exposure and vulnerability, in order to identify and prioritize areas and targets (i.e. key marine targets and hotspots) that could be at higher risk ~~of not attaining GES~~ in the investigated area and timeframe (EC, 2008). According to the IPCC (2014), the aggregation of hazard, exposure and vulnerability scores supports the assessment of risk in the case study, by applying the following general function (Equation 11):

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$$R_h = f(H, E_j, V_h) \qquad \text{Equation 11}$$

Where:

R_h = risk score related to the hazard of concern *h*;

H = hazard score according to Equations 1-8 (Section 3.1.1);

E_j = exposure score related to the presence/absence of the receptor *j*, according to Equation 9 (Section 3.1.2);

V_h = physical and environmental vulnerability score of the investigated cell and related to the hazard of concern *h*, according to Equation 10 (Section 3.1.3).

The result of this step is a set of relative risk maps for the whole case study highlighting areas and targets more affected by multiple endogenic and exogenic risks, considering different hazards stressing the marine region of concern and related vulnerability. As for the other assessment phases, resulting risk score ranges from 0 to 1, in which 0 represent cells with risk null (i.e. there is no hazard or no physical and environmental vulnerability) whereas 1 the higher risk in the investigated area.

4. Results and discussion

The application of the aforementioned operative steps allowed to produce a wide array of GIS-based hazard, exposure, vulnerability and risk maps, as well as key risk indicators calculated for the whole case study and selected marine targets (e.g. extent of relevant habitat potentially affected by human activities, alterations of physical and chemical parameters). Hazard, vulnerability and risk scores, ranging in a continuous scale from 0 to 1, were classified by applying the Equal Interval classification method, allowing the division of scores into 5 equal sized classes (i.e. very low, low, medium, high and very high) (Zald et al., 2006), thus simplifying maps understanding and ensure comparability among resulting maps.

The following sections describe, for each step of the proposed procedure, the output obtained for the Adriatic sea case study (Section 4.1-4.4), underlining their utility against a ~~in a~~ planning and management perspective of marine areas~~, as well as for the MSFD implementation~~ and related natural resources.

4.1 Hazard maps

The implementation of the hazard assessment in the Adriatic sea case study (Section 3.1.1) has led to the development of eight GIS-based hazard maps (see all hazard maps in SM6), one for each considered hazard, representing potentially significant hazard scenarios, against which the marine environments and habitats need to adapt in order to maintain their ecological functions. Figure 3A represents the hazard maps related to the sea surface temperature (SST) variation, showing quite homogenous very high hazard scores (i.e. ranging from 0.8 to 1) for the whole case study area due to the high occurrence of unusually warm temperatures calculated in the selected reference scenario 2000-2015 (see procedure in SM1). It is well known that global warming is transforming the Mediterranean sea into a much different sea than it was only 20 years ago (CIESM, 2008; http://www.ciesm.org/online/monographs/Helgoland08_ExecSum.pdf) and the resulting hazard map for the SST variation highlights this increasing warm up of the considered area. However, has to be underlined that the resulting hazard score is strictly connected with the methodological approach selected for the normalization of the final hazard indicator linked with the SST variation, which envisages to normalize the total number of positive anomalies calculated for each cell of the case study area (and considered time window) for the maximum number of positive anomalies detected in the case study (Supplementary Material 'SM1'). Others normalization methodologies could lead to different resulting output and related hazard scores. However, this methodological choice was performed in order to align this normalization approach to the other ones applied to the others hazards considered in this study, as reported in the SM1 (e.g. input of organic matter, introduction of Non-Indigenous Species).

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Finally, ~~S~~since the methodology applied for the evaluation of changes in sea surface temperature (SST) is based on the approach developed by Halpern et al. (2008), the resulting hazard map for the Adriatic sea assumes a similar pattern compared with the ‘sea temperature changes (SST)’ map realized at the global scale (Halpern et al., 2008), with very high hazard values mainly focused along the Italian shelf.

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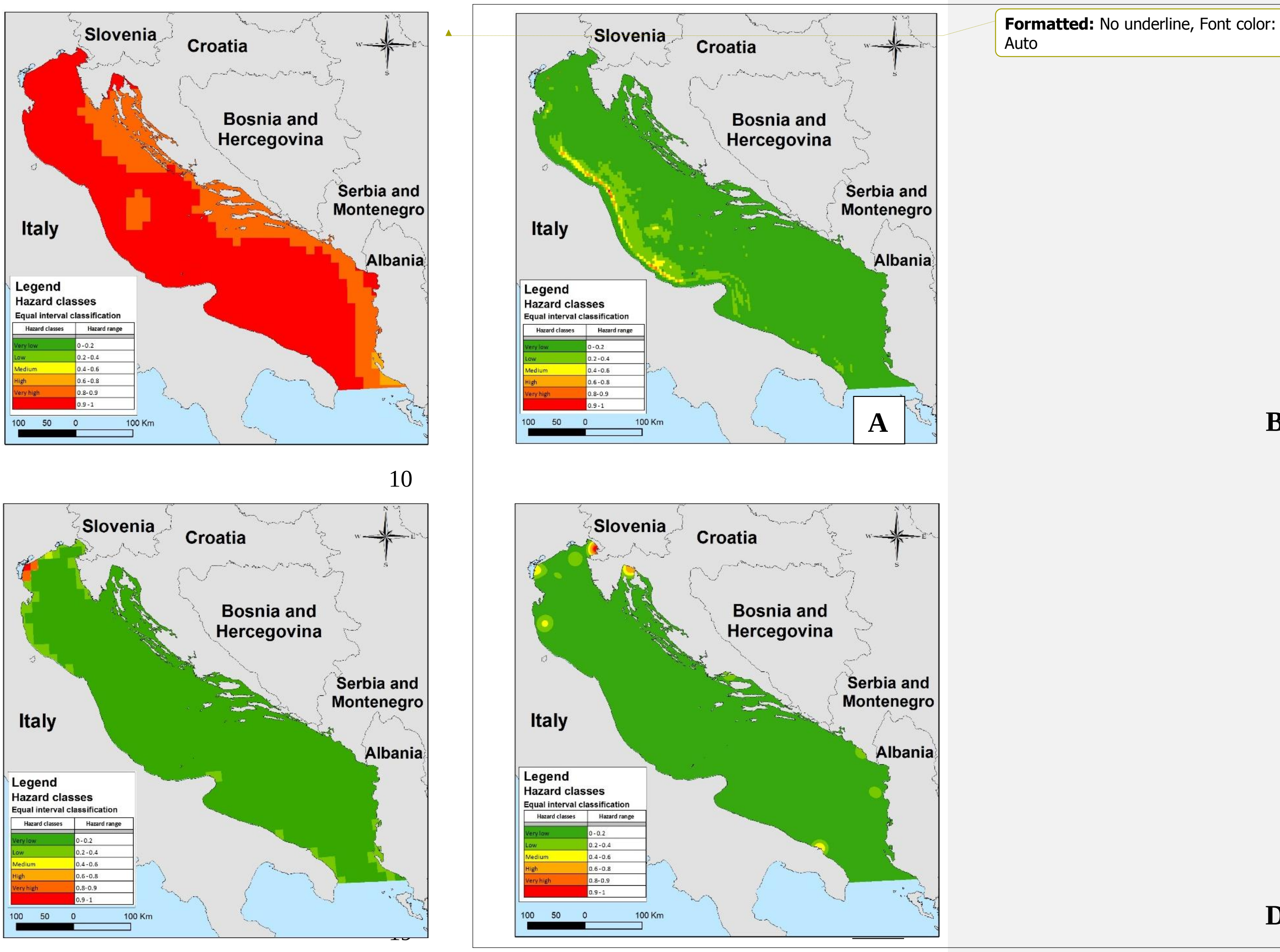

Figure 3 Example of hazard maps produced for the Adriatic sea case study representing: hazard of SST variation (A), abrasion of seabed (B), biological disturbance by the introduction of non-indigenous species (C), chemical hazard by oil-spills (D).

As far as the physical hazard induced by the abrasion and extraction of resources from the seabed is concerned, figure 3B shows higher scores (i.e. ranging from 0.6 to 1) limited in the western-central part of the Adriatic Sea caused by the high exploitation of the area for trawling fishing, unlike the North Adriatic sea where severe restrictions limit this activity in the area.

Analysing figure 3C, representing the biohazard related to the introduction of non-indigenous species, very high hazard scores (i.e. ranging from 0.8 to 1) can be observed in the North Adriatic sea mainly due to the massive maritime traffic around the port of Venice and the numerous aquaculture activities, recognized as the main forcing of this pressure (ISPRA, 2012b). Even though the supporting dataset and the implemented methodology diverges from those applied by Halpern et al. (2008) at the global scale and Micheli et al. (2013) within the Mediterranean sea, the same hot-spot with higher hazard scores can be detected in the north Adriatic sea as well as in the marine area close to the Apulia region (i.e. southern part of the Adriatic sea).

Finally, by considering the anthropogenic acute chemical hazard by oil-spills during shipping accidents (see procedure in SM1) (figure 3D), higher hazard scores (i.e. ranging from 0.4 to 1) are located in the North Adriatic sea, close to the port of Trieste, where numerous shipping accidents have been occurred in the 1977-2014 timeframe (IMO/UNEP, 2011; http://accidents.rempec.org/). Also in this case, the resulting hazard map presents the same spatial distribution compared with that developed by Micheli et al. (2013) for the Mediterranean sea (i.e. higher score corresponding to areas linked with the higher number of oil-releasing accidents within the considered time-window), due to the applied simplified plume modelling technique (see procedure in SM1) to distribute the quantities of released oil into the surrounding ocean waters (Micheli et al., 2013).

In order to support the cross comparison of results of this phase, based on the developed hazard maps a bar chart comparing the percentage of surface of the case study included in each hazard class (Figure 4) was produced.

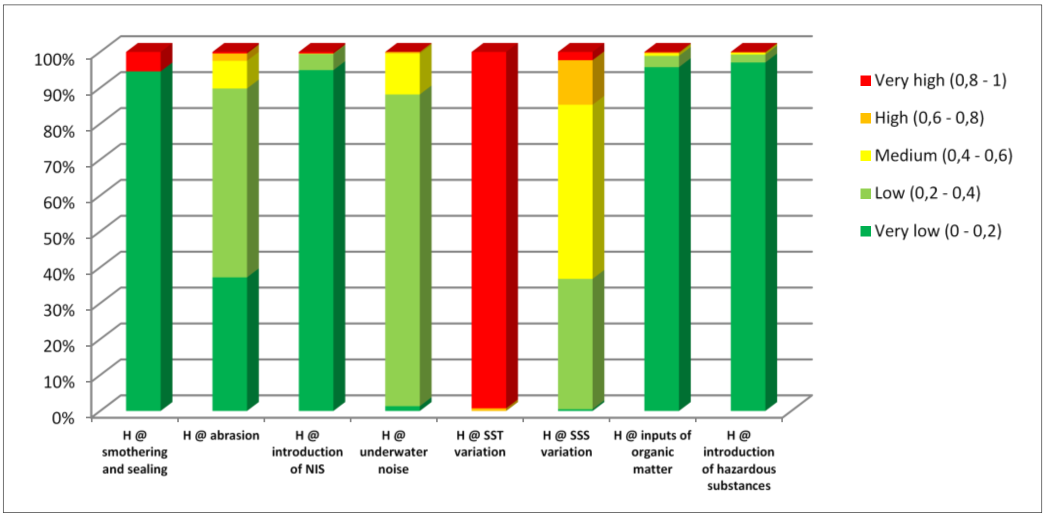

Figure 4 Bar chart representing the percentage of surface of the Adriatic sea case study included in each hazard class for all the considered pressures

The graph shows that the main hazard for the Adriatic sea is represented by the SST variation, with almost all the surface of the case study included in the very high hazard class (i.e. ranging from 0.8 to 1). High scores can be observed also for the other considered exogenic pressure related to the salinity regime variation (SSS) where more than 40% of the considered marine area is included in the higher hazard classes (i.e. ranging from 0.6 to 1). Finally, lower percentage of surface of the case study included in the higher hazard classes (i.e. ranging from 0.6-1) were detected for the endogenic pressures (e.g. abrasion, smothering and sealing of the seabed, introduction of hazardous substances) which severely affect more delimited areas in the Adriatic sea case study.

Hazard maps may facilitate the communication to potential end-users (e.g. policy makers, planners) about the most significant sources of hazard in the region and their spatial pattern, thus increasing knowledge and awareness on main environmental issues which need to be faced in the area of concern. Drawing on this, they represent a valuable support for addressing management decisions towards more sustainable alternative solutions, able to reduce potential hazards in areas already affected by the presence of multiple and overlapping pressures. Finally, hazard maps can be used by public authorities implementing ~~the MSFD~~EU's and International directives' requirements ~~(EC, 2008),~~ by supporting the assessment of different indicators of pressures (e.g. alterations of physical and chemical parameters, bottom stress) (EC, 2010), as well evaluating progress toward the improvement ~~as the evaluation~~ of the environmental quality ~~evaluating progress toward achieving GES in theof~~in the Adriatic sea.

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4.2 Exposure map

The exposure map produced by implementing the aforementioned procedure in Section 3.1.2 allowed the identification and spatial localization of receptors (i.e. elements at risk) that can be subject to potential losses and damages due to the considered hazards. Figure 5 shows the exposure map for the Adriatic sea case study considering as main elements at risk the marine environment of the Adriatic sea as a whole (blue boundary) and as hotspots targets: the seagrasses meadows (filled green pattern), coral and maërl beds (filled red pattern), protected areas (filled pattern with oblique pink lines) and aquacultures (filled yellow pattern).

Seagrasses and coral and maërl beds are mainly located close to the Italian coast (i.e. Veneto and Friuli Venezia region in the Northern part and the Apulia region and the southern one) and represent about the 2% of the case study, whereas aquacultures are mostly focused in the Northern Adriatic sea (i.e. Italy, Slovenia and Croatia). As showed in zoom in Figure 5A and 5B, most of the seagrasses and coral and maërl beds overlap with the marine protected areas established in the Adriatic sea, respectively the 30% and 99% of the related surface, underling complex and fragile ecosystems requiring specific protection status for their conservation.

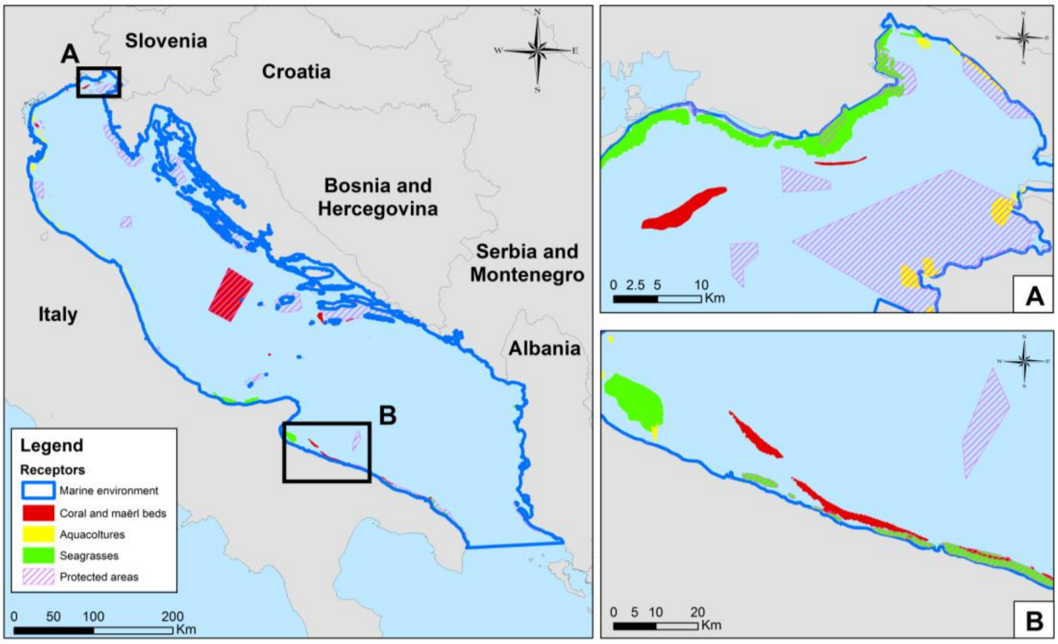

Figure 5 Exposure map identifying receptors for the Adriatic sea case study area

4.3 Vulnerability maps

The final output of the vulnerability assessment is represented by the vulnerability maps (SM7), evaluating the degree to which receptors could be adversely affected by the investigated hazards based on site-specific bio-physical and environmental features. As for the hazard maps, vulnerability maps were classified using the Equal Interval classification method setting the entire vulnerability values' range (i.e. from 0 to 1) in five categories equal in size (Zald et al., 2006). As can be observed in Figure 6, representing the vulnerability to SST variation (Figure 6A), abrasion of seabed (Figure 6B), biological disturbance by the introduction of non-indigenous species (Figure 6C) and to the underwater noise (Figure 6D), vulnerability scores assume homogenous relatively very high values in the whole case study depending on the considered factors and scores assigned to related classes. Results of the vulnerability assessment are summarized by the bar chart in Figure 7 representing the percentage of surface of the case study included in each vulnerability classes for the eight considered pressures. Almost all the developed maps show very high vulnerability values varying between 0.8 to 1. More specifically, the analysed marine environment presents higher vulnerability to climate-related hazards (e.g. sea surface temperature variation) as well as chemical ones (e.g. introduction of hazardous substances and input of organic matter) with more than 95% of the considered area included in higher vulnerability classes. Lower and more heterogeneous values can be observed for the vulnerability to the smothering and sealing of seabed with about the 40% of the case study area included in the high and very high classes (i.e. 0.8 to 1) and the remaining 60% in classes with lower vulnerability.

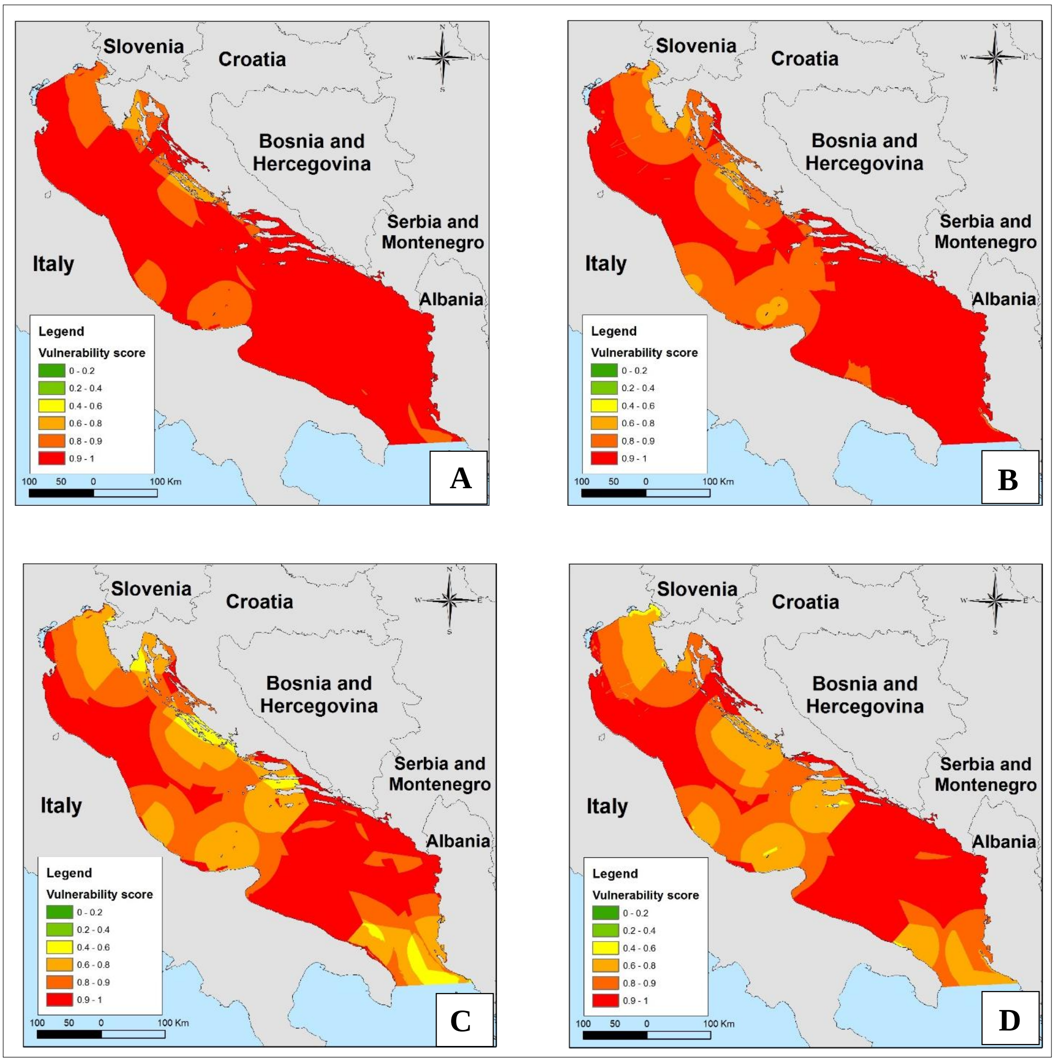

Figure 6 Example of vulnerability maps produced for the Adriatic sea case study representing: vulnerability to SST variation (A), abrasion of seabed (B), biological disturbance by the introduction of non-indigenous species (C), underwater noise (D).

Vulnerability maps and related statistics provide an overall picture of the vulnerability of the analysed marine ecosystem and related receptors to the multiple considered hazards. ~~Being~~Vulnerability maps (including the related vulnerability factors maps) are GIS-based and, as a consequence, they are all georeferenced with the same geographic coordinate system, thus allowing to perform specific 'overlap analysis' aimed at identifying ~~, they can be used for identifying~~ which factors have the most influence to increase the vulnerability of an area, thus providing valuable information for a more robust science-based decision making. More specifically, these kind of maps can support marine planner and managers designing and implementing management tools and nature-based solutions aimed at increasing the resilience of vulnerable targets to the considered impacts.

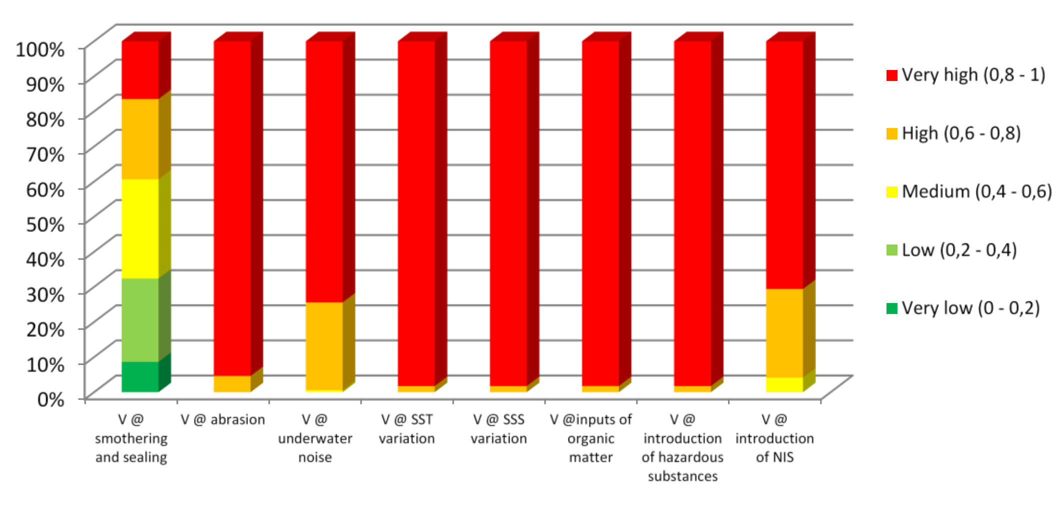

Figure 7 Bar chart representing the percentage of surface of the Adriatic sea case study included in each vulnerability classes for the considered hazards

These actions can include, for instance, the establishment of new Marine Protected Areas providing a focal area for protecting relevant ecosystems such as salt marshes and seagrass beds, as well as for monitoring environmental conditions and trends, acting in this was as ‘sentinel sites’ of changes. When appropriately placed and managed, Marine Protected Areas can contribute on conserving biological diversity, restoring fish populations and protecting relevant spawning areas and nursery habitats (Halpern, 2010; Selig & Bruno, 2010). A well-planned and functionally connected Marine Protected Areas network can provide benefits that go beyond those of a single area, acting as a corridor for shifting species and habitats, thus maximizing ecological connectivity between single Marine Protected Areas and serving to increase protection for marine resources (NOAA, 2013; IUCN-WCPA, 2008). Other solutions for increasing resilience of marine habitat can also include the widespread transplantations of submerged seagrasses representing an important carbon sink, helping to mitigate climate-related impacts. Seagrasses meadows contribute to improve water transparency and quality through trapping and storing solids particles and dissolved nutrients (Short aet al., 2007) and they can attenuate physical impacts influencing the hydrodynamic environment through reducing current velocity, dissipating wave energy and stabilizing the sediment (Ondiviela et al., 2014).

4.4 Relative risk maps

The implemented risk assessment phase has led to the development of eight relative risk maps (SM8) classified using the Equal Interval method of classification (i.e. very low, low, medium, high, very high) (Zald et al., 2006), as applied in the other assessment phases.

According to the Equation 11 (Section 3.1.4) risk maps show significant spatial variations in the case study area, mainly due to the spatial localization and intensity of human activities in the Adriatic sea, since vulnerability assumes quite homogeneous maximum value equal to 1 for almost all the considered pressures. These results are further proved by the bar chart in Figure 8A representing the percentage of surface of the Adriatic sea case study included in each risk classes for all the considered pressures. Can be observed that risk generally assumes lower values than the hazard ones represented in the bar chart in Figure 4, as they are multiplied by vulnerability (i.e. scores ranging in 0-1), however the same trend of hazard is visible. Accordingly, risk related to SST variation represents the major risk for the whole case study, with nearly the 90% of surface included in the higher risk class (i.e. 0.8-1), followed by the risk to SSS variation with a little less than the 40% of surface within the moderate and very high classes (i.e. 0.4-1). Lower values can be observed for the other endogenic pressures (e.g. abrasion, smothering and sealing of the seabed, introduction of hazardous substances), which severely affect (i.e. risk classes ranging from 0.6-1) more limited areas in the Adriatic sea case study (i.e. always less than the 4% of surface).

As a consequence, focusing the analysis on the selected targets (i.e. seagrasses, coral and maërl beds, aquacultures and protected areas) (Figure 8B), the risk assessment indicates that they could be all severely affected by the SST variation, especially as baseline will move due to climate change leading to more numerous and intense unusually warm condition. Higher values are assumed also by the receptor ‘aquacultures’ to risk concerning the input of organic matter and the introduction of non-indigenous species (NIS), mainly due to the straight link of this economic activity with the two considered risk, as main driver of related pressures.

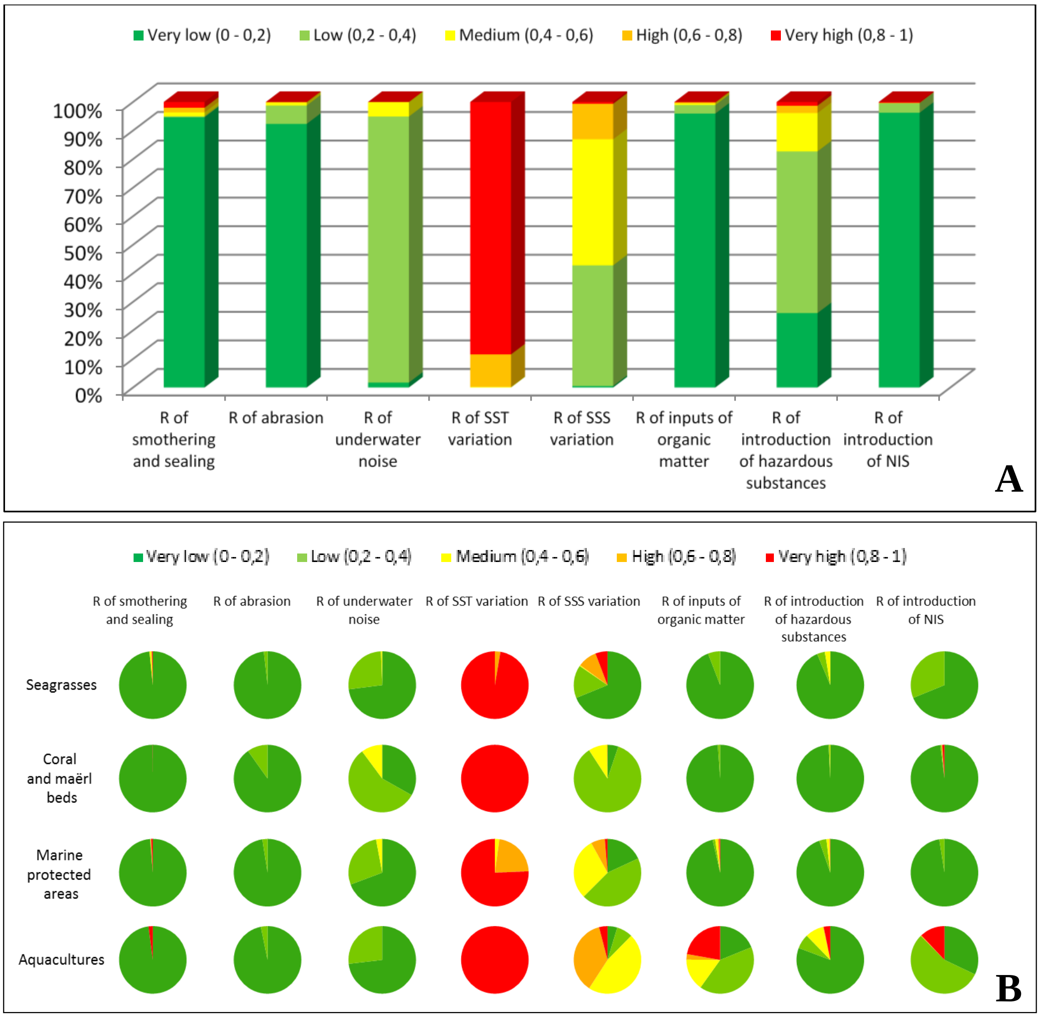

Figure 8 A) Bar chart representing the percentage of surface of the Adriatic sea case study included in each risk classes for the considered hazards; B) Pie chart representing the percentage of surface of receptors (i.e. seagrasses, coral and maërl beds, marine protected areas, aquacultures) included in each risk classes for the considered hazards

By integrating hazard with exposure and susceptibility, relative risk maps allow a quick screening of areas and receptors at greatest risk from multiple human-made and natural stressors~~, where the achievement of GES, as required by the MSFD (EC, 2008), can be compromised~~. They can be effectively used by planners and policy makers for the design of science-based policies and management measures of marine areas, that consider spatially relevant issues and are consistent with the objectives of a more sustainable use and organization of marine spaces and related natural resources ~~of the MSFD (EC, 2008)~~. By ranking more potentially affected targets, risk maps can support local public authorities to set priorities in maritime spatial planning and management, focusing economic efforts on more urgent actions. More specifically, they can back the development and implementation of integrated policies and plans aimed on one side at managing the conflicting uses of the sea thus reducing endogenic pressures (e.g. limit the shipping traffic on specific areas featured by vulnerable marine organisms), on the other side accommodating changes produced by exogenic unmanaged pressures (i.e. climate change) acting at the effective management scale on causes (need to be addressed locally) and consequences (require global action with mitigation strategies) (Patrício et al., 2014). Finally, by analysing risks induced by land-based drivers, which inevitably affect the sea (i.e. rivers discharge of nutrients and eutrophication-inducing substances), risk maps can be also used for addressing territorial planning and the development of new infrastructures (e.g. build of wastewater treatment plants), in order to reduce pressures on the sea and improve a land-sea interface planning and management.

5. Conclusion

Integrating climate pattern with socio-economic and environmental information of the considered marine area, the proposed multi-hazard methodology allows to develop a set of environmental relative risk scenarios, thus supporting a semi-quantitative evaluation and relative ranking of areas and targets potentially affected by multiple risks in the considered marine basin.

The approach is suitable and flexible to be applied in different marine regions even if featured by diverging combinations and levels of intensity of endogenic and exogenic pressures, as well as ~~morphological,~~ environmental and socio-economic conditions (e.g. Bosphorus strait, Mediterranean and Black sea).

~~and for m~~Multiple timeframe scenarios can be explored by applying the same methodological risk-based framework, supporting to evaluate ~~both the progress toward the achievement of GES and~~ the potential effects of medium and long-term climate change projections for multiple ~~s~~parameters affecting the environmental quality of marine areas. Indeed, the development of risk maps is part of an iterative process that is expected to progressively improve by considering different hazard scenarios (e.g. hazard of oceans' acidification, hypoxia), extending the analysis to longer term timeframes, relevant for planning and management purposes (e.g. 2035-2050, 2070-2100) and including other and more detailed targets and vulnerability factors as more research on environmental and anthropogenic data is available. ~~Future improvement of the performed analysis, should integrate dataset with higher spatial resolution acquired through direct measurements (and provided by local authorities), allowing to better represent local environmental dynamics (e.g. enrichment of nutrients and organic matter due to river discharge) and make more reliable and verifiable the resulting output of the assessment.~~

Moreover, the developed analysis can be easily up-scaled to evaluate the consequences of multiple pressures at a broader regional scale (e.g. Mediterranean scale) as well as down-scaled by improving the assessment with more detailed dataset. Finally, the methodology can be enhanced by fine-tuning vulnerabilities and hazards' spatial ~~modelling~~ mapping ~~according to metrics and thresholds updated by the EU member states for the step-by-step implementation of the MSFD requirements (EC, 2008; EC, 2010), as well as by considering indicators pointed out by the others EU surrounding nations of the case study, implementing the MSFD requirements~~by using new advanced modelling approaches (also taking into account the 3D dimension of the sea), as well as by integrating in the assessment ~~.Future improvement of the performed analysis, should integrate~~ dataset with higher spatial resolution acquired through direct measurements (and provided by local authorities), allowing to better represent local environmental dynamics (e.g. enrichment of nutrients and organic matter due to river discharge) and make more reliable and verifiable the resulting output of the assessment.

However, the proposed approach presents some limitations mainly related to the methodological assumptions and the use of experts' judgment applied during the assignation of scores in the vulnerability assessment phase that can be considered too simplistic for potential end-users to trust the reliability of the results of the analysis. For overcoming this limit, different setting of scenarios and scores for the same case study can be defined (sensitive analysis), comparing (and validating) the results of the assessment with reference data (i.e. historical monitoring data, field measurements, time-series) or across comparable studies performed in the same marine region and time slice by applying other impact assessment methods, spatial modelling approaches or analytical tools.

Moreover, the performed assessment captures a snapshot in time based on recent environmental and anthropogenic conditions (i.e. reference scenario 2000- 2015) of the marine area of concern, leaving aside the evaluation of more complex future climate change scenarios, although it is well known how climate change will affect seas and oceans in near and long-term futures (IPCC, 2014), acting as '*force majeure*' able to influence or inhibits~~ the MSFD application and the ability to meet GES (Elliott et al., 2015) as well as ~~the effective implementation of planning options. To be effective, marine strategies and policies need to identify ways of adapting to the effects of global warming and to reduce the vulnerability of natural ecosystem to climate change effects (EC, 2008). Accordingly, future climate change scenarios need to be evaluated in order to provide planners and policy makers credible risk ad vulnerability maps, against designing suitable plans ad projects, as well as long-term programmes and visions able to adapt to changes over time.

Comment [AC1]: Io questa parte qui la vedrei meglio nel paragrafo 4.1 dove parli di SST. Mi sembra una cosa un po' troppo tecnica e specifica da mettere in conclusioni.

Finally, so far the developed risk-based approach doesn't account for more complex cause-effect interactions among endogenic and exogenic pressures acting in concert on the same target in an interactive fashion (i.e. additive, antagonistic or synergic) (Brown et al., 2014; Crain et al., 2008). In this context further work is needed for developing novel approaches and models (e.g. more accurate ecological models coupling vulnerability of marine ecosystem to pressures; advanced methods simulating cascading and triggering effects due to synergic/antagonistic pressures) to predict, assess and understand changes induced by the interaction among all factors contributing to exacerbate cumulative impacts (i.e. multiple linked endogenic and exogenic pressures, rising vulnerability of marine habitat), in order to develop and implement new plans and policies leading to multifaceted and cross-sectorial benefits.

Acknowledgment

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Bibliography

Agardy, M. T. (1994). Advances in marine conservation: the role of marine protected areas. *Trends in Ecology & Evolution*, *9*(7), 267–270.

Allison, E. H., Perry, A. L., Badjeck, M., Neil Adger, W., Brown, K., Conway, D., … Andrew, N. L. (2009). Vulnerability of national economies to the impacts of climate change on fisheries. *Fish and Fisheries*, *10*(2), 173–196.

Andersen, J., Stock, A., Heinänen, S., Mannerla, M., & Vinther, M. (2013). *Human uses, pressures and impacts in the eastern North Sea*. Aarhus University, DCE-Danish Centre for Environment and Energy.

Andersen, M. C., Thompson, B., & Boykin, K. (2004). Spatial risk assessment across large landscapes with varied land use: lessons from a conservation assessment of military lands. *Risk Analysis*, *24*(5), 1231–42. http://doi.org/10.1111/j.0272-4332.2004.00521.x

Astles, K. L., Gibbs, P. J., Steffe, A. S., & Green, M. (2009). A qualitative risk-based assessment of impacts on marine habitats and harvested species for a data deficient wild capture fishery. *Biological Conservation*, *142*(11), 2759–2773. http://doi.org/10.1016/j.biocon.2009.07.006

Ban, N. C., Alidina, H. M., & Ardron, J. a. (2010). Cumulative impact mapping: Advances, relevance and limitations to marine management and conservation, using Canada's Pacific waters as a case study. *Marine Policy*, *34*(5), 876–886. http://doi.org/10.1016/j.marpol.2010.01.010

Borja, Á., Elliott, M., Carstensen, J., Heiskanen, A.-S., & van de Bund, W. (2010). Marine management – Towards an integrated implementation of the European Marine Strategy Framework and the Water Framework Directives. *Marine Pollution Bulletin*, *60*(12), 2175–2186. http://doi.org/10.1016/j.marpolbul.2010.09.026

Brown, C. J., Saunders, M. I., Possingham, H. P., & Richardson, A. J. (2014). Interactions between global and local stressors of ecosystems determine management effectiveness in cumulative impact mapping. *Diversity and Distributions*, *20*(5), 538–546. http://doi.org/10.1111/ddi.12159

CEC. (1992). Council Directive 92/43/EEC on the conservation of natural habitats and of wild fauna and flora, (April 1979), 1–52.

CIESM. (2008). Climate warming and related changes in Mediterranean marine biota. CIESM Workshop Monographs, (May), 27–31.

Cormier, R., Kannen, A., Nin, B. M., Davies, I., Greathead, C., Diedrich, A., … Sardá, R. (2010). Risk-based frameworks in ICZM and MSP decision-making processes. ICES CM 2010/B:07.

Crain, C. M., Halpern, B. S., Beck, M. W., & Kappel, C. V. (2009). Understanding and Managing Human Threats to the Coastal Marine Environment. *Annals of the New York Academy of Sciences*, *1162*(1), 39–62. http://doi.org/10.1111/j.1749-6632.2009.04496.x

Crain, C. M., Kroeker, K., & Halpern, B. S. (2008). Interactive and cumulative effects of multiple human stressors in marine systems. *Ecology Letters*, *11*(12), 1304–15. http://doi.org/10.1111/j.1461-0248.2008.01253.x

Douvere, F., & Ehler, C. N. (2009). New perspectives on sea use management: initial findings from

European experience with marine spatial planning. *Journal of Environmental Management*, *90*(1), 77–88. http://doi.org/10.1016/j.jenvman.2008.07.004

EC. (2008). Directive 2008/56/EC of the European Parliament and of the Council of 17 June 2008 establishing a framework for community action in the field of marine environmental policy (Marine Strategy Framework Directive)., 19–40.

EC. (2010). Commission Decision 2010/477/EU of 1 September 2010 on criteria and methodological standards on good environmental status of marine waters (notified under document C(2010) 5956)., (2008), 14–24.

EC. (2011). The potential of Maritime Spatial Planning in the Mediterranean Sea. Case study report : The Adriatic Sea.

EC. (2014). Directive 2014/89/EU of the European Parliament and of the Council of 23 July 2014 establishing a framework maritime spatial planning., *2014*(April), 135–145.

EEA (European Environment Agency). (2015). *The European environment — state and outlook 2015 — synthesis report*. Retrieved from http://www.eea.europa.eu/soer-2015/synthesis/report/table-of-contents

Ehler, C., & Douvere, F. (2009). Marine Spatial Planning: a step-by-step approach toward ecosystem-based management, (53).

Elliott, M. (2013). The 10-tenets for integrated, successful and sustainable marine management. *Marine Pollution Bulletin*, *1*(74), 1–5.

Elliott, M., Borja, Á., McQuatters-Gollop, A., Mazik, K., Birchenough, S., Andersen, J. H., … Peck, M. (2015). Force majeure: Will climate change affect our ability to attain Good Environmental Status for marine biodiversity? *Marine Pollution Bulletin*, *95*(1), 7–27. http://doi.org/10.1016/j.marpolbul.2015.03.015

Gabrié C., Lagabrielle E., Bissery C., Crochelet E., Meola B., Webster C., Claudet J., Chassanite A., Marinesque S., Robert P., G. M. (2012). *The Status of Marine Protected Areas in the Mediterranean Sea*.

Galgani, F., Hanke, G., Werner, S., & De Vrees, L. (2013). Marine litter within the European Marine strategy framework directive. *ICES Journal of Marine Science: Journal Du Conseil*, *70*(6), 1055–1064.

Grech, a., Coles, R., & Marsh, H. (2011). A broad-scale assessment of the risk to coastal seagrasses from cumulative threats. *Marine Policy*, *35*(5), 560–567. http://doi.org/10.1016/j.marpol.2011.03.003

Halpern, B. S. (2003). The Impact of Marine Reserves : Do Reserves Work and Does Reserve Size Matter ? *Society, Ecological Applications, Ecological*, *13*(1).

Halpern, B. S., Walbridge, S., Selkoe, K. a, Kappel, C. V, Micheli, F., D’Agrosa, C., … Watson, R. (2008). A global map of human impact on marine ecosystems. *Science (New York, N.Y.)*, *319*(5865), 948–52. http://doi.org/10.1126/science.1149345

Hayes, E. H., & Landis, W. G. (2004). Regional Ecological Risk Assessment of a Near Shore Marine Environment: Cherry Point, WA. *Human and Ecological Risk Assessment: An International Journal*, *10*(2), 299–325. http://doi.org/10.1080/10807030490438256

Hunsaker, C. T., Graham, R. L., Suter II, G. W., O'Neill, R. V, Barnthouse, L. W., & Gardner, R. H. (1990). Assessing ecological risk on a regional scale. *Environmental Management*, *14*(3), 325–332.

IMO/UNEP. (2011). Regional Information System; Part C2, Statistical Analysis - Alerts and Accidents Database, REMPEC, February 2011.

IPCC. (2014). Summary for Policy Makers. *Summary for Policymakers. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., ,* 1–32. http://doi.org/10.1016/j.renene.2009.11.012

ISPRA. (2012a). Strategia per l'ambiente marino. Valutazione iniziale. Sottoregione mar Adriatico. Danno fisico. Documenti per la consultazione pubblica del 2012. Bozza, 10 Maggio 2012.

ISPRA. (2012b). Strategia per l'ambiente marino. Valutazione iniziale. Sottoregione mar Adriatico. Specie non indigene + inventario. Documenti per la consultazione pubblica del 2012. Bozza, 10 Maggio 2012.

IUCN-WCPA. (2008). *Establishing Marine Protected Area Networks—Making It Happen. Washington, D.C.: IUCN-WCPA, National Oceanic and Atmospheric Administration and The Nature Conservancy. 118 p.*

Kalbfleisch J. G. (1985). Probability and Statistical Inference: Volume 1: Probability. *Springer Texts in Statistics-Sep 9, 1985.*

Kappel, C. V, Halpern, B. S., & Napoli, N. (2012). Mapping Cumulative Impacts of Human Activities on Marine Ecosystems. *Coastal and Marine Spatial Planning. Research Report #03.NCEAS.12*, (January).

Kenny, A. J., Skjoldal, H. R., Engelhard, G. H., Kershaw, P. J., & Reid, J. B. (2009). An integrated approach for assessing the relative significance of human pressures and environmental forcing on the status of Large Marine Ecosystems. *Progress in Oceanography*, *81*(1), 132–148.

Korpinen, S., Meski, L., Andersen, J. H., & Laamanen, M. (2012). Human pressures and their potential impact on the Baltic Sea ecosystem. *Ecological Indicators*, *15*(1), 105–114. http://doi.org/10.1016/j.ecolind.2011.09.023

Lamon, L., Rizzi, J., Bonaduce, A., Dubois, C., Lazzari, P., Ghenim, L., … Canu, D. M. (2014). An ensemble of models for identifying climate change scenarios in the Gulf of Gabes, Tunisia. *Regional Environmental Change*, *14*(1), 31–40.

Landis, W. G. (2004). *Regional scale ecological risk assessment: using the relative risk model*. CRC Press.

Lovato T., Vichi M., O. P. (2013). High resolution simulations of Mediterranean Sea physical oceanography under current and scenario climate conditions: model description, assessment and scenario analysis. *Research Papers, Issue RP0207*, (December 2013).

Micheli, F., Halpern, B. S., Walbridge, S., Ciriaco, S., Ferretti, F., Fraschetti, S., … Rosenberg, A. a. (2013). Cumulative human impacts on Mediterranean and Black Sea marine ecosystems: assessing current pressures and opportunities. *PloS One*, *8*(12), e79889. http://doi.org/10.1371/journal.pone.0079889

Millot, C., & Taupier-Letage, I. (2005). Circulation in the Mediterranean sea. *The Mediterranean Sea*, 323–334.

NOAA. (2013). Marine Protected Areas Building Resilience To Climate Change Impacts.

Oddo, P., Bonaduce, A., Pinardi, N., & Guarnieri, A. (2014). Sensitivity of the Mediterranean Sea level to atmospheric pressure and free surface elevation numerical formulation in NEMO. *Geoscientific Model Development*, *7*(6), 3001–3015. http://doi.org/10.5194/gmd-7-3001-2014

Okey, T. a., Agbayani, S., & Alidina, H. M. (2015). Mapping ecological vulnerability to recent climate change in Canada's Pacific marine ecosystems. *Ocean & Coastal Management*, *106*, 35–48. http://doi.org/10.1016/j.ocecoaman.2015.01.009

Ondiviela, B., Losada, I. J., Lara, J. L., Maza, M., Galván, C., Bouma, T. J., & van Belzen, J. (2014). The role of seagrasses in coastal protection in a changing climate. *Coastal Engineering*, *87*, 158–168. http://doi.org/10.1016/j.coastaleng.2013.11.005

Patrício J., Teixeira H., Borja A., Elliott M., Berg T., Papadopoulou N., Smith C., Luisetti T., Uusitalo L., Wilson C., Mazik K., Niquil N., Cochrane S., Andersen J.H., Boyes S., Burdon D., Carugati L., Danovaro R., H. N. (2014). DEVOTES recommendations for the implementation of the Marine Strategy Framework Directive. Deliverable 1.5, 71 pp. DEVOTES project. JRC92131.

Ramieri E., Andreoli E., Fanelli A., Artico, B. R. (2014). Methodological handbook on Maritime Spatial Planning in the Adriatic Sea. Final report of Shape Project WP4 "Shipping Towards Maritime Spatial Planning", issuing date: 10 February 2014. Printed by Veneto Region.

Rizzi, J., Torresan, S., Critto, A., Zabeo, A., Brigolin, D., Carniel, S., … Marcomini, A. (2015). Climate change impacts on marine water quality: The case study of the Northern Adriatic sea. *Marine Pollution Bulletin*. http://doi.org/10.1016/j.marpolbul.2015.06.037

Rizzi, J., Torresan, S., Zabeo, A., Critto, A., Tosoni, A., Tomasin, A., & Marcomini, A. (2017). Assessing storm surge risk under future sea-level rise scenarios: a case study in the North Adriatic coast. *Journal of Coastal Conservation*, 1–19.

Ronco, P., Bullo, M., Torresan, S., Critto, A., Olschewski, R., Zappa, M., & Marcomini, A. (2015). KULTURisk regional risk assessment methodology for water-related natural hazards–Part 2: Application to the Zurich case study. *Hydrology and Earth System Sciences*, *19*(3), 1561–1576.

Salomidi, M., Katsanevakis, S., Borja, Á., Braeckman, U., Damalas, D., Galparsoro, I., … Pipitone, C. (2012). Assessment of goods and services, vulnerability, and conservation status of European seabed biotopes: a stepping stone towards ecosystem-based marine spatial management. *Mediterranean Marine Science*, *13*(1), 49–88.

Savini, A., Basso, D., Bracchi, V., Corselli, C., & Pennetta, M. (2012). Maerl-bed mapping and carbonate quantification on submerged terraces offshore the Cilento peninsula (Tyrrhenian Sea, Italy). *Geodiversitas*, *34*(1), 77–98.

Selig, E. R., & Bruno, J. F. (2010). A Global Analysis of the Effectiveness of Marine Protected Areas in Preventing Coral Loss. *PLoS ONE*, *5*(2), e9278. http://doi.org/10.1371/journal.pone.0009278

Short, F., Carruthers, T., Dennison, W., & Waycott, M. (2007). Global seagrass distribution and diversity: a bioregional model. *Journal of Experimental Marine Biology and Ecology*, *350*(1), 3–20.

Sperotto, A., Torresan, S., Gallina, V., Coppola, E., Critto, A., & Marcomini, A. (2016). A multi-disciplinary approach to evaluate pluvial floods risk under changing climate: The case study of the municipality of Venice (Italy). *Science of The Total Environment*, *562*, 1031–1043.

Stelzenmüller, V., Lee, J., South, a., & Rogers, S. I. (2009). Quantifying cumulative impacts of human pressures on the marine environment: A geospatial modelling framework. *Marine Ecology Progress Series*, *398*, 19–32. http://doi.org/10.3354/meps08345

Suaria, G., & Aliani, S. (2014). Floating debris in the Mediterranean Sea. *Marine Pollution Bulletin*, *article in*(1–2), 494–504. http://doi.org/10.1016/j.marpolbul.2014.06.025

Sutherland, W. J., Bardsley, S., Bennun, L., Clout, M., Côté, I. M., Depledge, M. H., … Watkinson, A. R. (2011). Horizon scan of global conservation issues for 2011. *Trends in Ecology and Evolution*, *26*(1), 10–16. http://doi.org/10.1016/j.tree.2010.11.002

Torresan, S., Critto, A., Rizzi, J., & Marcomini, A. (2012). Assessment of coastal vulnerability to climate change hazards at the regional scale: the case study of the North Adriatic Sea. *Natural Hazards and Earth System Science*, *12*(7), 2347–2368. http://doi.org/10.5194/nhess-12-2347-2012

UN. (1982). United Nations Convention on the Law of the Sea (UNCLOS). Third United Nations Conference on the Law of the Sea (UNCLOS III). Montego Bay, Jamaica. Retrieved from http://www.un.org/Depts/los/index.htm.

UN. (1992). International Convention on Biological Diversity (CBD), Earth Summit, 5 June 1992 Rio de Janeiro, 30. Retrieved from http://www.cbd.int/doc/legal/cbd-en.pdf

UN. (2009). UNISDR Terminology on Disaster Risk Reduction. *International Stratergy for Disaster Reduction (ISDR)*, 1–30. Retrieved from www.unisdr.org/publications

UNEP. (2009). *Marine Litter : A Global Challenge*. *United Nations Environmental Programme (UNEP)*.

UNESCO. (2015). Global biodiversity indices from the Ocean Biogeographic Information System. Intergovernmental Oceanographic Commission of UNESCO. Web. http://www.iobis.org.

Waycott, M., Collier, C., Mcmahon, K., Ralph, P., Mckenzie, L., Udy, J., & Grech, A. (2007). Vulnerability of seagrasses in the Great Barrier Reef to climate change. *Climate Change and the Great Barrier Reef: A Vulnerability Assessment*, 193–236.

Zald, A. E., Summer, S., & Wade, T. (2006). A to Z GIS: An Illustrated Dictionary of Geographic Information Systems.

Spatially explicit risk approach for multi-hazard assessment and management in marine environment: the case study of the Adriatic sea

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Abstract

In the last few decades the health of marine ecosystems has been progressively endangered by the anthropogenic presence. Natural and human-made pressures, as well as climate change effects, are posing increasing threats on marine areas, triggering alteration of biological, chemical and physical processes. Planning of marine areas has become a challenge for decision makers involved in the design of sustainable management options. In order to address threats posed by climate drivers in combination with local to regional anthropogenic pressures affecting marine ecosystems and activities, a multi-hazard assessment methodology was developed and applied to the Adriatic sea for the reference scenario 2000-2015. Through a four-stages process based on the consecutive analysis of hazard, exposure, vulnerability and risk the methodology allows a semi-quantitative evaluation of the relative risk from anthropogenic and natural sources to multiple endpoints, thus supporting the identification and ranking of areas and targets more likely to be at risk . Resulting output showed that the higher relative hazard scores are linked to exogenic pressures (e.g. sea surface temperature variation) while the lower ones resulted from endogenic and more localized stressors (e.g. abrasion, nutrient input). Relatively very high scores were observed for vulnerability over the whole case study for almost all the considered pressures, showing seagrasses meadows, maërl and coral beds as the most susceptible targets. The approach outlined in this study provides planners and decision makers a quick-screening tool to evaluate progress toward attaining a good environmental status and to identify marine areas where management actions and adaptation strategies would be best targeted. Moreover, by focusing on risks induced by land-based drivers, resulting output can support the design of infrastructures for reducing pressures on the sea, contributing to improve the land-sea interface management.

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1. INTRODUCTION

According to the recent assessment of the European environment's state (EEA, 2015), Europe's seas are facing increasing threats and degradation due to a wide range of human activities, impairing marine ecosystems and their goods and services for human wellbeing. The growth of maritime activities is taking place without the full understanding of the complex interactions between natural and human-induced changes (Ehler & Douvere, 2009). Due to this overexploitation, happening across all of Europe’s regional seas, marine biodiversity is declining, jeopardizing the conservation status of ecosystems and compromising the achievement of the Good Environmental Status (GES) by 2020, as required by MSFD (EC, 2008). A further complication is determined by climate change which is posing additional pressures on marine ecosystems through rising sea levels, increased sea temperatures and ocean acidification. Climate change is already affecting the marine environment and will continue triggering changes on biological, chemical and physical processes (IPCC, 2014) with stronger and more numerous impacts projected for the future, leading to exacerbate others existing anthropogenic pressures (e.g. temperature-induced changes are expected to interact with existing nutrient inputs) (Brown et al., 2014). Accordingly, the provision of ecosystem services is expected to decline across all European seas in response to climate change, thus reducing the ecosystem resilience to other anthropogenic pressures taking place in marine areas (IPCC, 2014).

Over the course of the last 30 years several directives, laws and agreements were approved by the International and European organizations for ensuring the sustainable growth of our oceans and seas, by allocating marine space, rights and responsibilities of sovereign nations (United Nations Convention on the Law of the Sea -UNCLOS III) (UN, 1982), regulating use and exploitation of marine and coastal areas which inevitably lead to the deterioration of marine ecosystems’ environmental status (Maritime Spatial Planning Directive -MSP-) (EC, 2014), as well as posing specific requirements and procedures for the assessment of the environmental state and quality of marine areas (Marine Strategy Framework Directive 2008/56/EC) (EC, 2008). Within these regulatory frameworks the Ecosystem Based Approach (EBA) is widely recognized as the strategic tool to be integrated with planning and management processes in order to preserve marine biodiversity (Convention of Biological Diversity -CBD-) (UN, 1992).

According to several scientific studies (Elliott, 2013; Borja et al., 2010; Douvere & Ehler, 2009; Kenny et al., 2009) the assessment of pressures and impacts in marine areas requires new methodological approaches able to move forward the traditional sectorial management and analysis of marine spaces and related issues, towards a more holistic and coordinated development of marine areas, and the assessment of the relative significance of environmental and anthropogenic forcing on the marine ecological status. These kind of approaches will be able to strengthen sustainable economic and environmental development, achieving at the same time a higher environmental quality of marine areas. In this context, an environmental risk-based approach should be applied in order to support the identification of hot-spot areas and vulnerable targets that are more likely to be at risk due to multiple threats posed by climate drivers in combination with local to regional anthropogenic pressures. Spatial risk assessment, performed by means of Geographical Information Systems (GIS), is an effective approach allowing a quick scan and spatial visualization of risks produced by multiple sources of various stressors, considering the presence of multiple marine habitats at broad spatial scales (Hayes & Landis 2004; Grech et al. 2011). It supports the integration of spatial models on species and habitat distribution with qualitative and quantitative information on the relative impact produced by multiple endogenic (i.e. from anthropogenic activities within an area) and exogenic pressures (i.e. induced by natural drivers operating outside the control of management measures employed in a regional sea and where the management measures can only address the consequences rather than the cause) (Elliott et al., 2015; Halpern et al., 2008; Andersen et al. 2004; Andersen et al. 2013; Crain et al. 2009; Micheli et al. 2013; Kappel et al. 2012; Korpinen et al. 2012; Ban et al. 2010; Stelzenmüller et al. 2009), providing a structure and analysis' output able to facilitate and inform maritime spatial planning and management and aids science-based decision-making (Cormier et al., 2010).

In this setting, this paper aims at developing and applying in the Adriatic sea case study a risk-based methodology allowing to evaluate relative risk scenarios induced by endogenic and exogenic pressures over vulnerable marine targets. Based on recognized methodologies in scientific literature for regional scale comparative assessment (Rizzi et al., 2017 and 2015; Sperotto et al., 2016; Ronco et al., 2015; Lamon et al., 2014; Torresan et al., 2012; Hayes & Landis, 2004; Landis, 2004) it will attempts to produce, for the considered reference scenario (i.e. 2000-2015), a suite of spatial maps and statistics representing key risk metrics, useful to public authorities to identify and relative ranking areas and targets mostly at risk and requiring effective strategies for risks mitigation and priority actions for environmental restoration and conservation. Following a brief introduction to the case study area and the available dataset for the methodology implementation (Section 2), this paper describes in detail the developed multi-hazard approach, with its conceptual framework and operative steps (Section 3) and, finally, presents the resulting output from its application in the selected case study, including GIS-based maps and statistics obtained for the marine region of the Adriatic sea (Section 4).

2. Description and characterization of the case study area

This section introduces the case study area of the Adriatic sea marine sub-region (Section 2.1) focusing on its administrative, environmental and socio-economic aspects. Moreover, available input dataset retrieved for for the case study are described, including GIS-based data (i.e. vector and raster maps) and climate model outputs (Section 2.2). The supporting dataset has played an important role in the definition of the methodology since it is closely linked to the availability of consistent and homogeneous data covering the whole case study.

2.1 The Adriatic sea: main features and environmental issues

The case study area selected for the implementation of the multi-hazard assessment methodology is represented by the marine sub-region of the Adriatic sea located in the wider Mediterranean sea (Figure 1).

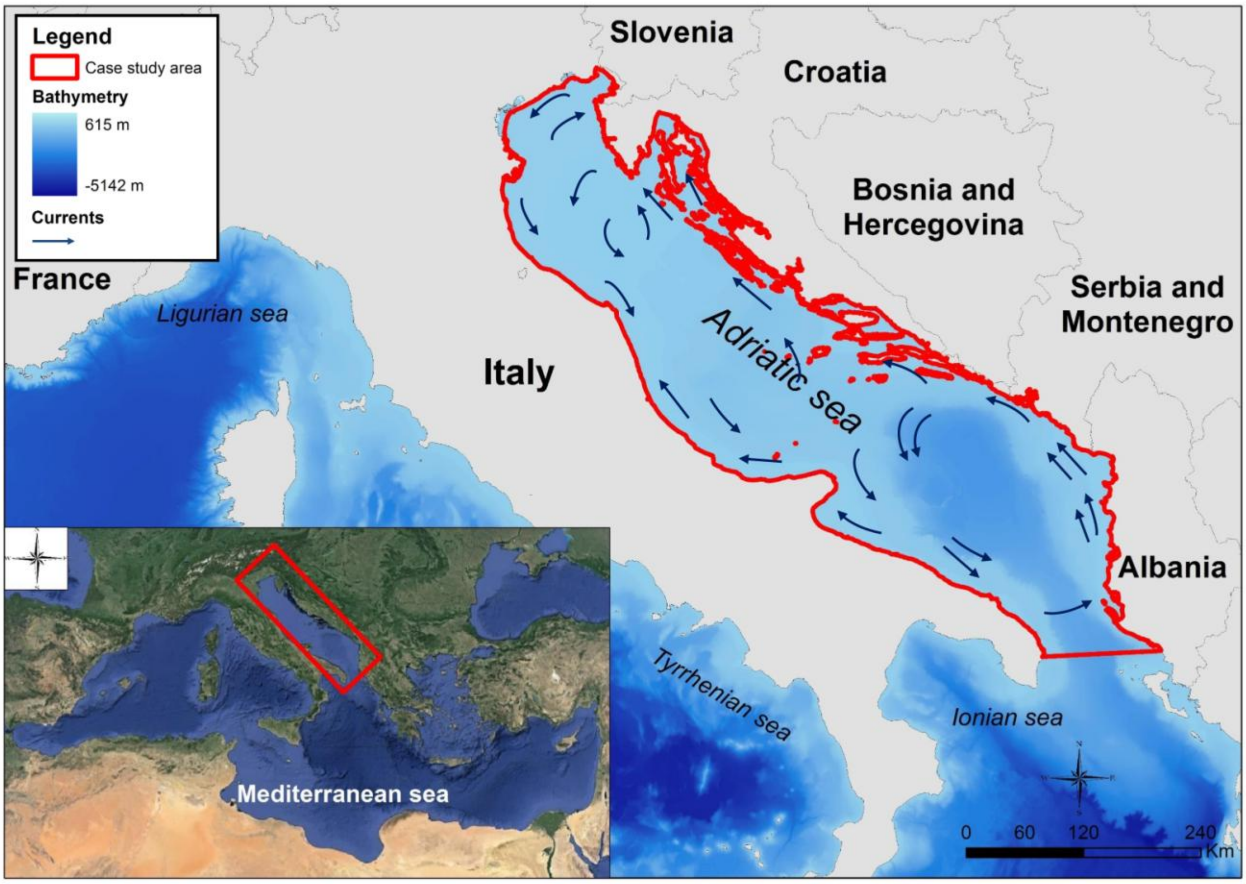

Figure 1 The Adriatic sea case study area (general circulation of the water masses adapted from Millot and Taupier-Letage, 2005)

The Adriatic Sea is a semi-enclosed basin with a total surface of about 138,600 km2 and a volume of 33,000 km3; Its shape can be approximated to a rectangle extending north-southwest, about 800 km long and 200 km wide (EC, 2011) (Ramieri E., 2014), bounded by the Italian peninsula at west, the Balkan peninsula at east and communicating with the Ionian Sea in the south through the Otranto Strait which is the narrowest part (75 Km wide). It is surrounded by six coastal states: Albania, Bosnia and Herzegovina, Croatia, Italy, Slovenia and Serbia-Montenegro. The basin is divided into three major geographical parts: Northern, Central and Southern, where the coastal areas correspond to three continental shelves. Overall, the Adriatic sea is featured as a shallow enclosed sea area; however, the southern part of the region is far deeper than the northern one in the areas of the Pomo depression (-260 m) and the Pelagosa sill (-170 m) in the middle Adriatic, the wide abyssal depression (-1200 m) and the Otranto sill (-800 m) in the South Adriatic. The northern and northwestern coastlines are featured by shallow waters and sandy beaches whereas the eastern part of the basin is deeper, rocky and comprises many islands and islets. The beauty and the high environmental value of the Adriatic Sea makes this region an attractive place to live and work: each year, more tourists spend holidays in the countries surrounding the Adriatic sea where important tourist destinations are located. However, this massive coastal and marine tourism, as well as multiple economic activities located along the coastline, are leading to increase sea pollution by marine litters, one of the major concern for the global oceans. Indeed, land-based drivers (including land-based activities and coastal tourism), rather than ocean-based ones (e.g. shipping transport), result as the main sources of anthropogenic debris in the Mediterranean Seas (Suaria & Aliani, 2014; Galgani et al., 2013; UNEP, 2009), representing a relevant environmental and economic threat for the biodiversity of marine ecosystems and the goods and services they provide (Sutherland et al., 2011).

As far as the economic side is concerned, the Adriatic sea is also an important maritime transport route, used by tourist and merchant ships in international and national trade, by yachts, fishing vessels and other non-merchant ships. A significant number of important industrial centers are located along the western Adriatic coasts and several mid-European countries highly depend on the Northern Adriatic ports (e.g. the port of Trieste, Venice, Koper and Rijeka) for importing energy. Moreover, apart from being an important maritime transport route, the Adriatic sea basin is among others a productive area for fishing (including aquaculture). Fishing has traditionally been an important sector for most the Adriatic countries and Italy is by far the largest fishing fleet in the Adriatic (EC, 2011). However, the share of the fisheries sector in the national economies is decreasing. Fish stocks have suffered from overfishing and pollution caused by water discharges of industrial activities, agriculture and urbanized areas, especially in the Italian part of the Northern Adriatic Sea.

In this context of multiple human-made pressures a further complication is determined by climate change which poses additional exogenic pressures on this environment through rising sea levels, increased sea temperatures and ocean acidification (IPCC, 2014). Climate change is a prominent issue for the Adriatic sea both considering the vulnerability of important ecosystems such as wetlands and seagrasses, and the concentration of cultural and socio-economic values. The basin is known to have a large spatial and temporal variability (both seasonal and interannual) depending on its driving forcing (atmospheric and land-based). In this setting, is therefore quite important to evaluate, at the regional scale, the localization and extent of changes in the Adriatic sea case study, according to both endogenic and exogenic forcing, also considering potentially affected sensitive targets and their vulnerability to multiple pressures.

Drawing on this, by considering the multiple anthropogenic activities taking place in its marine space (e.g. fisheries and aquacultures, commercial and touristic shipping traffic), the large spatial and temporal variability of temperature (both seasonal and interannual) depending on its driving forcing (atmospheric and land-based) (IPCC, 2014), and its great morphological diversity resulting in a high diversity in terms of productivity and biodiversity, the Adriatic sea represents a relevant case study where analyzing potential risks arising from multiple and overlapping endogenic and exogenic hazards, potentially affecting vulnerable environmental and socio-economic targets. Most of these environmental features and issues can be observed, with site-specific traits and combinations of human-made and natural pressures, in other marine areas worldwide (e.g. Bosphorus strait, Mediterranean and Black sea), thus making the proposed case study a reference area for the implementation of similar risk-based approach in others geographical contexts.

2.2 Available dataset for the case study area

Acquiring the necessary data to inform risk assessment approaches in marine areas is a difficult task, mainly because detailed data for coastal and marine habitats are far less organized and available than for terrestrial environments (Grech et al., 2011). Accordingly, with the main aim of evaluating the effect of multiple threats on relevant marine habitat in the Adriatic sea case study, an in-depth research and collection of GIS-based dataset was performed, paying specific attention to their spatial resolution and homogeneous coverage for the whole basin. A variety of physical and environmental data, as well as data on main endogenic (i.e. from anthropogenic activities) and exogenic pressures (i.e. related to natural drivers) acting on the Adriatic sea, were retrieved in order to characterise the spatial pattern and distribution of targets (e.g. seagrasses, marine protected areas), as well as to define appropriate indicators for spatially modelling hazards and vulnerabilities in the considered area. The available dataset for the Adriatic sea are summarized in Table 1 highlighting their spatial domain and resolution, data source and update. Most of dataset concerning the spatial distribution of human activities located in the Adriatic sea (i.e. ports, aquaculture facilities, shipping routes, offshore installations) were retrieved by the web data portals of the SHAPE project '*Shaping an Holistic Approach to Protect the Adriatic Environment between coast and sea*' (http://www.shape-ipaproject.eu) and the Adriplan project '*ADRiatic Ionian maritime spatial PLANning'* (http://adriplan.eu). As far as climate-related drivers are concerned (i.e. sea temperature and salinity), data for the reference scenario 2000-2015 were provided by the Euro Mediterranean center on Climate Change (CMCC, www.cmcc.it) within the climate simulation developed in the frame of the PERSEUS project '*Policy-oriented marine Environmental Research in the Southern EUropean Seas*' (http://www.perseus-net.eu) (Lovato et al., 2013; Oddo et al., 2014). More specifically, since the assessment of potential impacts from temperature and salinity change was focused on selected shallow benthic habitats (e.g. seagrasses meadows and coral beds), sea surface temperature and salinity data were used to represent water variations at the top layer of the Adriatic sea (Okey et al., 2015).

DATASET	SPATIAL DOMAIN AND RESOLUTION	UPDATE DATA	SOURCE
PHYSICAL AND ENVIRONMENTAL DATA			
Adriatic basin boundary	Adriatic sea, 1:50000	2013	http://atlas.shape-ipaproject.eu
Marine administrative zones	Adriatic sea, 1:50000	2013	http://atlas.shape-ipaproject.eu
Marine Protected areas	Global ocean 1: 1.000.000	2014	www.protectedplanet.net
	Adriatic sea, 1:50000	2013	http://atlas.shape-ipaproject.eu
Sites of Community Importance (SCI), Zone of Special Protection (ZSP)	Adriatic sea, 1:50000	2013	http://atlas.shape-ipaproject.eu
Nationally designated areas	Adriatic sea, 1:25000	2013	http://atlas.shape-ipaproject.eu
Biologic protection zones (BPZ)	Adriatic sea, 1:10000	2013	http://atlas.shape-ipaproject.eu
Fishing regulated areas	Adriatic sea, 1:1000000	2013	http://atlas.shape-ipaproject.eu
EUSeaMap -seabed habitat map-	Adriatic sea, 1: 1.000.000	2014	http://www.emodnet.eu/seabed-habitats
Biodiversity Shannon's Index	Global scale, hex grid	2014	http://www.iobis.org/mapper
Seagrass species richness	Global ocean 1: 1.000.000	2003	http://data.unep-wcmc.org
ENDOGENIC AND EXOGENIC DRIVERS			
Ports and harbours	Adriatic sea, 1:50000	2014	http://atlas.shape-ipaproject.eu
Platform and wells for hydrocarbon extraction	Adriatic sea, 1:50000	2014	http://atlas.shape-ipaproject.eu
	European seas, 1:100000		http://www.emodnet.eu/human-activities
Regasification terminals	Adriatic sea, 1:500000	2014	http://atlas.shape-ipaproject.eu
Underwater pipelines and cables	Adriatic sea, 1:50000	2014	http://atlas.shape-ipaproject.eu
Foul areas	Adriatic sea, 1:50000	2014	http://atlas.shape-ipaproject.eu
Wrecks	Adriatic sea, 1:50000	2014	http://atlas.shape-ipaproject.eu
Dumping disposal sites	Adriatic sea, 1:100000	2014	http://atlas.shape-ipaproject.eu
Dumped munitions sites	European seas, 1:100000	2014	http://www.emodnet.eu/human-activities
Dredge spoil dumping	European seas, 1:100000	2015	http://www.emodnet.eu/human-activities
Offshore dredged areas	Adriatic sea, 1:100000	2014	http://atlas.shape-ipaproject.eu
Offshore sand deposits	Adriatic sea, 1:100000	2015	http://adriplan.eu
Map of spatio-temporal distribution of trawling fishing pressure based on Vessel Monitoring System data (2007-	Adriatic sea, 3x3Km grid	2010	http://adriplan.eu

2010)			
Mineral titles	Adriatic sea, 1:50000	2015	http://adriplan.eu
Shipping traffic	Global ocean 1:1.000.000	2008	https://www.nceas.ucsb.edu/globalmarine
Distributional map of alien species	Mediterranena sea, 10x10Km grid	2015	http://easin.jrc.ec.europa.eu
Ship accidents points - oil spills (1977-2014)	Mediterranena sea, 1:100000	2014	http://accidents.rempec.org
Coastal artificial protection	Adriatic sea, 1:25000	2014	http://atlas.shape-ipaproject.eu
Military practice areas	Adriatic sea, 1:50000	2014	http://atlas.shape-ipaproject.eu
Sea surface temperature (SST)	Mediterranena sea, 1/7 degree	2015	http://www.perseus-net.eu
Sea surface salinity (SSS)	Mediterranena sea, 1/7 degree	2015	http://www.perseus-net.eu
Chlorophyll ‘a’	Mediterranena sea, 1/7 degree	2015	http://adriplan.eu

Table 1 Available dataset for the application of the multi-hazard methodological approach in the Adriatic sea case study area

Finally, also the environmental dataset, supporting the identification of sensitive marine targets and the characterization of their vulnerability to the considered pressures, were mainly acquired by the web data portal of the SHAPE project (e.g. fishing regulated areas, marine protected areas, biological protection zones), with the exception of the seabed habitat map retrieved from the web-GIS of the European Marine Observation and Data Network (http://www.emodnet.eu). Moreover, by means of the Ocean Biogeographic Information System (http://www.iobis.org/), a comprehensive open-access database of marine species datasets from all of the world's oceans, map representing the Shannon Diversity Index for the Adriatic sea, was retrieved with a hexagonal grid resolution (UNESCO, 2015).

All collected data were pre-processed in order to homogenize data format and their geographical reference system, as well as clip all layers on the Adriatic sea administrative boundaries for removing data outside the investigated area. As already mentioned, the process of data selection was focused on the availability of updated, homogenous and detailed (i.e. with high spatial resolution) data for the whole case study, in order to feature, as much as possible, marine targets and their vulnerability to the considered pressures in the area of concern. As a consequence, the accessible supporting dataset, including data measured (or modelled and validated for what concern the sea surface temperature and salinity) for the whole Adriatic sea, has played an important role in the definition of the multi-hazard methodology, leading to focus the analysis on environmental features and pressures that could be modelled with the available data.

3. The multi-hazard assessment methodology applied to marine areas

The multi-hazard assessment methodology proposed in this paper aims to evaluate multiple risks posed by natural and anthropogenic threats as well as climate-driven pressures in the Adriatic sea case study. More specifically, according to Landis et al. (2004) the methodology supports the identification and relative ranking of the sources of hazard, habitats and sensitive marine targets potentially exposed and, finally, the environmental impacts in the considered marine region (Hayes & Landis, 2004).

The following sections describe the conceptual framework (section 3.1) and the step-by-step procedure applied in the selected case study, highlighting, for each of them, input parameters and applied mathematical equations for the spatial modelling and data integration (section 3.1.1-3.1.4).

3.1 Methodological framework.

In order to evaluate the environmental impacts produced by human-made pressures in combination with climate-related hazards in marine areas, a risk-based approach was developed and applied in the Adriatic Sea. According to the IPCC (2014) and UNISDR (UN, 2009) conceptual frameworks, risk has been considered as result of the integration between hazard, exposure and vulnerability. As a consequence, the proposed approach is composed of four consecutive steps (highlighted in Figure 2 by different colored boxes) allowing a gradual analysis of all components contributing to risk increasing in a specific area.

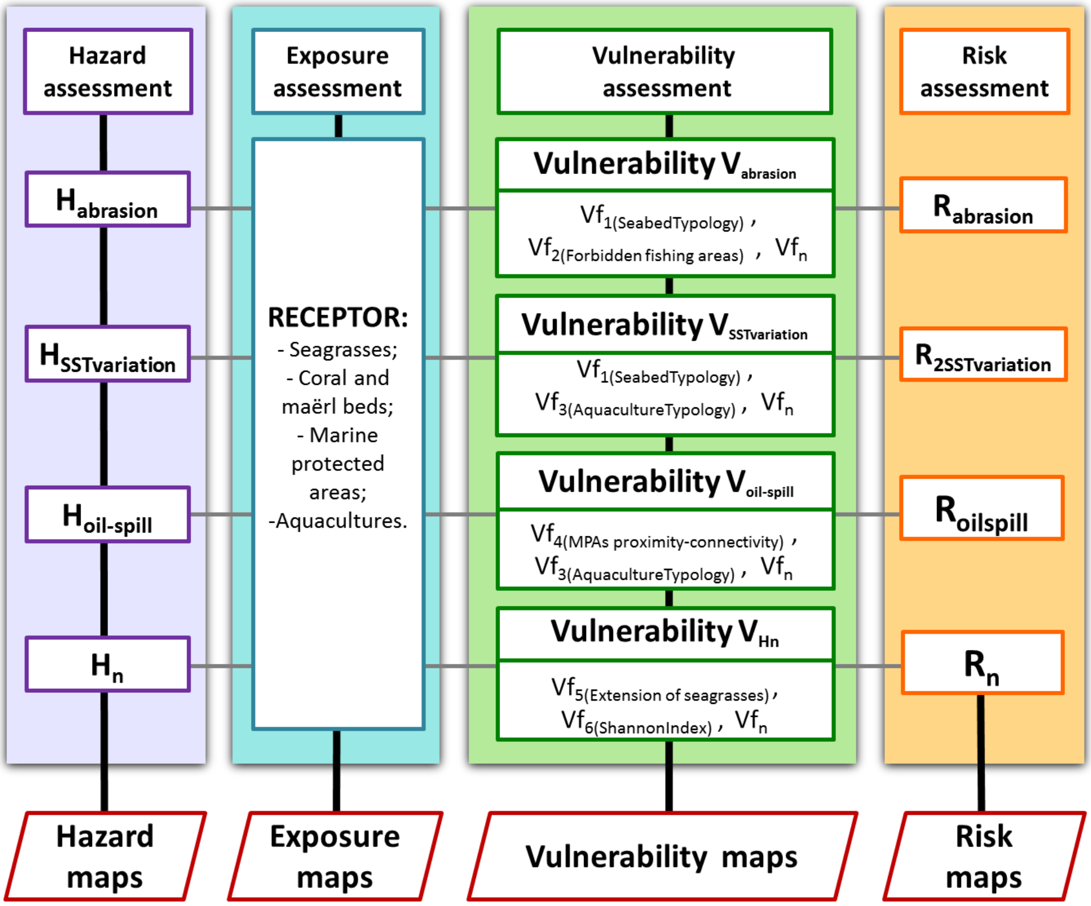

Figure 2 The multi-hazard assessment conceptual framework, where 'H' stands for Hazard; 'Vf' stands for Vulnerability factor; 'R' stands for Risk.

The first phase consists in the hazard assessment which aggregates metrics and scenarios of climate, ocean, bio-geochemical and anthropogenic pressures (e.g. temperature and salinity variation, bottom stress by abrasion and sealing of seabed) for determining potentially affected areas. The exposure assessment identifies and localizes key receptors that could be subject to potential losses in marine areas (e.g. seagrasses and coral and maërl beds). Subsequently, the vulnerability assessment is aimed at evaluating the degree to which receptors could be adversely affected by the considered hazards, based on their specific physical and environmental features (e.g. habitat extent and typology, biodiversity indexes). Finally, the relative risk assessment phase combines all the information about the considered hazards, exposure and vulnerabilities, in order to identify marine areas and targets at higher risk from multiple pressures. The application of each step of this methodology requires the management of a huge amount of heterogeneous input data (Table 1, Section 2.2) that are normalized and aggregated through Multi-Criteria Decision Analysis (MCDA), in order to provide spatial information useful for planners and decision makers involved in management and setting of marine areas (e.g. National Institutes for Environmental Protection and Research, Civil Protection, Water and port authorities, Regional agencies for the protection of the environment, Municipalities).

Following sections describe step by step the developed methodology explaining main aims, the specific equation applied for data integration and the resulting output, including GIS-based maps and related statistics.

3.1.1 Hazard assessment

The first step of the proposed methodology is the hazard assessment which allows to aggregate scenarios from ocean, climate, biogeochemical models with anthropogenic pressures, in order to identify and prioritize areas that could be affected by multiple and overlapping pressures, according to the considered timeframe scenario (i.e. reference scenario 2000-2015). For this purpose it is firstly required to identify the hazard stressors (e.g. installations for hydrocarbon extraction, maritime traffic, ports and harbours) and metrics (e.g. intensity of maritime traffic, goods and people per ports, sea surface temperature regime variation) for characterizing each pressures considered in the assessment procedure. Indeed, each hazard can be triggered by one or more stressors defined as the cause of environmental hazard impacting large geographic areas (Hunsaker et al., 1990). Accordingly, the hazard assessment is performed through the more specific following steps:

1. Identification of hazards' drivers and related metrics for the considered pressures.
2. Development of an ad-hoc spatial model and related equation for characterizing hazards' spatial distribution in the case study area;
3. Normalization of the hazard scores for all the considered pressures.

For the application of the hazard assessment phase we defined a set of hazards as human-derived stress factor causing either temporary or permanent physical disturbance, loss or damage for one or several components of an ecosystems. They were selected based on emerging methodologies for cumulative impact assessment in marine areas (Halpern et al., 2008; Andersen et al., 2013; Micheli et al., 2013; Kappel et al., 2012; Korpinen et al., 2012; Ban et al., 2010), pointing out, for almost all the considered hazards, their drivers, indicators and metrics for their evaluation in the Adriatic sea. However, has to be underlined that their assessment was performed by using input data measured or modelled for the whole case study. Moreover, we expanded the analysis by including exogenic pressures such as the variation in temperature and salinity regime, in order to analyse how climate drivers can threaten the environmental status of the analysed area. Indeed, it is well-known how climate change is triggering and will continue affecting the structure, function and processes of marine ecosystems (EEA, 2015) and, as such, will result in 'shifting baselines' which need to be accommodated in monitoring, and 'unbounded boundaries' (i.e. climate change-induced migrations and dispersal of highly-mobile, nekton and plankton specie) compromising the use of static reference conditions or targets in the evaluation of the environmental status of marine areas (Elliott et al., 2015; Patrício et al., 2014).

Hazards' selection was highly conditioned by the availability of homogeneous and high resolution data (Section 2.2) for the whole case study. The results of this process are summarized in Table 2 providing, for each selected hazard, main drivers, hazard metrics and equations applied for hazards' spatial modelling in the Adriatic sea (i.e. Equations 1-8). More specifically, based on literature review (Andersen et al., 2013; Micheli et al., 2013; Kappel et al., 2012; Korpinen et al., 2012; Ban et al., 2010; Halpern et al., 2008) the spatial modelling has followed specific procedures (reported in the Supplementary Material, SM1) aimed at developing credible hazard scenarios. In some cases, the retrieved data were directly used to represent hazards' intensity or their mere presence/absence in the case study area (e.g. artificial benthic infrastructures leading to smothering and sealing of seabed). In other ones, when data on their intensity and propagation were not available, different spatial modelling approaches were used as proxies to derive hazards spatial distribution and intensity (e.g. trawling fishing areas as a proxy for the seabed abrasion). In a nutshell, since there are no direct measurement for some of the considered hazards, they were estimated based of the causative human activities, thus providing a 'proxy spatial modelling' of their distribution in the case study (Andersen et al., 2013). They allow to represent potential circumstances where accidental emissions and pressures to the environment could more likely occur, based on the supporting dataset and at locations where higher potential damage might happen in the considered scenario (i.e. 2000-2015).

In order to maintain the highest spatial resolution and fit with methods pointed out in the Italian Initial Assessment Reports (ISPRA, 2012a and b), implementation of the hazard assessment phase was based on a spatial unit (i.e. grid cell) of 100m.

Hazards	Drivers	Hazard metrics	Equation
Smothering and sealing of seabed	- Platforms and wells for hydrocarbons’ extraction. - Regasification terminal. - Coastal artificial protections. - Ports and harbors. - Cables and pipelines. - Areas for unexploded ordinances' sinking. - Area of military practice. - Wrecks.	Presence/absence of benthic anthropogenic infrastructures.	**Equation 1:** $Hs_{smoth} = \begin{cases} 0 & \text{if no benthic structures are present in the investigated cell} \\ 1 & \text{else} \end{cases}$ Where: Hs_{smoth}= hazard score related to the smothering and sealing of the seabed.
Abrasion and extraction of seabed	- Trawling fishing area. - Dredging and extraction areas.	- Trawling fishing efforts expressed in hours of fishing activities. - Intensity of dredging activities expressed in m3 of dredged material.	**Equation 2:** $Hs_{abr} = \frac{(I_{traw}+I_{dredg})_i}{\text{maxItot}}$ Where: Hs_{abr}= abrasion and extraction hazard score. $(I_{traw} + I_{dredg})_i$ = sum of the intensities related to sand dredging and trawling fishing for the cell i, in 2013. max$Itot$ = maximum intensity of sand dredging and trawling fishing in the case study area for 2013.
Underwater noise	- Maritime traffic. - Platforms and wells.	- Intensity of maritime traffic. - Presence/absence of platforms and wells.	**Equation 3:** $Hs_{noise} = \frac{(I_{traff}+I_{hyd})_i}{\text{maxItot}}$ Where: Hs_{noise}= underwater noise hazard score; $(I_{traff} + I_{hyd})_i$ = sum of the intensities linked with the maritime traffic and platform for hydrocarbon extraction for the cell i. max$Itot$ = maximum intensity linked with the maritime traffic and platform for hydrocarbon extraction in the case study area.
Introduction of non-indigenous species	- Maritime traffic. - Ports and harbors. - Aquacultures.	Number of detected non-indigenous species.	**Equation 4:** $Hs_{NIS} = \frac{\text{TotNIS}_i}{\text{maxTotNIS}}$ Where: Hs_{NIS}= introduction of non-indigenous species hazard score. TotNIS_i = total number of indigenous species detected in the cell i until 2015. maxTotNIS = maximum number of potential ordinary emergencies in the case study area until 2015.
Inputs of organic matter	- Rivers discharge; - Urban waste water.	Chlorophyll concentration (Chl ‘a’).	**Equation 5:** $Hs_{OrgMat} = \frac{[Chl\,'a']_i}{\max\,[Chl\,'a']}$ Where: Hs_{OrgMat}= organic matter input hazard score; $[Chl\,'a']_i$ = sea surface chlorophyll ‘a’ mean concentration in the cell i for the timeframe window 2006-2012; max $[Chl\,'a']$ = maximum sea surface chlorophyll ‘a’ mean concentration in the case study area for the timeframe 2006-2012.
Introduction of hazardous substances by oil-spills	- Maritime accidents.	Occurrence of shipping accidents resulting in oil spills between 1977- 2014.	**Equation 6:** $Hs_{oilspill} = \frac{\sum_{p \in P} \max\left(0,1-\frac{d(p)}{k}\right)}{\text{maxOilSpill}}$ Where: $Hs_{oilspill}$= introduction of hazardous substances hazard score.

			P = overall of oil-spill points detected in the Adriatic sea. k = constant spatial threshold defined for the case study of 25 km (Micheli et al., 2013). $d(p)$= distance function that returns the points' distance p from th cell (pixel) of concern. maxOilSpill= maximum density of shipping accidents resulting in oil-spills within 25km radius from an accident source, calculated in the case study between 1977-2014.
Sea surface temperature regime variation	- Climate drivers.	Sea surface temperature anomalies in the reference scenario 2000-2015.	**Equation 7:** $Hs_{SST} = \frac{\mathrm{TotSSTanom}_c}{\mathrm{maxSSTanom}}$ Where: Hs_{SST}= sea surface temperature variation hazard score; $\mathrm{TotSSTanom}_c$= total number of sea surface temperature positive anomalies calculated in the cell i for the case study area and considered timeframe scenario 2000-2015; maxSSTanom = maximum number of Sea Surface Temperature positive anomalies calculated in the case study area and considered timeframe scenario 2000-2015.
Sea surface salinity regime variation	- Climate drivers.	Sea surface salinity anomalies in the reference scenario 2000-2015.	**Equation 8:** $Hs_{SSS} = \frac{\mathrm{TotSSSanom}_c}{\mathrm{maxSSSanom}}$ Where: Hs_{SSS}= sea surface salinity variation hazard score; $\mathrm{TotSSSanom}_c$= total number of sea surface salinity anomalies calculated in the cell i for the case study area and considered timeframe scenario 2000-2015; maxSSSanom = maximum number of Sea Surface Salinity anomalies calculated in the case study area and considered timeframe scenario 2000-2015.

🟩 Biological impacts	🟥 Physical impacts	🟦 Chemical impacts	🟨 Climatic impacts

Table 2 Selected hazards for the case study area with related driving forces, metrics and applied hazard equations for spatial modelling. Procedures applied for the spatial modelling are reported in the Supplementary Material, SM1

3.1.2 Exposure assessment

The exposure assessment phase aims to identify, select and localize key receptors (i.e. elements potentially at risk) and hot-spot areas characterized by high environmental and socio-economic value that could potentially be in contact with the considered hazard and, therefore, exposed to losses in affected marine areas. More specifically, this step allows the identification of all the receptors (i.e. r1, r2, r3,…, rn) to be considered in the geographic marine sub-region and for the selected timeframe; they can be chosen according to the objectives of the study, the spatial scale of the analysis and the available dataset. In this study, receptors were selected according to the availability of homogeneous GIS-based dataset for the area of concern and their environmental and socio-economic relevance for the selected case study. As a consequence the assessment was focused on valuable habitats such as seagrasses meadows and coral and maërl beds, both playing an important role as nursery areas for several species as well as for carbon regulation and fisheries (Salomidi et al., 2012; Savini et al., 2012). Moreover, according to their relevance in maintaining biodiversity in marine regions and support, in a well-connected network of multiple sites, functional ecological linkages such as larval and/or species exchanges (Gabrié C. et al., 2012; Agardy, 1994), protected areas located in the case study area, including marine protected areas, Site of Community Importance (CEC, 1992), zone of biological protection and nursery habitat, were included in the analysis. Finally, even though they represent a driver of pressure in marine areas, we also considered as target of the analysis the aquacultures (i.e. including mussel and fish farms), due to their high economic relevance in the Adriatic sea as a significant sources of income (Allison et al., 2009). However other relevant receptors could be considered in the assessment process (e.g. marine relevant mammals and fish species), but homogenous dataset were not available for the case study. Table reported in the Supplementary Material SM2 summarizes receptors considered in the analysis, also providing a brief description of their main environmental features and value in the area of concern.

In order to keep the highest feasible detail, according to the available dataset (Section 2.2), the exposure assessment was based on a spatial unit (i.e. grid cells) of 100m as applied in the hazard assessment phase (Section 3.1.1). An exposure score equal to 1 was assigned to cells where the receptor is located and equal to 0 in case of absence.

The exposure score is, therefore, evaluated as follows:

$$E = \begin{cases} 0 & \text{if no receptor is present in the investigated cell} \\ 1 & \text{else} \end{cases} \qquad \text{Equation 9}$$

Where:

$E =$ represents the exposure score related to the geographical area covered by the investigated marine receptors.

Equation 9 returns a value of 0 in the cell where no receptors are located whereas 1 where there is the presence of one or more overlapping receptors. The main output of this step is the exposure map showing the localization and geographic extent of all the investigated elements potentially at risk from multiple endogenic and exogenic pressures in the case study.

3.1.3 Vulnerability assessment

The third phase of the developed methodology is the vulnerability assessment aimed at evaluating the degree to which receptors could be adversely affected by the considered hazards, based on site-specific physical and environmental information (e.g. seabed typology, species diversity index, habitat extension, protection level, habitat connectivity). The choice of relevant vulnerability factors was performed based on scientific literature applying similar methodological approaches (Halpern et al., 2008; Rizzi et al., 2015; Micheli et al., 2013), also taking into account data constraints posed by the available dataset for the Adriatic sea case study (Section 2.2). For each considered hazard a set of vulnerability factors was selected in order to characterize environmental vulnerability of the area of concern to the analyzed pressures (Table 3).

	VULNERABILITY FACTORS							
HAZARDS	Seabed typology	Marine Protected Areas proximity-connectivity	Extension of coral and maërl beds	Extension of seagrasses	Seagrasses species richness	Shannon index	Aquaculture typology	Forbidden fishing areas
Smothering and sealing		▨	▨	▨				
Abrasion and extraction	▨	▨	▨	▨	▨			▨
Underwater noise		▨				▨		▨
SST variation	▨	▨	▨	▨		▨	▨	
SSS variation	▨	▨	▨	▨		▨	▨	
Input of organic matter	▨	▨	▨	▨	▨	▨		
Introduction of hazardous substances	▨	▨	▨	▨	▨	▨	▨	
Introduction of NIS	▨	▨	▨	▨	▨	▨	▨	

Table 3 Vulnerability factors VS hazards matrix
(SST: Sea Surface Temperature; SSS: Sea Surface Salinity; NIS: Non-indigenous species)

For instance, by considering the physical hazards (i.e. anthropogenic smothering and sealing and extractive technological hazards), vulnerability factors more related to the seabed features (where these kind of hazards mainly threaten) were selected (e.g. seabed typology extension of coral and maërl beds, extension of seagrasses). On the other side, vulnerability factors such as the ‘forbidding fishing areas' were associated to the physical hazards induced by underwater noise and extractive activities (including trawling fishing), since the presence or absence of specific regulations, can limit or not the shipping traffic (one of the main source of noise in marine areas) and extraction of resources on a marine areas.

Once vulnerability factors were selected for each hazard, they were then classified and scored, in a 0 to 1 range, following the qualitative linguistic evaluations reported in the Supplementary Material SM3. Scores were assigned at the case study level, according to expert judgement and literature review (Micheli et al., 2013; Salomidi et al., 2012; Astles et al., 2009; Halpern et al., 2008), in order to allow the process of integration of vulnerability scores, by the application of MCDA functions, in the relative risk estimate and provide a ranking of more vulnerable areas. However, they are flexible to be applied to other case studies characterized by similar physical and environmental features.

The results of this process are summarized in Table 4 reporting, for each selected factors, classes and scores considered during the application of the methodology in the Adriatic sea.

VULNERABILITY FACTORS	CLASS	SCORE	DESCRIPTION
Marine Protected Areas proximity-connectivity (km)	0 - 25.63	0,2	Spatial proximity was used as a proxy representing the connectivity within the Marine Protected Areas' network, which allows for linkages whereby protected sites benefit from larval and/or species exchanges, and functional linkages from other network sites. In a connected network individual sites benefit for one another (Gabrié C. et al., 2012).
	25.64 - 48.33	0,4	
	48.34 - 70.58	0,6	
	70.59 - 95.54	0,8	
	95.55 - 137.55	1	
Extension of seagrasses (Km^2)	0.02 - 6.01	1	Small seagrasses were considered to have higher vulnerability as they could be more vulnerable to natural and anthropogenic pressures than wider ones. Habitats have to be sufficiently large lo maintain their population, taking into account any threats of deterioration or loss of such habitats (Rizzi et al., 2015; EC 2008).
	6.02 - 27.37	0,6	
	27.38 - 103.75	0,2	
Shannon Index	1.39 - 2.62	1	Ecosystems with high Shannon index (high number of species) were considered to have lower vulnerability since they are characterized by a greater variety of interactions between species and, as a consequence, they are able to better maintain or restore its own balance (Gabrié C. et al., 2012).
	2.63 - 3.65	0,8	
	3.66 - 4.34	0,6	
	4.35 - 4.80	0,4	
	4.81 - 5.55	0,2	
Extension of coral and maërl beds habitats (Km^2)	0.07 - 17.79	1	As applied for seagrasses meadows, to smaller coral and maërl beds higher vulnerability score was assigned since habitats have to be sufficiently large lo maintain their population, taking into account any threats of deterioration or loss of such habitats. (EC, 2008).
	17.80 - 53.45	0,6	
	53.46 - 2014.49	0,2	
Aquaculture typology	Fish farms	0,6	Mussels were considered to be more vulnerable to changes in water biogeochemical and physical parameters as they act as filter feeders both on the water column and water sediments and, therefore, they are more vulnerable compared with fish (Rizzi et al., 2015).
	Mussel farms	1	

Forbidden fishing areas	Forbidden areas	0,2	Areas closed to fishing were considered with a moderate vulnerability since they result 'protected' by the presence of specific fishing regulation limiting, in some cases, the shipping traffic linked with this kind of activity as well as the resulting hazards (e.g. underwater noise, seabed abrasion).
	Not forbidden areas	0,5	
Seagrasses Species Richness	Very low richness (n° 1 of species)	1	Different seagrasses species vary in their tolerance and resilience to the changing of environmental conditions caused by both natural and anthropogenic pressures. As a consequence, to areas with higher seagrasses species richness a lower vulnerability score was associated due to the greater probability of finding an appropriate number of species able to withstand to adverse environmental conditions (Gabrié et al., 2012; Waycott et al., 2007).
	Low richness (n° 2 of species)	0,8	
	Medium richness (n° 3 of species)	0,6	
	High richness (n° 4 of species)	0,4	
	Very high richness (n° 5 of species)	0,2	

Table 4 Classes and scores associated to the vulnerability factors identified for the considered hazards in the Adriatic sea case study

Almost all the selected vulnerability factors were evaluated as hazard-independent (e.g. extension of seagrasses, Shannon Index) and, as a consequence, score associates to each class doesn't change depending on the considered hazard. Differently, concerning the factor related to the 'seabed typology' a specific vulnerability score was assigned to each typology according to the different hazards, as reported and explained in the Supplementary Material SM4 (Halpern et al., 2008; Micheli et al., 2013). After the normalization, vulnerability factors were then aggregated by applying the "probabilistic or" function (Kalbfleisch J. G, 1985), aimed at providing a single normalized score of physical and environmental vulnerability for each cell (i.e. pixel of raster map) and considered hazard in the area of concern, following the Equation 10:

$$V_h = \otimes_i^n [vf_i] \qquad \text{Equation 10}$$

Where:

V_h= physical and environmental vulnerability score, representing the predisposition of the marine environment to be affected by the considered hazard h;

$\otimes$= "probabilistic or" function (see Supplementary Material SM5);

vf_i = i^{th} physical and environmental vulnerability factor.

Resulting score ranges from 0 (i.e. no vulnerability) to 1 (i.e. higher vulnerability in the case study area) and is calculated cell by cell aggregating information from overlaid vulnerability factors for each selected hazard.

3.1.4 Relative risk assessment

The final step of the developed methodological approach is the relative risk assessment which allows to integrate information about the hazard with the receptors' exposure and vulnerability, in order to identify and prioritize areas and targets (i.e. key marine targets and hotspots) that could be at higher risk in the investigated area and timeframe (EC, 2008).

According to the IPCC (2014), the aggregation of hazard, exposure and vulnerability scores supports the assessment of risk in the case study, by applying the following general function (Equation 11):

$$R_h = f(H, E_j, V_h) \qquad \text{Equation 11}$$

Where:

$R_h =$ risk score related to the hazard of concern h;

$H =$ hazard score according to Equations 1-8 (Section 3.1.1);

$E_j =$ exposure score related to the presence/absence of the receptor j, according to Equation 9 (Section 3.1.2);

$V_h =$ physical and environmental vulnerability score of the investigated cell and related to the hazard of concern h, according to Equation 10 (Section 3.1.3).

The result of this step is a set of relative risk maps for the whole case study highlighting areas and targets more affected by multiple endogenic and exogenic risks, considering different hazards stressing the marine region of concern and related vulnerability. As for the other assessment phases, resulting risk score ranges from 0 to 1, in which 0 represent cells with risk null (i.e. there is no hazard or no physical and environmental vulnerability) whereas 1 the higher risk in the investigated area.

4. Results and discussion

The application of the aforementioned operative steps allowed to produce a wide array of GIS-based hazard, exposure, vulnerability and risk maps, as well as key risk indicators calculated for the whole case study and selected marine targets (e.g. extent of relevant habitat potentially affected by human activities, alterations of physical and chemical parameters). Hazard, vulnerability and risk scores, ranging in a continuous scale from 0 to 1, were classified by applying the Equal Interval classification method, allowing the division of scores into 5 equal sized classes (i.e. very low, low, medium, high and very high) (Zald et al., 2006), thus simplifying maps understanding and ensure comparability among resulting maps.

The following sections describe, for each step of the proposed procedure, the output obtained for the Adriatic sea case study (Section 4.1-4.4), underlining their utility against a planning and management perspective of marine areas and related natural resources.

4.1 Hazard maps

The implementation of the hazard assessment in the Adriatic sea case study (Section 3.1.1) has led to the development of eight GIS-based hazard maps (see all hazard maps in SM6), one for each considered hazard, representing potentially significant hazard scenarios, against which the marine environments and habitats need to adapt in order to maintain their ecological functions. Figure 3A represents the hazard maps related to the sea surface temperature (SST) variation, showing quite homogenous very high hazard scores (i.e. ranging from 0.8 to 1) for the whole case study area due to the high occurrence of unusually warm temperatures calculated in the selected reference scenario 2000-2015 (see procedure in SM1). It is well known that global warming is transforming the Mediterranean sea into a much different sea than it was only 20 years ago (CIESM, 2008; http://www.ciesm.org/online/monographs/Helgoland08_ExecSum.pdf) and the resulting hazard map for the SST variation highlights this increasing warm up of the considered area. However, has to be underlined that the resulting hazard score is strictly connected with the methodological approach selected for the normalization of the final hazard indicator linked with the SST variation, which envisages to normalize the total number of positive anomalies calculated for each cell of the case study area (and considered time window) for the maximum number of positive anomalies detected in the case study (Supplementary Material ‘SM1’). Others normalization methodologies could lead to different resulting output and related hazard scores. However, this methodological choice was performed in order to align this normalization approach to the other ones applied to the others hazards considered in this study, as reported in the SM1 (e.g. input of organic matter, introduction of Non-Indigenous Species).

Finally, since the methodology applied for the evaluation of changes in sea surface temperature (SST) is based on the approach developed by Halpern et al. (2008), the resulting hazard map for the Adriatic sea assumes a similar pattern compared with the ‘sea temperature changes (SST)’ map realized at the global scale (Halpern et al., 2008), with very high hazard values mainly focused along the Italian shelf.

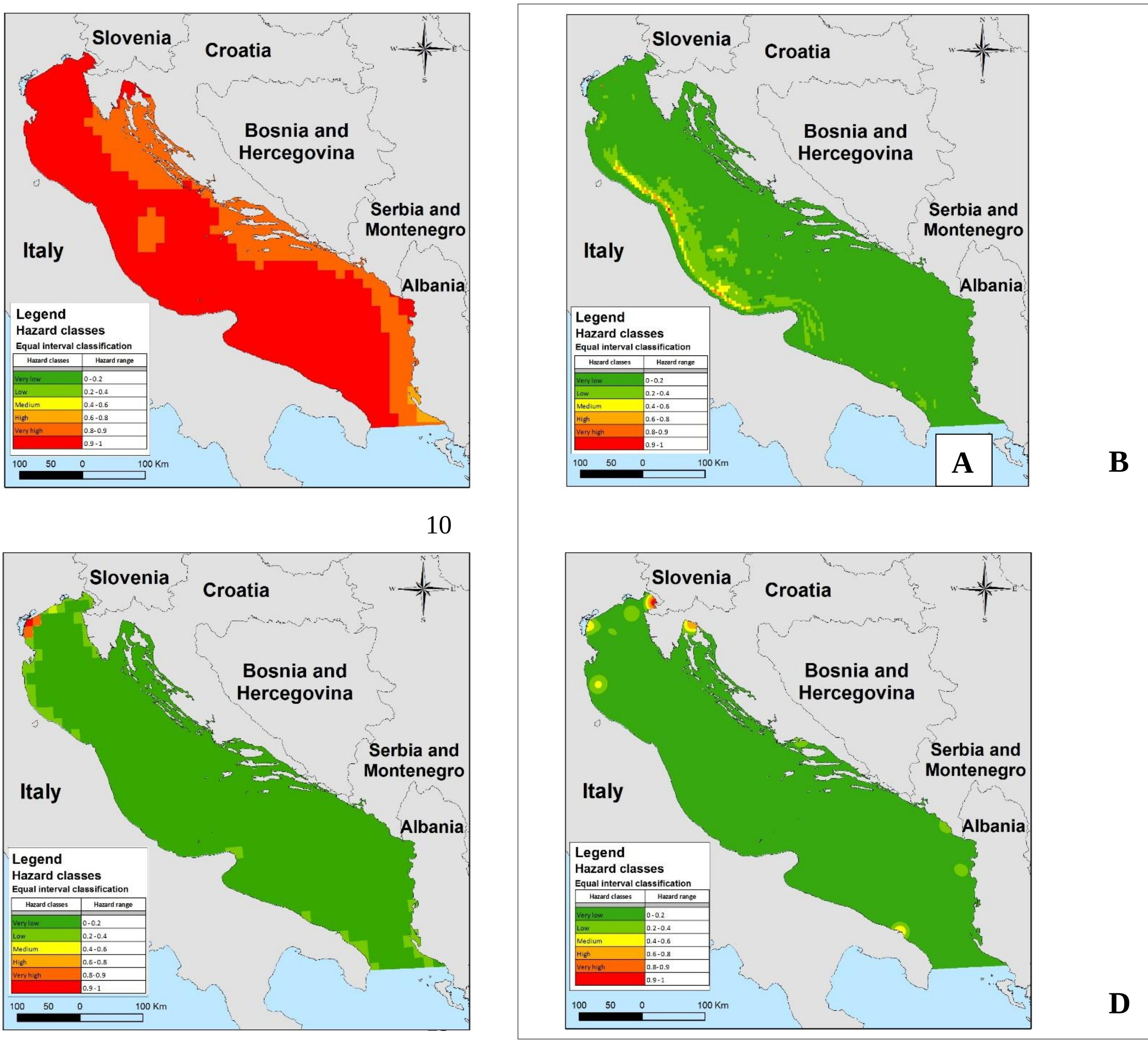

Figure 3 Example of hazard maps produced for the Adriatic sea case study representing: hazard of SST variation (A), abrasion of seabed (B), biological disturbance by the introduction of non-indigenous species (C), chemical hazard by oil-spills (D).

As far as the physical hazard induced by the abrasion and extraction of resources from the seabed is concerned, figure 3B shows higher scores (i.e. ranging from 0.6 to 1) limited in the western-central part of the Adriatic Sea caused by the high exploitation of the area for trawling fishing, unlike the North Adriatic sea where severe restrictions limit this activity in the area.

Analysing figure 3C, representing the biohazard related to the introduction of non-indigenous species, very high hazard scores (i.e. ranging from 0.8 to 1) can be observed in the North Adriatic sea mainly due to the massive maritime traffic around the port of Venice and the numerous aquaculture activities, recognized as the main forcing of this pressure (ISPRA, 2012b). Even though the supporting dataset and the implemented methodology diverges from those applied by Halpern et al. (2008) at the global scale and Micheli et al. (2013) within the Mediterranean sea, the same hot-spot with higher hazard scores can be detected in the north Adriatic sea as well as in the marine area close to the Apulia region (i.e. southern part of the Adriatic sea).

Finally, by considering the anthropogenic acute chemical hazard by oil-spills during shipping accidents (see procedure in SM1) (figure 3D), higher hazard scores (i.e. ranging from 0.4 to 1) are located in the North Adriatic sea, close to the port of Trieste, where numerous shipping accidents have been occurred in the 1977-2014 timeframe (IMO/UNEP, 2011; http://accidents.rempec.org/). Also in this case, the resulting hazard map presents the same spatial distribution compared with that developed by Micheli et al. (2013) for the Mediterranean sea (i.e. higher score corresponding to areas linked with the higher number of oil-releasing accidents within the considered time-window), due to the applied simplified plume modelling technique (see procedure in SM1) to distribute the quantities of released oil into the surrounding ocean waters (Micheli et al., 2013).

In order to support the cross comparison of results of this phase, based on the developed hazard maps a bar chart comparing the percentage of surface of the case study included in each hazard class (Figure 4) was produced.

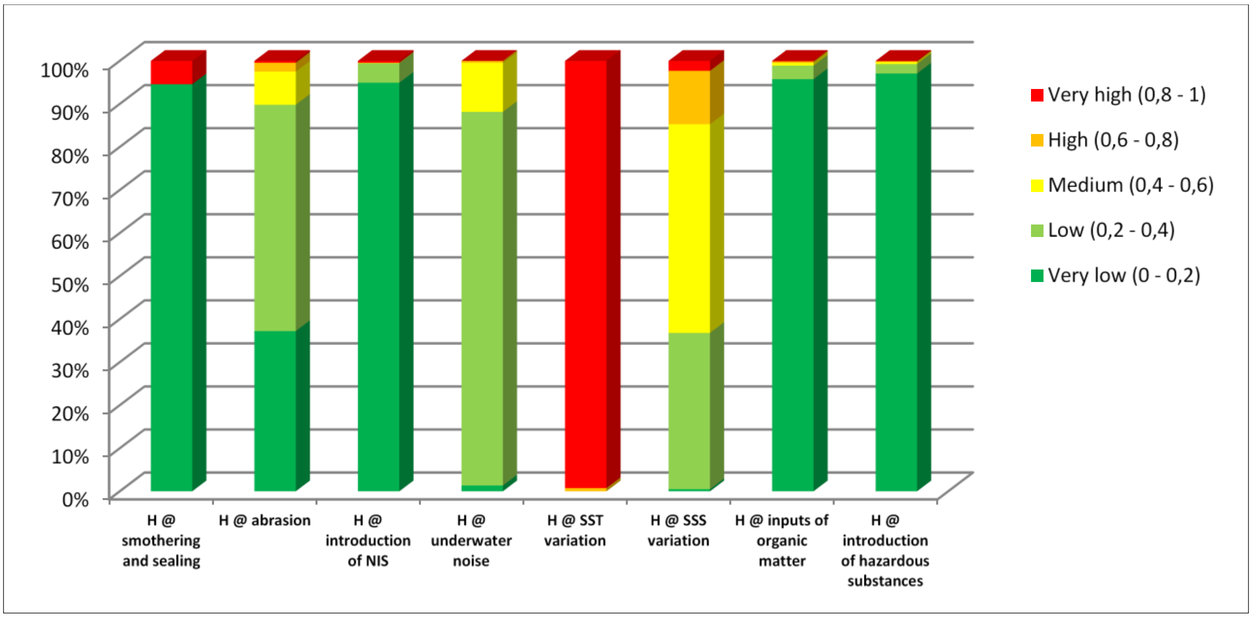

Figure 4 Bar chart representing the percentage of surface of the Adriatic sea case study included in each hazard class for all the considered pressures

The graph shows that the main hazard for the Adriatic sea is represented by the SST variation, with almost all the surface of the case study included in the very high hazard class (i.e. ranging from 0.8 to 1). High scores can be observed also for the other considered exogenic pressure related to the salinity regime variation (SSS) where more than 40% of the considered marine area is included in the higher hazard classes (i.e. ranging from 0.6 to 1). Finally, lower percentage of surface of the case study included in the higher hazard classes (i.e. ranging from 0.6-1) were detected for the endogenic pressures (e.g. abrasion, smothering and sealing of the seabed, introduction of hazardous substances) which severely affect more delimited areas in the Adriatic sea case study.

Hazard maps may facilitate the communication to potential end-users (e.g. policy makers, planners) about the most significant sources of hazard in the region and their spatial pattern, thus increasing knowledge and awareness on main environmental issues which need to be faced in the area of concern. Drawing on this, they represent a valuable support for addressing management decisions towards more sustainable alternative solutions, able to reduce potential hazards in areas already affected by the presence of multiple and overlapping pressures. Finally, hazard maps can be used by public authorities implementing EU's and International directives' requirements by supporting the assessment of different indicators of pressures (e.g. alterations of physical and chemical parameters, bottom stress) (EC, 2010), as well evaluating progress toward the improvement of the environmental quality in the Adriatic sea.

4.2 Exposure map

The exposure map produced by implementing the aforementioned procedure in Section 3.1.2 allowed the identification and spatial localization of receptors (i.e. elements at risk) that can be subject to potential losses and damages due to the considered hazards. Figure 5 shows the exposure map for the Adriatic sea case study considering as main elements at risk the marine environment of the Adriatic sea as a whole (blue boundary) and as hotspots targets: the seagrasses meadows (filled green pattern), coral and maërl beds (filled red pattern), protected areas (filled pattern with oblique pink lines) and aquacultures (filled yellow pattern).

Seagrasses and coral and maërl beds are mainly located close to the Italian coast (i.e. Veneto and Friuli Venezia region in the Northern part and the Apulia region and the southern one) and represent about the 2% of the case study, whereas aquacultures are mostly focused in the Northern Adriatic sea (i.e. Italy, Slovenia and Croatia). As showed in zoom in Figure 5A and 5B, most of the seagrasses and coral and maërl beds overlap with the marine protected areas established in the Adriatic sea, respectively the 30% and 99% of the related surface, underling complex and fragile ecosystems requiring specific protection status for their conservation.

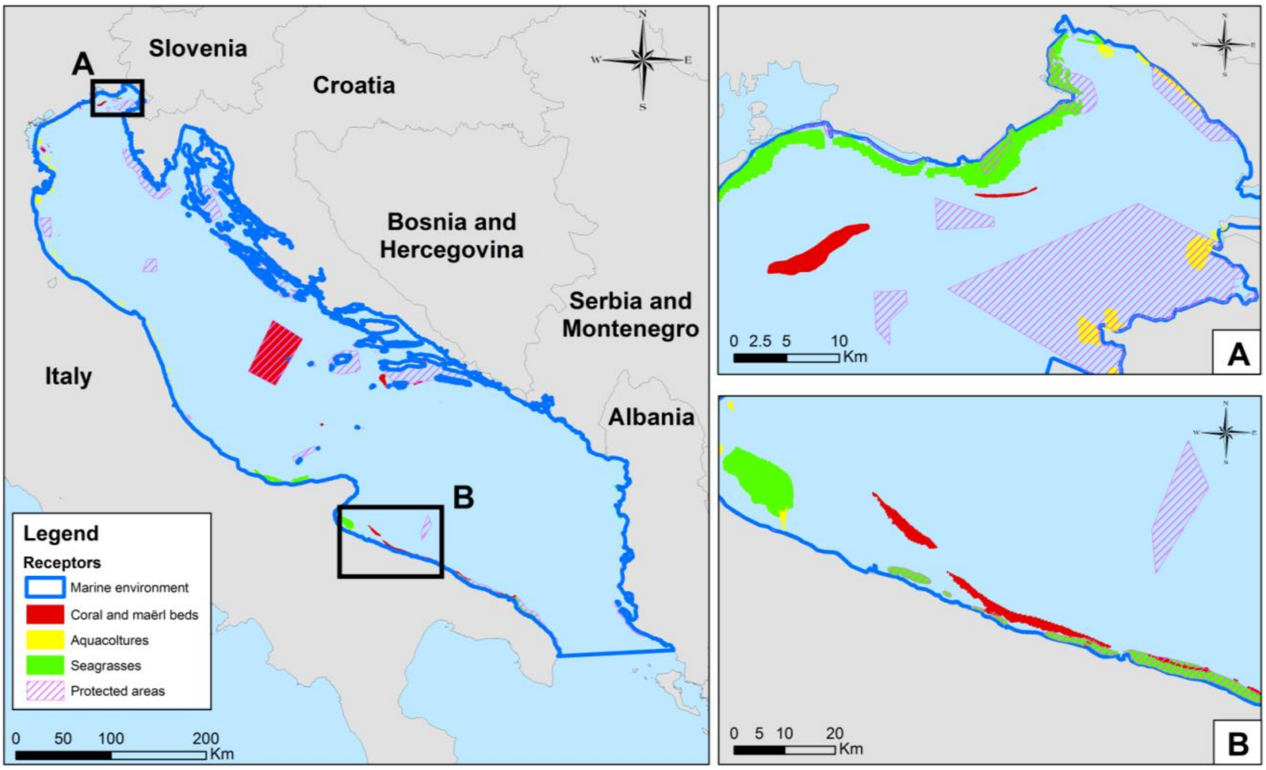

Figure 5 Exposure map identifying receptors for the Adriatic sea case study area

4.3 Vulnerability maps

The final output of the vulnerability assessment is represented by the vulnerability maps (SM7), evaluating the degree to which receptors could be adversely affected by the investigated hazards based on site-specific bio-physical and environmental features. As for the hazard maps, vulnerability maps were classified using the Equal Interval classification method setting the entire vulnerability values' range (i.e. from 0 to 1) in five categories equal in size (Zald et al., 2006). As can be observed in Figure 6, representing the vulnerability to SST variation (Figure 6A), abrasion of seabed (Figure 6B), biological disturbance by the introduction of non-indigenous species (Figure 6C) and to the underwater noise (Figure 6D), vulnerability scores assume homogenous relatively very high values in the whole case study depending on the considered factors and scores assigned to related classes. Results of the vulnerability assessment are summarized by the bar chart in Figure 7 representing the percentage of surface of the case study included in each vulnerability classes for the eight considered pressures. Almost all the developed maps show very high vulnerability values varying between 0.8 to 1. More specifically, the analysed marine environment presents higher vulnerability to climate-related hazards (e.g. sea surface temperature variation) as well as chemical ones (e.g. introduction of hazardous substances and input of organic matter) with more than 95% of the considered area included in higher vulnerability classes. Lower and more heterogeneous values can be observed for the vulnerability to the smothering and sealing of seabed with about the 40% of the case study area included in the high and very high classes (i.e. 0.8 to 1) and the remaining 60% in classes with lower vulnerability.

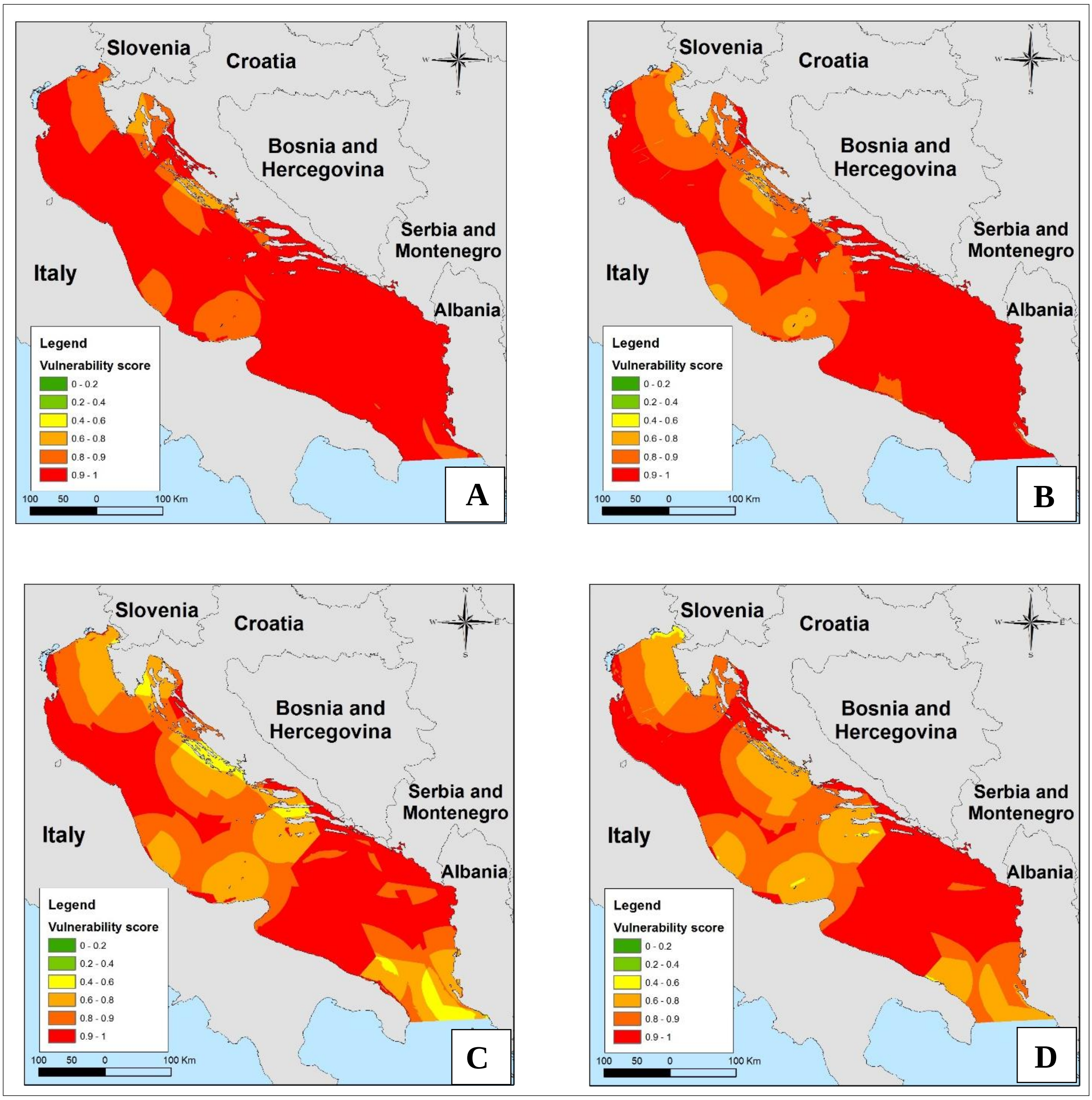

Figure 6 Example of vulnerability maps produced for the Adriatic sea case study representing: vulnerability to SST variation (A), abrasion of seabed (B), biological disturbance by the introduction of non-indigenous species (C), underwater noise (D).

Vulnerability maps and related statistics provide an overall picture of the vulnerability of the analysed marine ecosystem and related receptors to the multiple considered hazards. Vulnerability maps (including the related vulnerability factors maps) are GIS-based and, as a consequence, they are all georeferenced with the same geographic coordinate system, thus allowing to perform specific ‘overlap analysis’ aimed at identifying which factors have the most influence to increase the vulnerability of an area, thus providing valuable information for a more robust science-based decision making. More specifically, these kind of maps can support marine planner and managers designing and implementing management tools and nature-based solutions aimed at increasing the resilience of vulnerable targets to the considered impacts.

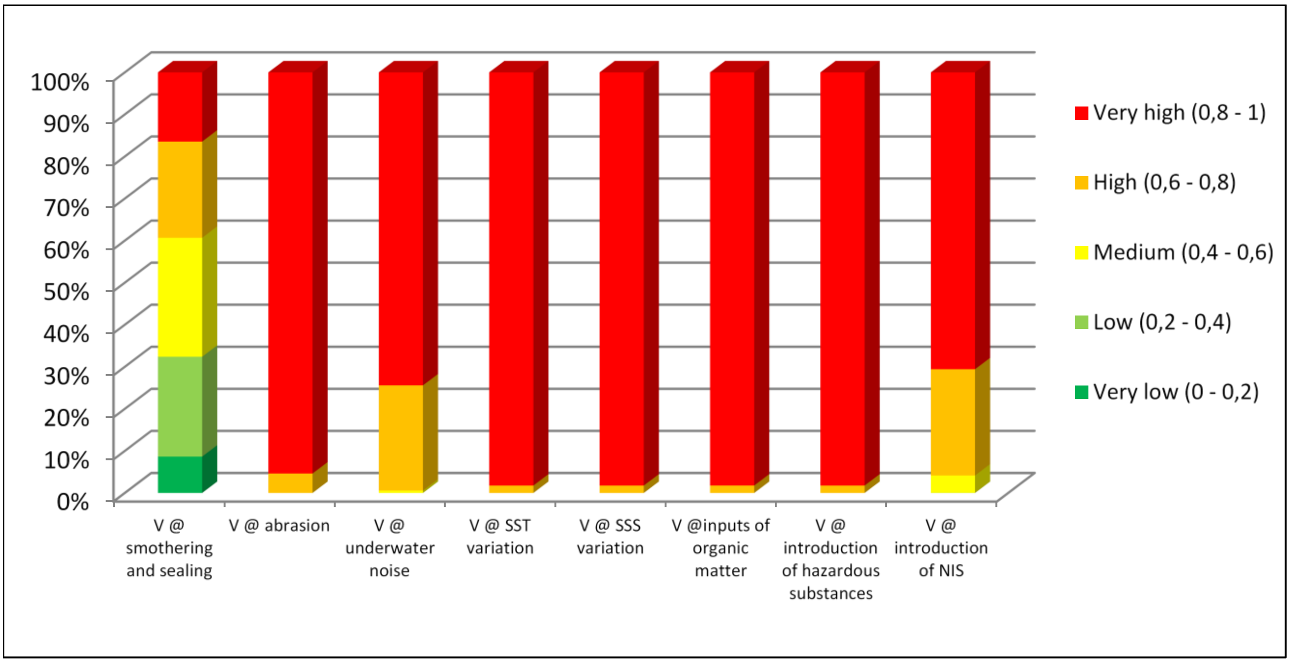

Figure 7 Bar chart representing the percentage of surface of the Adriatic sea case study included in each vulnerability classes for the considered hazards

These actions can include, for instance, the establishment of new Marine Protected Areas providing a focal area for protecting relevant ecosystems such as salt marshes and seagrass beds, as well as for monitoring environmental conditions and trends, acting in this was as ‘sentinel sites’ of changes. When appropriately placed and managed, Marine Protected Areas can contribute on conserving biological diversity, restoring fish populations and protecting relevant spawning areas and nursery habitats (Halpern, 2010; Selig & Bruno, 2010). A well-planned and functionally connected Marine Protected Areas network can provide benefits that go beyond those of a single area, acting as a corridor for shifting species and habitats, thus maximizing ecological connectivity between single Marine Protected Areas and serving to increase protection for marine resources (NOAA, 2013; IUCN-WCPA, 2008). Other solutions for increasing resilience of marine habitat can also include the widespread transplantations of submerged seagrasses representing an important carbon sink, helping to mitigate climate-related impacts. Seagrasses meadows contribute to improve water transparency and quality through trapping and storing solids particles and dissolved nutrients (Short aet al., 2007) and they can attenuate physical impacts influencing the hydrodynamic environment through reducing current velocity, dissipating wave energy and stabilizing the sediment (Ondiviela et al., 2014).

4.4 Relative risk maps

The implemented risk assessment phase has led to the development of eight relative risk maps (SM8) classified using the Equal Interval method of classification (i.e. very low, low, medium, high, very high) (Zald et al., 2006), as applied in the other assessment phases.

According to the Equation 11 (Section 3.1.4) risk maps show significant spatial variations in the case study area, mainly due to the spatial localization and intensity of human activities in the Adriatic sea, since vulnerability assumes quite homogeneous maximum value equal to 1 for almost all the considered pressures. These results are further proved by the bar chart in Figure 8A representing the percentage of surface of the Adriatic sea case study included in each risk classes for all the considered pressures. Can be observed that risk generally assumes lower values than the hazard ones represented in the bar chart in Figure 4, as they are multiplied by vulnerability (i.e. scores ranging in 0-1), however the same trend of hazard is visible. Accordingly, risk related to SST variation represents the major risk for the whole case study, with nearly the 90% of surface included in the higher risk class (i.e. 0.8-1), followed by the risk to SSS variation with a little less than the 40% of surface within the moderate and very high classes (i.e. 0.4-1). Lower values can be observed for the other endogenic pressures (e.g. abrasion, smothering and sealing of the seabed, introduction of hazardous substances), which severely affect (i.e. risk classes ranging from 0.6-1) more limited areas in the Adriatic sea case study (i.e. always less than the 4% of surface).

As a consequence, focusing the analysis on the selected targets (i.e. seagrasses, coral and maërl beds, aquacultures and protected areas) (Figure 8B), the risk assessment indicates that they could be all severely affected by the SST variation, especially as baseline will move due to climate change leading to more numerous and intense unusually warm condition. Higher values are assumed also by the receptor ‘aquacultures’ to risk concerning the input of organic matter and the introduction of non-indigenous species (NIS), mainly due to the straight link of this economic activity with the two considered risk, as main driver of related pressures.

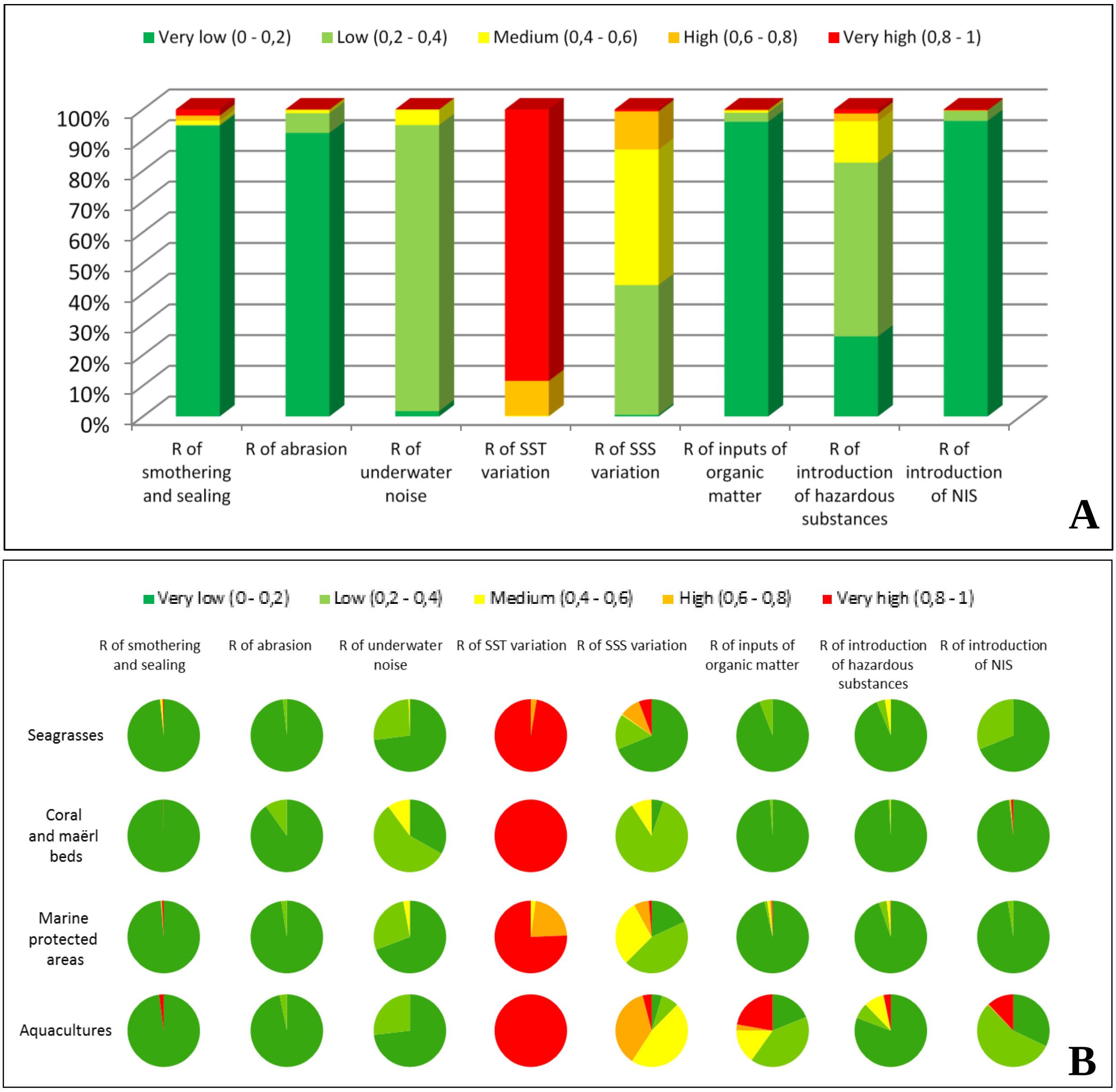

Figure 8 A) Bar chart representing the percentage of surface of the Adriatic sea case study included in each risk classes for the considered hazards; B) Pie chart representing the percentage of surface of receptors (i.e. seagrasses, coral and maërl beds, marine protected areas, aquacultures) included in each risk classes for the considered hazards

By integrating hazard with exposure and susceptibility, relative risk maps allow a quick screening of areas and receptors at greatest risk from multiple human-made and natural stressors. They can be effectively used by planners and policy makers for the design of science-based policies and management measures of marine areas, that consider spatially relevant issues and are consistent with the objectives of a more sustainable use and organization of marine spaces and related natural resources . By ranking more potentially affected targets, risk maps can support local public authorities to set priorities in maritime spatial planning and management, focusing economic efforts on more urgent actions. More specifically, they can back the development and implementation of integrated policies and plans aimed on one side at managing the conflicting uses of the sea thus reducing endogenic pressures (e.g. limit the shipping traffic on specific areas featured by vulnerable marine organisms), on the other side accommodating changes produced by exogenic unmanaged pressures (i.e. climate change) acting at the effective management scale on causes (need to be addressed locally) and consequences (require global action with mitigation strategies) (Patrício et al., 2014). Finally, by analysing risks induced by land-based drivers, which inevitably affect the sea (i.e. rivers discharge of nutrients and eutrophication-inducing substances), risk maps can be also used for addressing territorial planning and the development of new infrastructures (e.g. build of wastewater treatment plants), in order to reduce pressures on the sea and improve a land-sea interface planning and management.

5. Conclusion

Integrating climate pattern with socio-economic and environmental information of the considered marine area, the proposed multi-hazard methodology allows to develop a set of environmental relative risk scenarios, thus supporting a semi-quantitative evaluation and relative ranking of areas and targets potentially affected by multiple risks in the considered marine basin.

The approach is suitable and flexible to be applied in different marine regions even if featured by diverging combinations and levels of intensity of endogenic and exogenic pressures, as well as environmental and socio-economic conditions (e.g. Bosphorus strait, Mediterranean and Black sea).

Multiple timeframe scenarios can be explored by applying the same methodological risk-based framework, supporting to evaluate the potential effects of medium and long-term climate change projections for multiple parameters affecting the environmental quality of marine areas. Indeed, the development of risk maps is part of an iterative process that is expected to progressively improve by considering different hazard scenarios (e.g. hazard of oceans' acidification, hypoxia), extending the analysis to longer term timeframes, relevant for planning and management purposes (e.g. 2035-2050, 2070-2100) and including other and more detailed targets and vulnerability factors as more research on environmental and anthropogenic data is available. Moreover, the developed analysis can be easily up-scaled to evaluate the consequences of multiple pressures at a broader regional scale (e.g. Mediterranean scale) as well as down-scaled by improving the assessment with more detailed dataset. Finally, the methodology can be enhanced by fine-tuning vulnerabilities and hazards' spatial mapping by using new advanced modelling approaches (also taking into account the 3D dimension of the sea), as well as by integrating in the assessment dataset with higher spatial resolution acquired through direct measurements (and provided by local authorities), allowing to better represent local environmental dynamics (e.g. enrichment of nutrients and organic matter due to river discharge) and make more reliable and verifiable the resulting output of the assessment.

However, the proposed approach presents some limitations mainly related to the methodological assumptions and the use of experts' judgment applied during the assignation of scores in the vulnerability assessment phase that can be considered too simplistic for potential end-users to trust the reliability of the results of the analysis. For overcoming this limit, different setting of scenarios and scores for the same case study can be defined (sensitive analysis), comparing (and validating) the results of the assessment with reference data (i.e. historical monitoring data, field measurements, time-series) or across comparable studies performed in the same marine region and time slice by applying other impact assessment methods, spatial modelling approaches or analytical tools.

Moreover, the performed assessment captures a snapshot in time based on recent environmental and anthropogenic conditions (i.e. reference scenario 2000- 2015) of the marine area of concern, leaving aside the evaluation of more complex future climate change scenarios, although it is well known how climate change will affect seas and oceans in near and long-term futures (IPCC, 2014), acting as '*force majeure*' able to influence or inhibits the effective implementation of planning options. To be effective, marine strategies and policies need to identify ways of adapting to the effects of global warming and to reduce the vulnerability of natural ecosystem to climate change effects (EC, 2008). Accordingly, future climate change scenarios need to be evaluated in order to provide planners and policy makers credible risk ad vulnerability maps, against designing suitable plans ad projects, as well as long-term programmes and visions able to adapt to changes over time.

Finally, so far the developed risk-based approach doesn't account for more complex cause-effect interactions among endogenic and exogenic pressures acting in concert on the same target in an interactive fashion (i.e. additive, antagonistic or synergic) (Brown et al., 2014; Crain et al., 2008). In this context further work is needed for developing novel approaches and models (e.g. more accurate ecological models coupling vulnerability of marine ecosystem to pressures; advanced methods simulating cascading and triggering effects due to synergic/antagonistic pressures) to predict, assess and understand changes induced by the interaction among all factors contributing to exacerbate cumulative impacts (i.e. multiple linked endogenic and exogenic pressures, rising vulnerability of marine habitat), in order to develop and implement new plans and policies leading to multifaceted and cross-sectorial benefits.

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Bibliography

Agardy, M. T. (1994). Advances in marine conservation: the role of marine protected areas. *Trends in Ecology & Evolution*, *9*(7), 267–270.

Allison, E. H., Perry, A. L., Badjeck, M., Neil Adger, W., Brown, K., Conway, D., … Andrew, N. L. (2009). Vulnerability of national economies to the impacts of climate change on fisheries. *Fish and Fisheries*, *10*(2), 173–196.

Andersen, J., Stock, A., Heinänen, S., Mannerla, M., & Vinther, M. (2013). *Human uses, pressures and impacts in the eastern North Sea*. Aarhus University, DCE-Danish Centre for Environment and Energy.

Andersen, M. C., Thompson, B., & Boykin, K. (2004). Spatial risk assessment across large landscapes with varied land use: lessons from a conservation assessment of military lands. *Risk Analysis*, *24*(5), 1231–42. http://doi.org/10.1111/j.0272-4332.2004.00521.x

Astles, K. L., Gibbs, P. J., Steffe, A. S., & Green, M. (2009). A qualitative risk-based assessment of impacts on marine habitats and harvested species for a data deficient wild capture fishery. *Biological Conservation*, *142*(11), 2759–2773. http://doi.org/10.1016/j.biocon.2009.07.006

Ban, N. C., Alidina, H. M., & Ardron, J. a. (2010). Cumulative impact mapping: Advances, relevance and limitations to marine management and conservation, using Canada’s Pacific waters as a case study. *Marine Policy*, *34*(5), 876–886. http://doi.org/10.1016/j.marpol.2010.01.010

Borja, Á., Elliott, M., Carstensen, J., Heiskanen, A.-S., & van de Bund, W. (2010). Marine management – Towards an integrated implementation of the European Marine Strategy Framework and the Water Framework Directives. *Marine Pollution Bulletin*, *60*(12), 2175–2186. http://doi.org/10.1016/j.marpolbul.2010.09.026

Brown, C. J., Saunders, M. I., Possingham, H. P., & Richardson, A. J. (2014). Interactions between global and local stressors of ecosystems determine management effectiveness in cumulative impact mapping. *Diversity and Distributions*, *20*(5), 538–546. http://doi.org/10.1111/ddi.12159

CEC. (1992). Council Directive 92/43/EEC on the conservation of natural habitats and of wild fauna and flora, (April 1979), 1–52.

CIESM. (2008). Climate warming and related changes in Mediterranean marine biota. CIESM Workshop Monographs, (May), 27–31.

Cormier, R., Kannen, A., Nin, B. M., Davies, I., Greathead, C., Diedrich, A., … Sardá, R. (2010). Risk-based frameworks in ICZM and MSP decision-making processes. ICES CM 2010/B:07.

Crain, C. M., Halpern, B. S., Beck, M. W., & Kappel, C. V. (2009). Understanding and Managing Human Threats to the Coastal Marine Environment. *Annals of the New York Academy of Sciences*, *1162*(1), 39–62. http://doi.org/10.1111/j.1749-6632.2009.04496.x

Crain, C. M., Kroeker, K., & Halpern, B. S. (2008). Interactive and cumulative effects of multiple human stressors in marine systems. *Ecology Letters*, *11*(12), 1304–15. http://doi.org/10.1111/j.1461-0248.2008.01253.x

Douvere, F., & Ehler, C. N. (2009). New perspectives on sea use management: initial findings from

European experience with marine spatial planning. *Journal of Environmental Management*, *90*(1), 77–88. http://doi.org/10.1016/j.jenvman.2008.07.004

EC. (2008). Directive 2008/56/EC of the European Parliament and of the Council of 17 June 2008 establishing a framework for community action in the field of marine environmental policy (Marine Strategy Framework Directive)., 19–40.

EC. (2010). Commission Decision 2010/477/EU of 1 September 2010 on criteria and methodological standards on good environmental status of marine waters (notified under document C(2010) 5956)., (2008), 14–24.

EC. (2011). The potential of Maritime Spatial Planning in the Mediterranean Sea. Case study report : The Adriatic Sea.

EC. (2014). Directive 2014/89/EU of the European Parliament and of the Council of 23 July 2014 establishing a framework maritime spatial planning., *2014*(April), 135–145.

EEA (European Environment Agency). (2015). *The European environment — state and outlook 2015 — synthesis report*. Retrieved from http://www.eea.europa.eu/soer-2015/synthesis/report/table-of-contents

Ehler, C., & Douvere, F. (2009). Marine Spatial Planning: a step-by-step approach toward ecosystem-based management, (53).

Elliott, M. (2013). The 10-tenets for integrated, successful and sustainable marine management. *Marine Pollution Bulletin*, *1*(74), 1–5.

Elliott, M., Borja, Á., McQuatters-Gollop, A., Mazik, K., Birchenough, S., Andersen, J. H., … Peck, M. (2015). Force majeure: Will climate change affect our ability to attain Good Environmental Status for marine biodiversity? *Marine Pollution Bulletin*, *95*(1), 7–27. http://doi.org/10.1016/j.marpolbul.2015.03.015

Gabrié C., Lagabrielle E., Bissery C., Crochelet E., Meola B., Webster C., Claudet J., Chassanite A., Marinesque S., Robert P., G. M. (2012). *The Status of Marine Protected Areas in the Mediterranean Sea*.

Galgani, F., Hanke, G., Werner, S., & De Vrees, L. (2013). Marine litter within the European Marine strategy framework directive. *ICES Journal of Marine Science: Journal Du Conseil*, *70*(6), 1055–1064.

Grech, a., Coles, R., & Marsh, H. (2011). A broad-scale assessment of the risk to coastal seagrasses from cumulative threats. *Marine Policy*, *35*(5), 560–567. http://doi.org/10.1016/j.marpol.2011.03.003

Halpern, B. S. (2003). The Impact of Marine Reserves : Do Reserves Work and Does Reserve Size Matter ? *Society, Ecological Applications, Ecological*, *13*(1).

Halpern, B. S., Walbridge, S., Selkoe, K. a, Kappel, C. V, Micheli, F., D’Agrosa, C., … Watson, R. (2008). A global map of human impact on marine ecosystems. *Science (New York, N.Y.)*, *319*(5865), 948–52. http://doi.org/10.1126/science.1149345

Hayes, E. H., & Landis, W. G. (2004). Regional Ecological Risk Assessment of a Near Shore Marine Environment: Cherry Point, WA. *Human and Ecological Risk Assessment: An International Journal*, *10*(2), 299–325. http://doi.org/10.1080/10807030490438256

Hunsaker, C. T., Graham, R. L., Suter II, G. W., O'Neill, R. V, Barnthouse, L. W., & Gardner, R. H. (1990). Assessing ecological risk on a regional scale. *Environmental Management*, *14*(3), 325–332.

IMO/UNEP. (2011). Regional Information System; Part C2, Statistical Analysis - Alerts and Accidents Database, REMPEC, February 2011.

IPCC. (2014). Summary for Policy Makers. *Summary for Policymakers. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B.*, , 1–32. http://doi.org/10.1016/j.renene.2009.11.012

ISPRA. (2012a). Strategia per l'ambiente marino. Valutazione iniziale. Sottoregione mar Adriatico. Danno fisico. Documenti per la consultazione pubblica del 2012. Bozza, 10 Maggio 2012.

ISPRA. (2012b). Strategia per l'ambiente marino. Valutazione iniziale. Sottoregione mar Adriatico. Specie non indigene + inventario. Documenti per la consultazione pubblica del 2012. Bozza, 10 Maggio 2012.

IUCN-WCPA. (2008). *Establishing Marine Protected Area Networks—Making It Happen. Washington, D.C.: IUCN-WCPA, National Oceanic and Atmospheric Administration and The Nature Conservancy. 118 p.*

Kalbfleisch J. G. (1985). Probability and Statistical Inference: Volume 1: Probability. *Springer Texts in Statistics-Sep 9, 1985.*

Kappel, C. V, Halpern, B. S., & Napoli, N. (2012). Mapping Cumulative Impacts of Human Activities on Marine Ecosystems. *Coastal and Marine Spatial Planning. Research Report #03.NCEAS.12*, (January).

Kenny, A. J., Skjoldal, H. R., Engelhard, G. H., Kershaw, P. J., & Reid, J. B. (2009). An integrated approach for assessing the relative significance of human pressures and environmental forcing on the status of Large Marine Ecosystems. *Progress in Oceanography*, *81*(1), 132–148.

Korpinen, S., Meski, L., Andersen, J. H., & Laamanen, M. (2012). Human pressures and their potential impact on the Baltic Sea ecosystem. *Ecological Indicators*, *15*(1), 105–114. http://doi.org/10.1016/j.ecolind.2011.09.023

Lamon, L., Rizzi, J., Bonaduce, A., Dubois, C., Lazzari, P., Ghenim, L., … Canu, D. M. (2014). An ensemble of models for identifying climate change scenarios in the Gulf of Gabes, Tunisia. *Regional Environmental Change*, *14*(1), 31–40.

Landis, W. G. (2004). *Regional scale ecological risk assessment: using the relative risk model*. CRC Press.

Lovato T., Vichi M., O. P. (2013). High resolution simulations of Mediterranean Sea physical oceanography under current and scenario climate conditions: model description, assessment and scenario analysis. *Research Papers, Issue RP0207*, (December 2013).

Micheli, F., Halpern, B. S., Walbridge, S., Ciriaco, S., Ferretti, F., Fraschetti, S., … Rosenberg, A. a. (2013). Cumulative human impacts on Mediterranean and Black Sea marine ecosystems: assessing current pressures and opportunities. *PloS One*, *8*(12), e79889. http://doi.org/10.1371/journal.pone.0079889

Millot, C., & Taupier-Letage, I. (2005). Circulation in the Mediterranean sea. *The Mediterranean Sea*, 323–334.

NOAA. (2013). Marine Protected Areas Building Resilience To Climate Change Impacts.

Oddo, P., Bonaduce, A., Pinardi, N., & Guarnieri, A. (2014). Sensitivity of the Mediterranean Sea level to atmospheric pressure and free surface elevation numerical formulation in NEMO. *Geoscientific Model Development*, *7*(6), 3001–3015. http://doi.org/10.5194/gmd-7-3001-2014

Okey, T. a., Agbayani, S., & Alidina, H. M. (2015). Mapping ecological vulnerability to recent climate change in Canada's Pacific marine ecosystems. *Ocean & Coastal Management*, *106*, 35–48. http://doi.org/10.1016/j.ocecoaman.2015.01.009

Ondiviela, B., Losada, I. J., Lara, J. L., Maza, M., Galván, C., Bouma, T. J., & van Belzen, J. (2014). The role of seagrasses in coastal protection in a changing climate. *Coastal Engineering*, *87*, 158–168. http://doi.org/10.1016/j.coastaleng.2013.11.005

Patrício J., Teixeira H., Borja A., Elliott M., Berg T., Papadopoulou N., Smith C., Luisetti T., Uusitalo L., Wilson C., Mazik K., Niquil N., Cochrane S., Andersen J.H., Boyes S., Burdon D., Carugati L., Danovaro R., H. N. (2014). DEVOTES recommendations for the implementation of the Marine Strategy Framework Directive. Deliverable 1.5, 71 pp. DEVOTES project. JRC92131.

Ramieri E., Andreoli E., Fanelli A., Artico, B. R. (2014). Methodological handbook on Maritime Spatial Planning in the Adriatic Sea. Final report of Shape Project WP4 "Shipping Towards Maritime Spatial Planning", issuing date: 10 February 2014. Printed by Veneto Region.

Rizzi, J., Torresan, S., Critto, A., Zabeo, A., Brigolin, D., Carniel, S., … Marcomini, A. (2015). Climate change impacts on marine water quality: The case study of the Northern Adriatic sea. *Marine Pollution Bulletin*. http://doi.org/10.1016/j.marpolbul.2015.06.037

Rizzi, J., Torresan, S., Zabeo, A., Critto, A., Tosoni, A., Tomasin, A., & Marcomini, A. (2017). Assessing storm surge risk under future sea-level rise scenarios: a case study in the North Adriatic coast. *Journal of Coastal Conservation*, 1–19.

Ronco, P., Bullo, M., Torresan, S., Critto, A., Olschewski, R., Zappa, M., & Marcomini, A. (2015). KULTURisk regional risk assessment methodology for water-related natural hazards–Part 2: Application to the Zurich case study. *Hydrology and Earth System Sciences*, *19*(3), 1561–1576.

Salomidi, M., Katsanevakis, S., Borja, Á., Braeckman, U., Damalas, D., Galparsoro, I., … Pipitone, C. (2012). Assessment of goods and services, vulnerability, and conservation status of European seabed biotopes: a stepping stone towards ecosystem-based marine spatial management. *Mediterranean Marine Science*, *13*(1), 49–88.

Savini, A., Basso, D., Bracchi, V., Corselli, C., & Pennetta, M. (2012). Maerl-bed mapping and carbonate quantification on submerged terraces offshore the Cilento peninsula (Tyrrhenian Sea, Italy). *Geodiversitas*, *34*(1), 77–98.

Selig, E. R., & Bruno, J. F. (2010). A Global Analysis of the Effectiveness of Marine Protected Areas in Preventing Coral Loss. *PLoS ONE*, *5*(2), e9278. http://doi.org/10.1371/journal.pone.0009278

Short, F., Carruthers, T., Dennison, W., & Waycott, M. (2007). Global seagrass distribution and diversity: a bioregional model. *Journal of Experimental Marine Biology and Ecology*, *350*(1), 3–20.

Sperotto, A., Torresan, S., Gallina, V., Coppola, E., Critto, A., & Marcomini, A. (2016). A multi-disciplinary approach to evaluate pluvial floods risk under changing climate: The case study of the municipality of Venice (Italy). *Science of The Total Environment*, *562*, 1031–1043.

Stelzenmüller, V., Lee, J., South, a., & Rogers, S. I. (2009). Quantifying cumulative impacts of human pressures on the marine environment: A geospatial modelling framework. *Marine Ecology Progress Series*, *398*, 19–32. http://doi.org/10.3354/meps08345

Suaria, G., & Aliani, S. (2014). Floating debris in the Mediterranean Sea. *Marine Pollution Bulletin, article in*(1–2), 494–504. http://doi.org/10.1016/j.marpolbul.2014.06.025

Sutherland, W. J., Bardsley, S., Bennun, L., Clout, M., Côté, I. M., Depledge, M. H., … Watkinson, A. R. (2011). Horizon scan of global conservation issues for 2011. *Trends in Ecology and Evolution*, *26*(1), 10–16. http://doi.org/10.1016/j.tree.2010.11.002

Torresan, S., Critto, A., Rizzi, J., & Marcomini, A. (2012). Assessment of coastal vulnerability to climate change hazards at the regional scale: the case study of the North Adriatic Sea. *Natural Hazards and Earth System Science*, *12*(7), 2347–2368. http://doi.org/10.5194/nhess-12-2347-2012

UN. (1982). United Nations Convention on the Law of the Sea (UNCLOS). Third United Nations Conference on the Law of the Sea (UNCLOS III). Montego Bay, Jamaica. Retrieved from http://www.un.org/Depts/los/index.htm.

UN. (1992). International Convention on Biological Diversity (CBD), Earth Summit, 5 June 1992 Rio de Janeiro, 30. Retrieved from http://www.cbd.int/doc/legal/cbd-en.pdf

UN. (2009). UNISDR Terminology on Disaster Risk Reduction. *International Stratergy for Disaster Reduction (ISDR)*, 1–30. Retrieved from www.unisdr.org/publications

UNEP. (2009). *Marine Litter : A Global Challenge*. *United Nations Environmental Programme (UNEP)*.

UNESCO. (2015). Global biodiversity indices from the Ocean Biogeographic Information System. Intergovernmental Oceanographic Commission of UNESCO. Web. http://www.iobis.org.

Waycott, M., Collier, C., Mcmahon, K., Ralph, P., Mckenzie, L., Udy, J., & Grech, A. (2007). Vulnerability of seagrasses in the Great Barrier Reef to climate change. *Climate Change and the Great Barrier Reef: A Vulnerability Assessment*, 193–236.

Zald, A. E., Summer, S., & Wade, T. (2006). A to Z GIS: An Illustrated Dictionary of Geographic Information Systems.