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Climate change impacts on marine water quality: The case study of the Northern Adriatic sea

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ABSTRACT

Climate change is posing additional pressures on coastal ecosystems due to variations in water biogeochemical and physico-chemical parameters (e.g., pH, salinity) leading to aquatic ecosystem degradation.

With the main aim of analyzing the potential impacts of climate change on marine water quality, a Regional Risk Assessment methodology was developed and applied to coastal marine waters of the North Adriatic. It integrates the outputs of regional biogeochemical and physico-chemical models considering future climate change scenarios (i.e., years 2070 and 2100) with site-specific environmental and socio-economic indicators.

Results showed that salinity and temperature will be the main drivers of changes, together with macronutrients, especially in the area of the Po' river delta.

The final outputs are exposure, susceptibility and risk maps supporting the communication of the potential consequences of climate change on water quality to decision makers and stakeholders and provide a basis for the definition of adaptation and management strategies.

1. Introduction

Marine ecosystems are very important in the regulation of the climate, and are very sensitive to climate change (Hoegh-Guldberg and Bruno, 2010). In recent years, they are suffering several impacts such as loss of habitat forming species (e.g., coral reefs, seagrasses) (Short and Neckles, 1999; Hoegh-Guldberg et al., 2007), decline in the productivity of the oceans (Behrenfeld et al., 2006; Polovina et al., 2008) or changes in the geographic distribution of marine organism (Perry et al., 2005; Last et al., 2011). The main drivers of these impacts are the increase of sea surface temperature together with the ice melting in the arctic regions (Wang and Overland, 2009) and the changes in the marine currents, which causes variations in biogeochemical and physical parameters (e.g., primary production, pH, salinity) that may exceed the thresholds of ecosystem tolerance, and thus lead to marine ecosystems degradation (Hoegh-Guldberg and Bruno, 2010; Xia et al., 2010).

Several international laws and regulation were approved to protect and regulate the use of marine environments. The main international agreement was the United Convention on the Law of the Sea (UNCLOS) which entered into force in the year 1994. The protection of the marine biodiversity was addressed also by the Convention of Biological Diversity (CBD), approved in 1992 and entered into force the following year. Within the European Commission several directives and policies related to coastal and marine environments were approved since the year 2000. The most important are the Integrated Maritime Policy (IMP), the Marine Strategy Framework Directive (MSFD), the Water Framework Directive (WFD), the Floods Directive, the Reform of the Common Fisheries Policy (CFP), the Recommendation for Integrated Coastal Zone Management (ICZM) and the directive establishing a framework for Maritime Spatial Planning (MSP). Among these, the Water Framework Directive (WFD; 2000/60/EC), and the Marine Strategy Framework Directive (MSFD; 2008/56/EC) represent the umbrella used to address the ecological quality of coastal/marine water systems in Europe. Both the directives aim at achieving a Good Environmental Status (GES) and require the comparison of the current state of water quality with the quality that would be expected under minimal or sustainable human use (Mee et al., 2008). The process of setting attainable environmental targets must also account for highly uncertain changes of the physical and biological environment driven by climate

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(Roth and O'Higgins, 2010), as stated also in the White Paper on adapting to climate change (EC, 2009). The main aim of this document is to provide an overall framework to stimulate and guide national, regional and local adaptation measures and policies, including sector specific dimensions, in order to increase resilience to the impacts of climate change (EC, 2009). Emphasis is placed on the need for an integrated approach to increase resilience in coastal and marine environments and interrelated human activities, as well as the need to integrate adaptation into sectorial policies (EC, 2009).

Several recent studies focused on the assessment of the environmental status of marine waters in an integrative manner (e.g., Borja et al., 2011; HELCOM, 2010) but it is still not clear how marine ecosystems respond to human activities and to climate change (Borja et al., 2013). In fact, researches on climate change effects in marine aquatic ecosystems are still far behind researches related to terrestrial ecosystems (Richardson and Poloczanska, 2008). This is mainly due to the dimension, complexity and variability of seas and to the lack of long time series of data of relevant variables (Pratchett et al., 2011). Moreover, many studies focused on specific marine ecosystems or their specific components, such as coral reefs (e.g., Walther et al., 2002; Munday, 2004; Pandolfi et al., 2011), seagrasses (e.g., Björk et al., 2008; Jorda et al., 2013; Koch et al., 2013), or fishes (e.g., Roessig et al., 2004; Munday et al., 2009; Koehn et al., 2011) without performing an overall assessment on the entire aquatic ecosystem.

Developed approaches have been applied over several coastal zones which are affected by a dynamical interaction with anthropogenic pressures and climate change, e.g., the Baltic sea, the North sea, the North Adriatic sea and other enclosed basins such as the Black sea (Melvasalo, 2000). Among these, the North Adriatic sea is one of the most investigated basins of the Mediterranean (e.g., Braga et al., 2013; Loos et al., 2013; Wolf et al., 2012) but none of the studies analyzed the potential environmental risks related to water quality variations due to climate change on the whole marine biological system.

Water quality can be defined in several ways according to its final use, but in general terms it is an overall evaluation based on a suite of measurements and analyses of chemical, physical, and biological characteristics conducted in the field and in laboratory (Diersing, 2009). In order to analyse the potential consequences of climate change on marine water quality and evaluate the related impacts on coastal receptors (e.g., marine biological systems and aquaculture), in this study, a Regional Risk Assessment (RRA) methodology was developed and applied to the coastal marine water bodies of the Northern Adriatic Italian coast (Veneto and Friuli Venezia regions, Italy). The analysis is based on the use of biogeochemical and physical models of marine water at the regional scale and integrate site-specific environmental and socio-economic information. The methodology uses Geographic Information Systems to manage, process, analyse, and visualize data and employs Multi-Criteria Decision Analysis to integrate stakeholders' preferences and experts' judgments into the analysis, in order to obtain a relative risk index in the considered region. The methodology has been implemented within the DEcision support SYstem for COastal climate change impact assessment (DESYCO) (Torresan et al., 2010).

The main aim of this paper is to present the RRA methodology and its application to coastal marine water bodies of the Northern Adriatic area. In the next paragraphs, after the presentation of the case study area (Section 2), the RRA methodology will be described in detail (Section 3) and the output (i.e., hazard, exposure, vulnerability and risk maps) will be presented and discussed (Section 4).

2. The case study area

The case study area is represented by the coastal water bodies defined by the Veneto and Friuli Venezia Giulia regions (North Adriatic sea, Italy) according to the Water Framework Directive (Fig. 1). The boundaries were defined using three macrodescriptors (i.e., geographical localization, geomorphological and hydrological descriptors) that allowed identifying areas with homogeneous geomorphological and hydrodynamic characteristics.

From a morphological point of view, the sedimentary shores of the case study area include straight littoral coasts, lagoonal barrier islands, spits, river outlets and salt marshes, with a quite low bathymetry that is never deeper than 20 m.

The physical properties and dynamics of the case study area are influenced by the atmospheric forcings (e.g., wind stress and heat flux) and by the freshwater inputs coming from the major rivers (i.e., Tagliamento, Isonzo, Livenza, Piave, Brenta, Adige and Po, the latter having an average outflow of about 1500 m^3/s) and from two lagoons (i.e., the Marano and Grado Lagoon and the Venice Lagoon). The intense winter evaporation, caused by cold and dry winds blowing over the North Adriatic, contributes to the formation of dense waters (Artegiani et al., 1989; Gačić et al., 1999). Sirocco (from the southeast) and Bora (from the northeast) are the dominant winds in the region. The circulation induced by Bora winds, more frequent in autumn and winter, might generate a configuration able to push the Po freshwater flux up to the Istrian coast and the Gulf of Trieste on the eastern part of the basin (Kuzmić and Orlić, 2006; Carniel et al., 2009; Boldrin et al., 2009). Moreover, Sirocco events tend to pile up water along the Italian coast and the circulation results more uniform. The Po river in the southern part of the North Adriatic and the Isonzo River in the Gulf of Trieste are regulators of the circulation of the water masses (Malačič and Petelin, 2001; Querin et al., 2006) and main external nutrient source (Olivotti et al., 1986). These physical features and the large freshwater discharges (mainly from the Po river), generate a marked west–east gradient of nutrient and chlorophyll concentrations (Bignami et al., 2007; Socal et al., 2008; Solidoro et al., 2009).

The North Adriatic sea is particularly important also for the economy of the Veneto and Friuli Venezia Giulia regions, because of the fisheries and aquaculture sectors. Despite a decreasing trend in the number of workers and in the numbers of ships, the North Adriatic sea is still characterized by a high productivity (i.e., around 40% of the production of the whole Adriatic is from the North Adriatic) and by a high number of companies operating in this sector (i.e., around 25% of the companies are located in the North Adriatic) (Veneto Agricoltura, 2013) compared to the Medium–Low Adriatic sea. Variations in coastal waters quality can heavily impact these activities. In particular, changes in hydrological and biogeochemical parameters (e.g., concentration of chlorophyll, nutrients) could led to loss of habitats (Pirrone et al., 2005), replacement of species (Cheung et al., 2009; Azzurro et al., 2011; Albouy et al., 2012) and to an overall decrease of fish stock over long term scenarios (Albouy et al., 2013), producing negative consequences on the fisheries and aquaculture sectors. It is therefore important to identify areas that could be subject to these impacts in order to set up adequate adaptation measures and avoid negative consequences on the local economy.

Moreover, the economy of the North Adriatic coastal areas is based also on the tourism sector, as this region is a favoured touristic destination for many Italian and foreigner tourists. One of the main reasons is the good quality of bathing waters, which is higher than the average of the Adriatic sea (i.e., 90% of sampling sites with excellent quality in the North Adriatic and 82% in the whole Adriatic sea; ARPAV, 2013). Changes in the hydrodynamic circulation could affect water quality, e.g., through an increase of the concentration of *Escherichia coli* coming from waste waters, with negative consequences on the bathing and tourist activities (Scroccaro et al., 2010). Consequently, the prevention of water degradation is particularly important in order to avoid – or at least reduce – the potential negative consequences on the tourism sector.

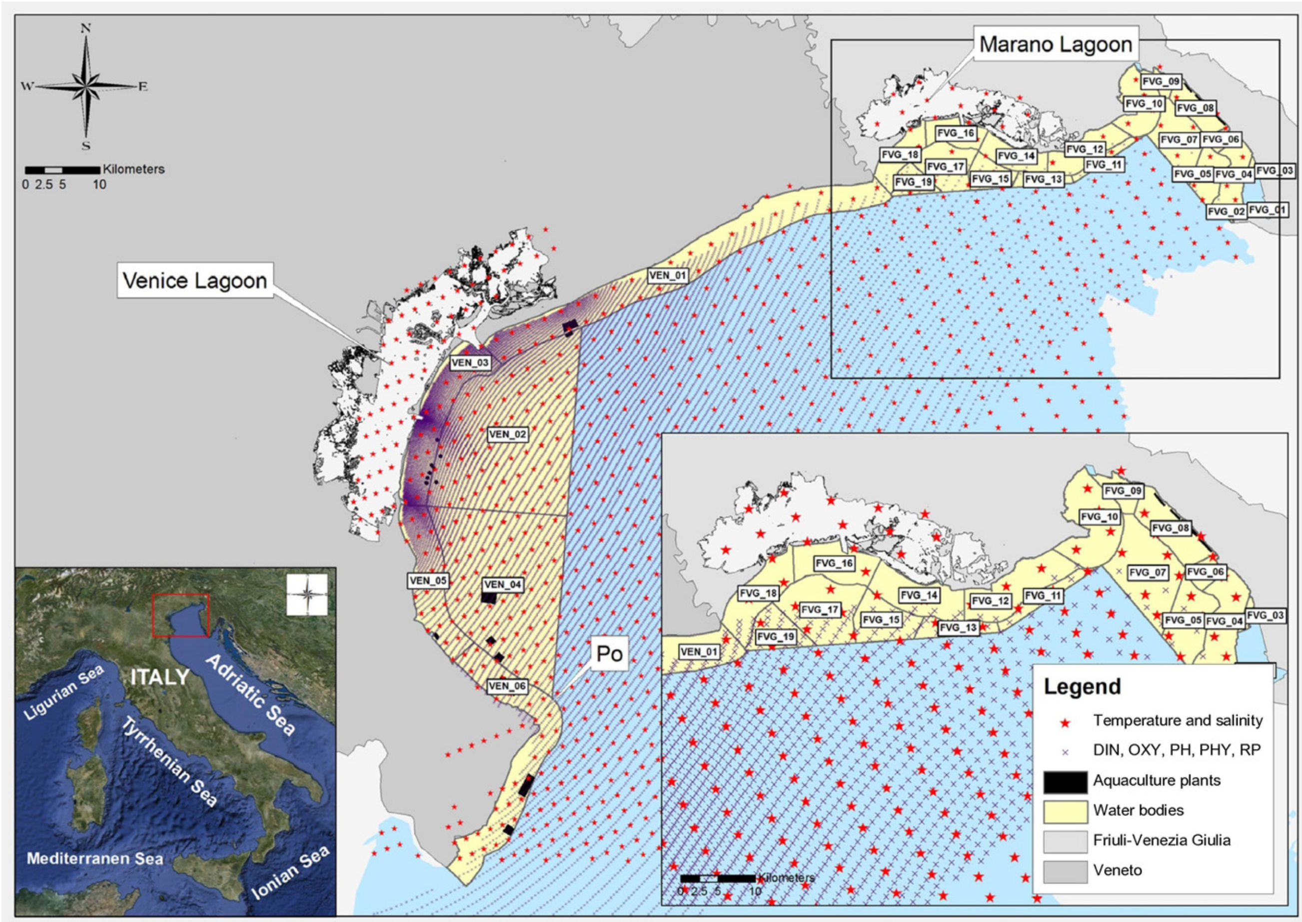

Fig. 1. The North Adriatic sea case study area and exposed water bodies. Localization of water bodies and model grids used for the estimation of hazard metrics are shown. DIN: Dissolved Inorganic Nitrogen; OXY: Dissolved Oxygen; pH: pH; PHY: Phytoplankton; RP: Reactive Phosphorus.

3. Materials and methods

Regional Risk Assessment (RRA) aims at providing a quantitative and systematic way to estimate and compare the impacts of environmental problems that affect large geographic areas (Hunsaker et al., 1990) considering the presence of multiple habitats, stressors and endpoints (Landis, 2005). The methodology is used to assess environmental vulnerability and risks related to water quality variations under climate change scenarios; applying Geographic Information Systems (GIS) for the analysis and management of input data, and Multi Criteria Decision Analysis (MCDA) for the consideration of stakeholder's interests and technical evaluations within the assessment process (Giove et al., 2009). The final aim is to estimate the relative risks in the considered region, compare different stressors, rank targets and exposure units at risk, and select those risks that need to be investigated more thoroughly.

The main output of the RRA include: (i) hazard maps representing the hazard against which a system operates (e.g., changes in physico-chemical and biological parameter of marine coastal waters); (ii) vulnerability maps representing the spatial distribution of environmental vulnerability factors; (iii) risk maps identifying and prioritizing areas and targets at risk. These maps allow an easy and flexible visualization of vulnerabilities and risks related to climate change for stakeholders and decision makers, supporting the implementation of sustainable ICZM strategies.

The overall RRA methodology is based on four operative steps that will be described in the successive paragraphs:

(1) Hazard assessment;
(2) Exposure assessment;
(3) Biophysical and environmental vulnerability assessment;
(4) Risk assessment.

The maps produced at each step can be analyzed through synthetic statistics summarizing key impact metrics (e.g., surface and percentage of receptors in different risk classes) that can support stakeholders and decision makers in the definition of adaptation Plans, Policies and Programs.

3.1. Hazard assessment

The first step of the RRA (i.e., the hazard assessment) is aimed at defining future hazard scenarios representing potential water quality variations threatening the health of marine ecosystems, in relation to expected climate change dynamics. This step requires the identification of key stressors (influencing water quality) and of relevant hazard metrics, representing proxy indicators of water quality measurable over time (Table 1). Within the North Adriatic case study, hazard metrics were provided by a chain of climate, hydrodynamic and biogeochemical models (Fig. 2).

As described in Torresan et al. (2015), the overall models chain starts with two Global Climate Models (GCMs; SINTEX G and CMCC-CM) forced by the IPCC SRES A1B[1] scenario (Nakićenović et al., 2000) for the period 2070–2100. The A1B scenario (already employed in numerous climate change impact studies) describes a future world with rapid economic growth where new and more efficient technologies are progressively introduced. Assuming a balanced emphasis between fossil fuels and other energy sources, A1B represent an intermediate case, if compared to the more intense A2 and the much weaker B1 scenarios or also if compared to the more recent RCP4.5 and RCP8.5 scenarios (IPCC, 2013).

The Regional Climate Models (RCMs) COSMO-CLM (Bucchignani et al., 2013) and EBU-POM (Djurdjevic and Rajkovic, 2008), nested in the SINTEX G and CMCC-CM models respectively, provided future projections of temperature, precipitation and wind variations at the Mediterranean scale that were successively used as input for a suite of hydrodynamic, wave and biogeochemical models running at the more detailed Adriatic and North Adriatic scale. Within the described chain, the input of water coming from rivers and lagoons was considered as constant and the current values were used for both the reference and future scenarios.

Accordingly, the model chain was an effective way to obtain relevant information about climate scenarios (linked to global and subcontinental dynamics) and the cascading physical–chemical processes, more specifically dependant on regional and local scale processes. As shown in Fig. 2 and Table 2, the information provided by high resolution physical impact models reach a suitable resolution to be embedded in spatial risk assessment studies (i.e., from 5 km to 50 m).

Detailed information about numerical models used in the chain are reported in Table 2, describing the domain where the models were applied, the spatial resolution, the investigated time scenario and the hazard metrics that can be provided by each model. The output parameters that are used for the hazard assessment phase are the metrics highlighted in bold (i.e., sea temperature and salinity from the ROMS (Rutgers Ocean Modeling System, Haidvogel et al., 2008) model, relying on SINTEX-G initial conditions of the 2070 time-slice; primary production, dissolved inorganic nitrogen, reactive phosphorus, dissolved oxygen and pH from the ADRI2BC model).

For each hazard metric, the average seasonal value (i.e., January–March, April–June, July–September, October–December) was provided as map of points. Temperature and salinity were available over a regular grid (Fig. 1, red[2] stars), while the other five parameters were available over an irregular grid (Fig. 1, gray crosses). Maps were produced for each season of the two future scenarios (i.e., the years 2070 and 2100) and of the reference scenario (i.e., the year 2005).

The hazard assessment was then performed based on the comparison of future maximum/minimum values with reference tolerance ranges that were defined for each hazard metric. The boundaries of the reference tolerance ranges (i.e., the maximum and minimum value of each hazard metric in the year 2005) represent the chemical and/or physico-chemical thresholds that could potentially limit the existence, growth, abundance, or distribution of an organism. If the values of one or more parameters exceed these thresholds, the ecosystem could be potentially affected by water quality variation impacts (e.g., variations of time of reproduction and growth, changes in the distribution and abundance of the organisms). Within the North Adriatic case, the hazard assessment was performed in homogeneous areas corresponding to the water bodies identified by the Veneto and Friuli Venezia Giulia regions (Fig. 1) for the implementation of the Water Framework Directive (i.e., 6 water bodies for the Veneto region and 19 water bodies for the Friuli Venezia Giulia region). Tolerance ranges were identified for each hazard metric, for each period (i.e., each season) and for all the considered water bodies using data of the reference year (i.e., 2005).

In order to obtain an overall hazard score for each water body, the variation of the biogeochemical and physico-chemical parameters from the reference to the future climate change scenarios was considered. The range of each hazard metric in the future scenario was compared with the reference range and values were successively aggregated using the Ordered Weighted Average (OWA) operator. The OWA operator was originally introduced by Yager (1988) to provide a way for generalizing different aggregation patterns like maximum, minimum and average. It is applied here in order to integrate, in a single comparable number, positive and negative deviations from the initial reference status: the greater is the integrated variation in the future, the higher could be the hazard. Results obtained by the application of OWA to each hazard metric, were successfully normalized to solve the problem of aggregating heterogeneous data in the assessment. The normalization was done in two steps: (i) values obtained by the application of OWA for each hazard metric were divided by their corresponding reference range, defined considering all water bodies, in order to obtain the percentage of variance of the future values respect to the reference scenario; (ii) obtained percentage values were then normalized by the maximum percentage value obtained for all hazard metrics and all seasons. Finally, normalized values were aggregated using the probabilistic or operator to obtain a single overall hazard score for each water body. Obtained hazard scores can range between 0 (no hazard) and 1 (maximum hazard within the considered region for all seasons and scenarios).

The final output of the hazard assessment are seasonal hazard maps showing water bodies' hazard scores for each scenario. Maps are classified into 5 hazard qualitative classes (i.e., Very low, Low, Medium, High, Very high) using the equal interval method. The produced maps will be presented and discussed in Section 4.1.

3.2. Exposure assessment

The second step is the exposure assessment that aims at identifying and selecting the receptors (i.e., elements at risk) that can be subject to potential losses due to changes in water quality. The exposure represents the presence of people, livelihoods, environmental services and resources, infrastructures, and other economic, social, or cultural assets in places that could be adversely affected by the considered impact (UNISDR, 2009; IPCC, 2012). Within the proposed application, exposure includes only coastal waters and the related environmental resources (e.g., fish stock, fisheries and aquaculture plant) that could be adversely affected by changes in water quality.

Specifically, the exposure for coastal waters is represented by the marine water bodies defined by the Veneto and Friuli-Venezia Giulia regions (Fig. 1) that represent areas with homogeneous geomorphological and hydrodynamic characteristics.

The output of this step is an exposure map where 0 indicate absence of exposure and 1 indicate exposure to the considered impact (i.e., areas inside the considered water bodies).

3.3. Biophysical and environmental vulnerability assessment

Vulnerability represents the propensity or predisposition of a community, system, or asset to be adversely affected by a certain hazard (IPCC, 2012). Within the RRA methodology, the biophysical and environmental vulnerability assessment (i.e., the third step) is aimed at evaluating the degree to which coastal water bodies could be affected by water quality variation impacts based on physical/environmental site-specific information (e.g., presence and extension of seagrasses,

[1] The A1B scenario belongs to the A1 storyline family, which describes a future world of very rapid economic growth. In this potential future, global population peaks mid-century and declines thereafter, and new and more efficient technologies are rapidly introduced. Moreover, the A1B scenario predicts carbon dioxide emissions increasing until around 2050 and then decreasing, and it assumes a balanced emphasis between fossil fuels and other energy sources.

[2] For interpretation of color in Fig. 1, the reader is referred to the web version of this article.

Table 1
List of hazard stressors and related hazard metrics considered for the construction of climate change hazard scenarios applied to the North Adriatic coasts.

Stressors	Primary production	Macronutrients	Dissolved oxygen	pH	Sea temperature	Salinity
Hazard metrics	Phytoplanktonic C concentration (mg L^{-1})	Dissolved inorganic N, reactive P concentration (mg L^{-1})	Concentration of O_2 (mg L^{-1})	Mean pH (–)	Mean T (°C)	Salinity (PSU)

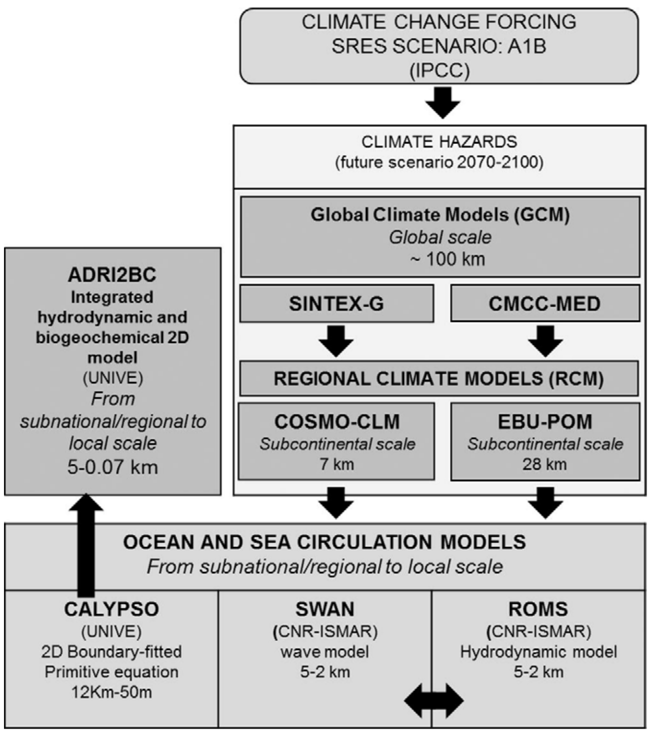

Fig. 2. The model chain supporting the construction of hazard scenarios for the North Adriatic case study (adapted from Torresan et al. (2015)).

adapted Evenness index, aquaculture typology). It is calculated as a function of a set of vulnerability factors that are defined for coastal waters based on available site-specific territorial information (Table 3). Classes and scores of each factor were based on literature or on experts' judgement, as described below.

The adapted Evenness index is a measure of biodiversity which quantifies how equal the community is numerically. This index has been adapted from the standard version of Pielou (1969) because available data included only the abundance of species relevant for fisheries, and not for all species living in the North Adriatic sea. Furthermore, according to the available dataset, the abundance was expressed as classes (e.g., from 100 to 1000 individuals) and not as exact number of individuals. The adapted version of the Evenness index is always represented by a number ranging from 0 (less variation in communities between the species) to 1 (high variation in communities between the species). Higher vulnerability scores were attributed to areas with a higher index value, as changes in water biogeochemical and physical parameters can easily modify the existing equilibrium in the abundance of the different species. Seagrasses are marine flowering plants that are particularly important in coastal zones as they provide several ecosystem goods and ecosystem services (e.g., fishing grounds, wave protection, oxygen production and protection against coastal erosion). The maximum vulnerability score (i.e., 1) was attributed where seagrasses are present. Moreover, seagrasses with a greater extension are characterized by a lower susceptibility score as they are assumed to be less vulnerable to external perturbations (i.e., changes in water biogeochemical and physical parameters). In fact, when changes on the water quality occur, a smaller area occupied by seagrasses can disappear quite fast, while a bigger surface can adapt to changes and/or recover. *Tegnùe* are biogenic carbonate rocks built by marine organisms. They initially grow on existing hard bottoms formed by cemented sand. They have developed into natural reefs over the last 3–4.000 years. They differ from tropical coral reefs because their main builder organisms are not corals but calcareous red algae, called “Corallines”. Areas where *Tegnùe* are present are characterized by the highest vulnerability score (i.e., 1). Finally, aquaculture typology indicates whether an aquaculture plant is devoted to fisheries or mussels cultures; mussel cultures, that are more sensitive to changes in water biogeochemical and physical parameters, are characterized by a higher level of vulnerability than fish farms.

In order to obtain a single final biophysical and environmental vulnerability score, all factors were aggregated using the *probabilistic or* operator (Kalbfleisch, 1985). This aggregation operator gives the same importance to situations where one or few factors are simultaneously high (i.e., close or equal to 1) as well as where all or many factors are simultaneously low (i.e., close but not equal to 0).

The application of the *probabilistic or* operator requires the classification and normalization of each vulnerability factor map, which is represented by a raster dataset with a resolution – for the North Adriatic case – of 10 m. This activity was supported by a group of experts in environmental risk assessment who defined classes and scores previously described for each vulnerability factor. Normalized factors' scores (Table 3) and the final vulnerability score can range from 0 to 1, according to the degree of vulnerability: 0 represents no vulnerability and 1 represents the higher vulnerability class. The output is a vulnerability map identifying and prioritizing areas more vulnerable to changes in water quality parameters based on 5 qualitative classes from Very low to Very High vulnerability (i.e., 0–0.25; 0.25–0.5; 0.5–0.75; 0.75–0.99; 0.99–1). The vulnerability map that will be presented in Section 4.3 can support decision makers in the definition of measures aimed at boosting the resilience of receptors in the considered region (e.g., regulating fisheries and other activities in coastal zones in order to preserve seagrasses).

3.4. Risk assessment

The last step of the RRA is the risk assessment, aimed at quantifying and classifying, in relative/semi-quantitative terms, the potential consequences of the considered hazard on the investigated areas and receptors (i.e., elements potentially at risk). According to the risk paradigm defined in IPCC (2012), this phase combines the information about each hazard scenario with receptors' exposure and vulnerability (Eq. (1)). Obtained relative risk scores are values ranging between 0 (no risk) and 1 (higher relative risk).

$$R = H \cdot E \cdot V \tag{1}$$

where
H = Hazard score;
E = Exposure score;
V = Biophysical and environmental vulnerability score.

The output of this step for the water quality impact is represented by seasonal relative risk maps for each future scenario (i.e., the year 2070 and 2100) aimed at identifying and prioritizing areas characterized by different levels of risk. The produced maps classify the relative risk scores in five equal classes between 0 (no risk) and 1 (higher risk).

Table 2
Description of the models included in the model chain supporting the construction of hazard scenarios. Metrics in bold are the parameters used in the hazard assessment step.
Source: adapted from Torresan (2012).

Name	Category	Domain	Spatial resolution	Metrics	Time Scenario
SINTEX G	Climate Model	Global	Atmospheric resolution 120 km Oceanic resolution 200 km	Air/sea temperature Atmospheric pressure Cloudiness Rainfall Relative humidity Salinity Winds	2070–2100
EBU-POM	Climate Model	Mediterranean sea	28 km	Air/sea temperature Atmospheric pressure Cloudiness Rainfall Relative humidity Salinity Winds	2070–2100
CMCC-MED	Climate Model	Global	Atmospheric resolution 80 km	Air/sea temperature Atmospheric pressure Cloudiness Rainfall Relative humidity Winds	2070–2100
COSMO-CLM	Climate Model	Mediterranean sea	14 km	Air/sea temperature Atmospheric pressure Cloudiness Rainfall Relative humidity Salinity Winds	2070–2100
SWAN	Wave model	North Adriatic sea	From 5 to 2 km	Wave energy Wave direction Wave height Wave period	2070–2100
ROMS	3D Ocean circulation model	Adriatic sea	From 5 to 2 km	Bottom stress **Salinity** **Sea temperature** Water velocity	2070–2100
ADRI2-BC	Reaction-transport biogeochemical model (2D)	North Adriatic sea	From 5 to 0.7 km	**Primary production (PHY)** **Dissolved inorganic nitrogen**[a] **Reactive phosphorus (RP)**[b] **Dissolved oxygen (OXY)** **pH**	2070–2100
CALYPSO	Coastal and sea circulation model	Adriatic sea and Lagoon of Venice	From 12 to 0.05 km	Bottom stress Current velocity Water levels Submerged areas	2070–2100

[a] DIN includes nitrogen in oxydized (NO_x^-) and reduced (NH_4^+) forms.
[b] Reactive phosphorus (PO_4^{3-}).

The proposed regional risk classifications do not attempt to provide absolute predictions about the impacts of climate change, but are relative indices which provide information about the areas/targets within a region likely to be affected more severely than others.

4. Results and discussion

The described RRA methodology was implemented and applied through the DSS DESYCO (Torresan et al., 2010) in order to produce hazard, exposure, vulnerability and risk maps and calculate relevant statistics. In the following paragraphs, the main results are presented and discussed.

4.1. Hazard maps

Hazard maps were based on the integration of seven hazard metrics for which future and reference ranges of values were compared. In order to support the analysis of climate change scenarios and to allow identifying seasons with greater changes, graphs comparing hazard metrics' seasonal average of maximum/minimum values for all water bodies in the reference scenario (i.e., 2005) and in the future scenarios (i.e., 2070 and 2100) were produced (Fig. 3). The plots do not represent the seasonal average value for each hazard metric, but show the mean of all the extreme situations of the different water bodies. Although these extremes may be affecting very small portions of each water body, we think that this representation is more adapt to convey the information pertinent to this work, and this caveat should be kept in mind when looking at the figure. For example, in agreement with other studies (see Djurdjevic and Rajkovic, 2008), sea temperature extremes are denoting a trend toward an increase in most of the considered water bodies during all seasons, with a lower rate of increment during spring. The distribution of the mean salinity extremes in the water bodies presents a general decrease in almost all water bodies and seasons. However, as explained above, the information contained in Fig. 3 should be

Table 3
Vulnerability factors selected for the water quality variation impact applied to the North Adriatic coastal water bodies and related scores.

Factor	Source	Class	Score
Species diversity index for fish -adapted Evenness index-	AdriBlu, 2006	0.56–0.70	0.6
		0.71–0.85	0.8
		0.86–1	1
Presence of seagrasses	Veneto region, 2009; Friuli Venezia Giulia region, 2009	Absence	0.4
		Presence	1
Extension of seagrasses km^2	Veneto region, 2009; Friuli Venezia Giulia region, 2009	0–6.67	1
		6.68–13.34	0.75
		13.35–20.01	0.5
		20.02–26.68	0.25
Tegnùe	Veneto region, 2009; Friuli Venezia Giulia region, 2009	Absence	0.4
		Presence	1
Aquaculture typology	Veneto region, 2008; Friuli Venezia Giulia region, 2008	Mussel culture	1
		Fish farms	0.6

carefully considered when dealing with a shallow, semi-enclosed, river dominated environment such as the Northern Adriatic basin. The mutual influence of lagoons and open seas in this coastal region (see also Bergamasco et al., 1998) is not completely considered in the modeling suite adopted, standing the relatively coarse numerical resolution. The inclusion of small relatively fresh water bodies – such as the Venice and Marano lagoons – may impact the assessment of such maxima/minima. In addition, the time-slice experiment in the period 2070–2100 reflects the initial salinity distribution and spatial resolution obtained by the SINTEX-G model (Djurdjevic and Rajkovic, 2008). The feasibility of dynamical downscaling procedure from global to regional model through different modeling suites has already been discussed in Benetazzo et al. (2012). Some parameters may adjust to the new model configuration and physics rather quickly (e.g., 2D currents, waves); some others may take relatively longer time to reflect the effects of the new spatial (horizontal and vertical) resolution, new definition of lateral forcings (such as the river inclusion) etc., possibly originating confined portions with extreme temperatures and salinity values. In any case, even when these problems may be mitigated by the use of a single modeling suite (e.g., Benetazzo et al., 2013) we need to recall that there is still a high and intrinsic uncertainty related to the seasonal variations, e.g., of the river discharges in the context of climate change and future scenarios (see Coppola et al., 2014), especially when related to extreme events that, once included in the modeling framework, may lead to exceptional values (e.g., salinity minima, nutrient maxima, and consequently oxygen hypoxic and anoxic) due to a severe increase of river runoff during very limited periods. Notwithstanding all these aspects, that should however be recalled, we believe it is worth to retain the parameters shown in Fig. 3 in the current effort, since they represent the best simulations at the moment and can show the potentiality in a RRA assessment in coastal areas without a loss of generality. New and more consolidated data can be easily and promptly uploaded whenever will be available.

By Fig. 3 is also possible to see that the mean of the extreme values of Dissolved Oxygen (OXY) will increase in most water bodies in winter and decrease in most water bodies in the other seasons. As far as pH is concerned, it will decrease in most water bodies and seasons, with higher changes during the spring season. The concentration of phytoplankton (PHY) will generally increase, with higher changes during the winter season, but the trend is not uniform across water bodies in the different seasons. Dissolved Inorganic Nitrogen (DIN) and concentration of Reactive Phosphorus (RP) will generally increase. All considered metrics showed grater changes (i.e., higher increments or decreases compared to the other water bodies) in the coastal areas located from the Po river delta to the Chioggia inlet and from the Lido inlet to Bibione, in correspondence to the water bodies VEN_01, VEN_05 and VEN_06. Some more details about extreme values of the two hazard metrics mainly contributing to the final hazard score (i.e., Salinity and Temperature) for coastal water bodies are included in the supplementary material (Figs. SM1 and SM2). Particularly relevant is the increment of nutrients (i.e., DIN and RP) in autumn in these three water bodies; situation which could be driven by the presence of a seasonal thermo-cline and by variations in time of the transfer of mass from the boundary layer, caused by periodic events of intense water movements at the bottom (Brigolin et al., 2011; Mann and Lazier, 2006). Finally, the comparison of the values for all seasons of the two future timeframe scenarios does not show great differences between values in 2070 and 2100, and, except few cases (e.g., temperature, OXY or DIN in winter), there is a deterioration in the condition in 2100 compared to 2070.

Hazard maps show a ranking of water bodies' hazard scores, based on the variation of the considered biogeochemical parameters in the future scenarios (i.e., 2070 and 2100) compared to the reference one (i.e., 2005). The higher scores represent water bodies where there is a higher increase/decrease of maximum/minimum hazard metrics' values compared to the reference values. Hazard scores were calculated as described in Section 3.1 within each homogenous area (i.e., marine water bodies defined by the Veneto and Friuli-Venezia Giulia regions, Fig. 1).

Fig. 4 shows seasonal hazard maps for the two considered future scenarios (i.e., 2070 and 2100 respectively). In both the considered timeframes, the southern part of the considered region (from Chioggia to the Po river delta) and the part from the Lido inlet to Bibione are characterized by higher hazard scores in all considered seasons and scenarios. In addition, the season where higher hazard scores are forecasted is spring (i.e., April/June) in both the future timeframes. Additionally, the comparison shows that the hazard in 2100 is always equal or higher than in 2070. Greater changes will be located in the water bodies in front of the Friuli Venezia Giulia region, where models estimated a greater variation of the considered hazard metrics.

A detailed investigation of the hazard metrics contributing to the definition of the final hazard score was performed in order to better understand which metrics contribute more to the result, showing that those contributing more to the definition of the final hazard score are salinity and temperature.

4.2. Exposure and vulnerability maps

The exposure map represents the key receptors of the analysis (Fig. 1) and includes the coastal water bodies of the Veneto and Friuli Venezia Giulia regions (colored in yellow), defined according to the criteria listed in Section 3.2. This area comprises also several aquaculture plants, colored in black in Fig. 1, representing key hotspots of the analysis.

The vulnerability map (Fig. 5) highlights and prioritize areas that could be affected more severely than others by climate change impacts on water quality. Within the considered region, coastal water bodies are always characterized by a High or Very high vulnerability score. Higher vulnerability is identified in the area in front of the Venice Lagoon (i.e., close to the inlets of Malamocco and Lido) and in the northern part of the case study area, from Caorle to Trieste. Several water bodies are completely classified within a single vulnerability class and 18 out of 25 are classified within for more than 85% of their surface within the same class, showing that the variability within water bodies is very low.

Vulnerability factors that mainly contributed to the definition of the vulnerability score are the adapted Evenness index, and those related to the presence of vulnerable targets, i.e., seagrasses, aquaculture plants and *Tegnùe*. In fact, these are the elements that could be threatened by a worsening of the water quality.

In order to reduce the vulnerability and boost the resilience of the region some action could be taken by local authorities. Examples of

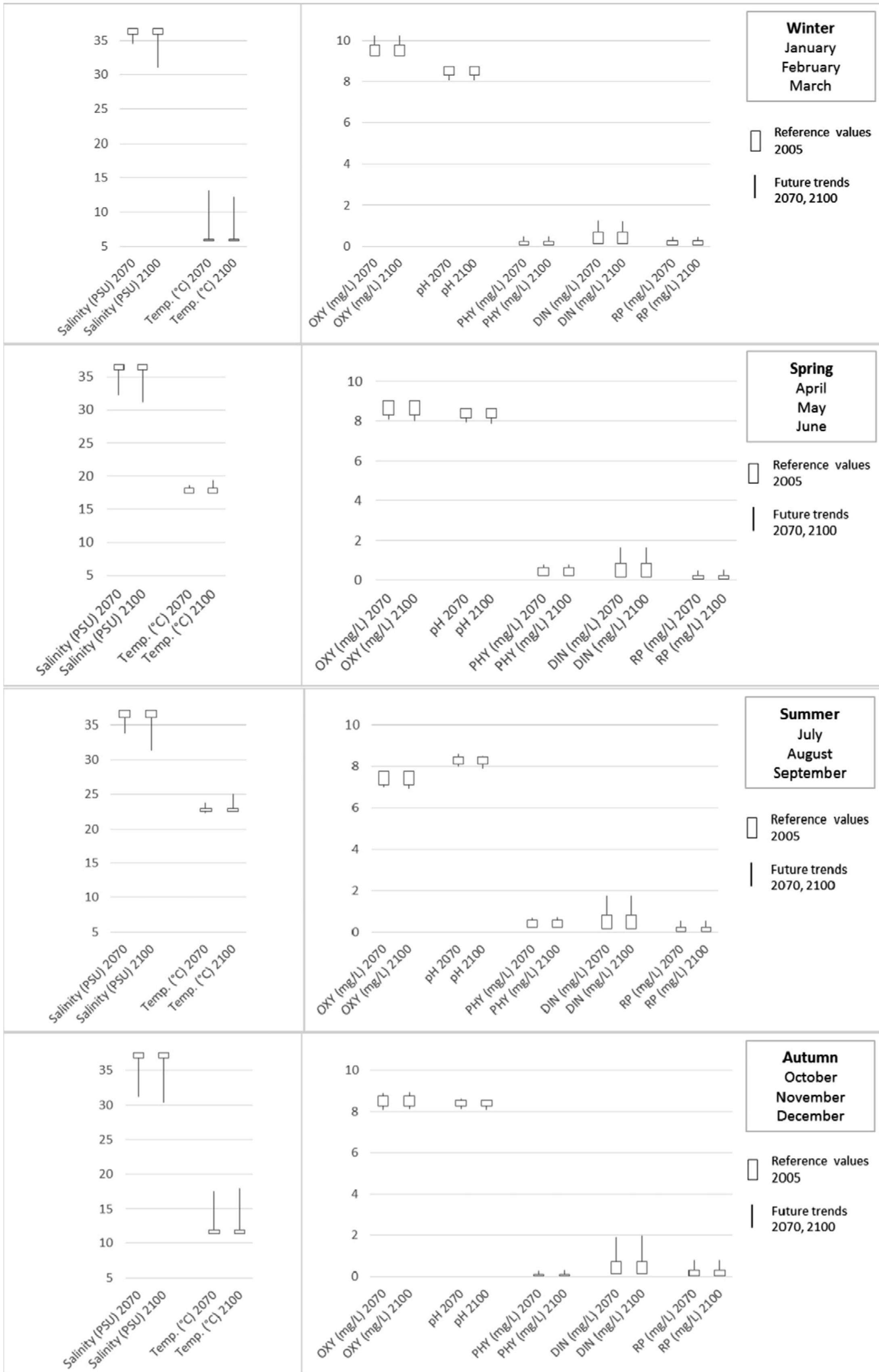

Fig. 3. Comparison of hazard metrics' seasonal average of maximum/minimum values for all water bodies in the reference scenario (i.e., 2005) and in the future scenarios (i.e., 2070 and 2100).

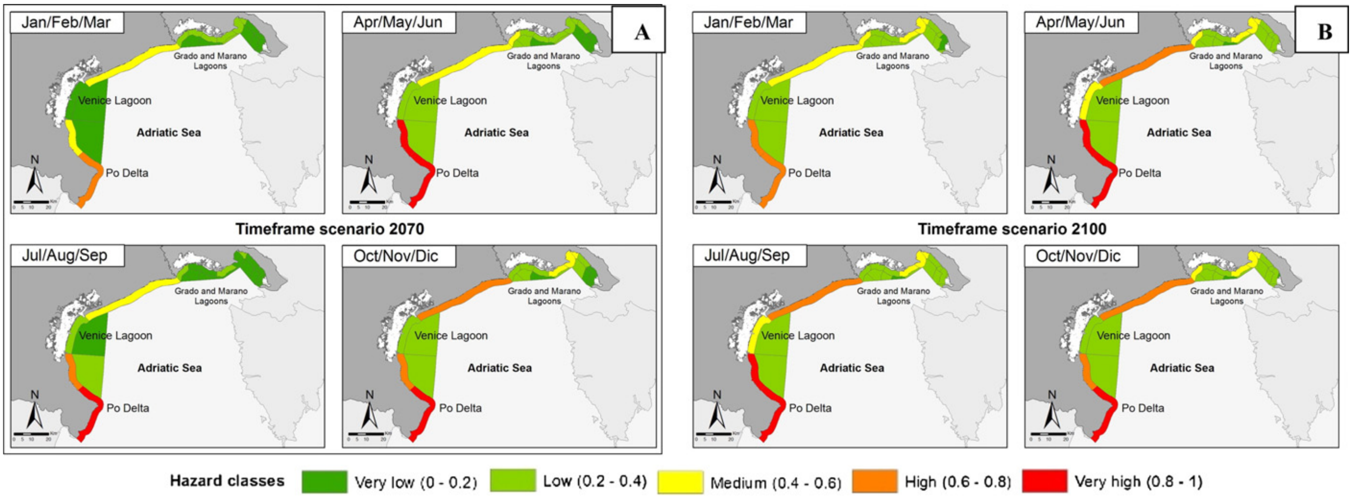

Fig. 4. Hazard map of water quality variations under climate change for the North Adriatic coastal water bodies for the years 2070 (A) and 2100 (B).

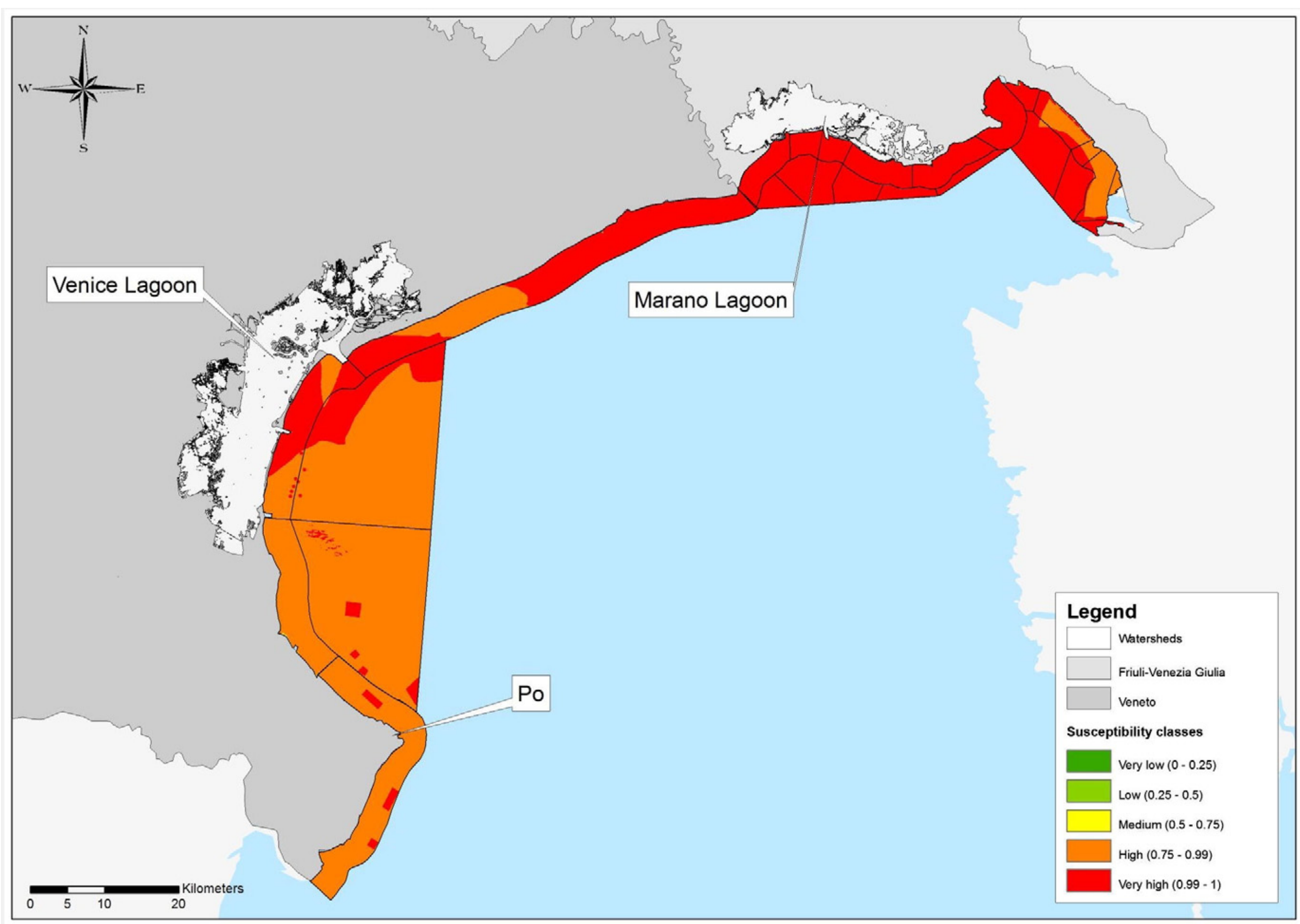

Fig. 5. Vulnerability map of coastal waters to water quality variations under climate change for the North Adriatic sea.

adaptation measures can be the change of typology and/or location of aquaculture plants or the definition of new regulations for fisheries aimed at preserving the biodiversity.

4.3. Risk maps

Risk maps identify and rank areas and targets that could be impacted by changes in water quality by integrating hazard, exposure and vulnerability. The relative risk maps produced for the North Adriatic sea for the spring season in the years 2070 (Fig. 6A) and 2100 (Fig. 6B), which is the worst season, show scores varying from very low to very high, with higher relative risk scores located in the areas closer to the Po river delta and from the Lido inlet to Bibione (i.e., the water body VEN_01). In addition, the analysis of all the seasons shows that the situation in 2100 is always worse than in 2070 (Fig. 6).

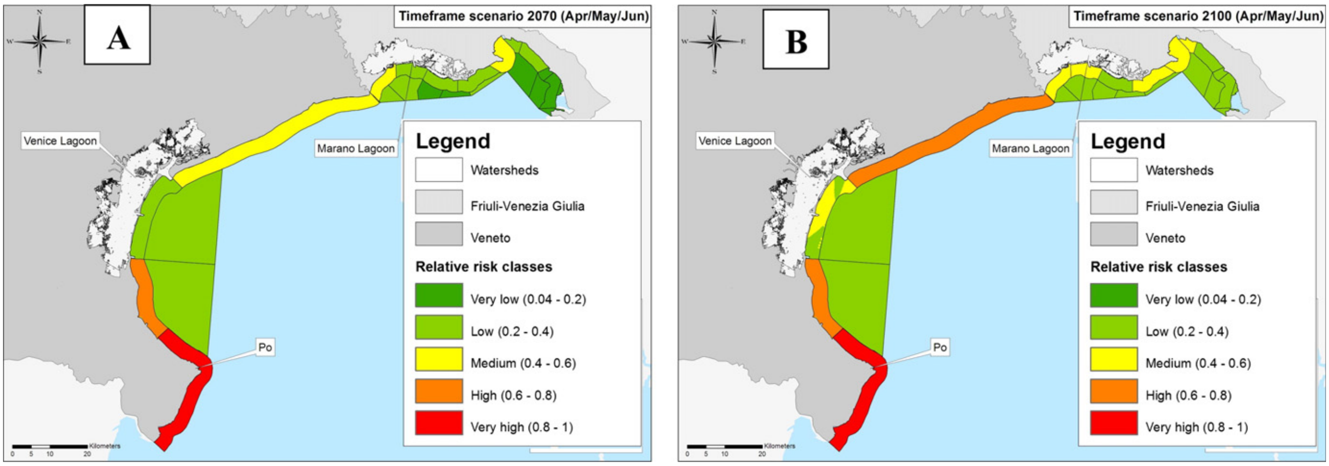

Fig. 6. Relative risk map of water quality variations under climate change for the North Adriatic sea.

The risk is highly influenced by the hazard assessment. In fact, vulnerability scores are quite homogenous across all the case study area (always high or very high), while hazard scores changes for the different water bodies across the studied region. Accordingly, water bodies with higher hazard scores have also higher relative risk scores (i.e., from the Po river delta to the Chioggia inlet and from the Lido inlet to Bibione, in correspondence to the water bodies VEN_01, VEN_05 and VEN_06). By the comparison of the risk maps for the years 2070 and 2100 it emerges that most of the water bodies (i.e., 14) increase they relative risk score of one class (i.e., from very low to low, from low to medium and from medium to high).

Some additional analyses were performed in order to evaluate risks for the main aquaculture plants in the year 2100. By overlapping the risk maps and the map of fisheries and mussel's culture, is possible to see that, five out of 27 were classified with very high or high relative risk scores, 15 with medium risk scores and 7 with low risk scores. This means that the majority of the aquaculture plants could have risks in the long term scenarios and some initiatives should be taken in order to reduce the potential impacts of climate changes.

The produced risk maps can be useful for the definition of adaptation plans aimed at reducing the risk in the considered region. In particular, in addition to the possible adaptation measures that were previously listed, some actions could be taken in order to improve the quality of marine coastal waters. In particular, the control of river discharges into the sea could be improved by reducing the discharge of nutrients and eutrophication-inducing substances through the construction of wastewater treatment plants. Another action could be the reduction of the impacts of boat traffic in areas with high production/high biodiversity or to establish new Marine Protected Areas in order to protect biodiversity in particularly important regions.

5. Conclusions

The proposed methodology and the related application to the North Adriatic sea allowed to evaluate and rank relative vulnerabilities/risks related to climate changes on marine coastal waters at the regional scale. RRA can support the development of effective adaptation strategies and sustainable Integrated Coastal Zone Management, coherently with European directives and documents related, directly or indirectly, to climate changes, such as the Marine Strategy Framework Directive. One of the strengths of the proposed approach is the implementation of a multi-model chain which allows investigating cascading processes at the regional/local level integrating several models from the global to the regional scale.

The use of indicators and the application of the RRA methodology can be improved through the integration of participatory methods. In fact, the involvement of stakeholders and experts can support the identification of appropriate indicators and the attribution of scores and weights to vulnerability factors. Participative processes in this phase can be applied through the organization of workshops where experts can present and discuss their opinions providing judgements to feed (and tailor) the risk assessment procedure. Simple questionnaires or more advanced approaches (e.g., group decision theory) can also be used to summarize the results of the participative process and to allow large groups to combine individual responses, reaching a collective group decision. Finally, the application of the RRA methodology and of the DSS DESYCO could be very useful to support the definition of Plans, Policies and Programs according to ICZM principles taking into account the potential impacts of climate change. The proposed approach allows understanding the main drivers of changes in marine water quality and can support the definition of adaptation measures aimed at reducing consequences of climate changes in the future. The methodology applied to the North Adriatic case can be replicated in any other coastal region of the Mediterranean sea and Black sea using set of indicators, dataset and models customized for each application.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.marpolbul.2015.06.037.

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