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TITLE: Multi-objective spatial tools to inform Maritime Spatial Planning in the Adriatic Sea

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Abstract

This research presents a set of multi-objective spatial tools for maritime spatial planning and environmental management in the Adriatic Sea Basin. The tools address four objectives: 1) assessment of cumulative impacts from anthropogenic sea uses on environmental components of marine areas, 2) 3-D hydrodynamic modelling of nutrient dispersion (nitrogen and phosphorus) from riverine sources in the Adriatic Sea Basin; 3) analysis of sea use conflicts and 4) marine ecosystem services capacity assessment from benthic habitats based on an ES matrix approach. Modelling results were presented and discussed for their spatial distribution and relevance for national and international regulatory frameworks in the Adriatic-Ionian Region.

1.Introduction

Maritime Spatial Planning (MSP) is a rapidly expanding approach for ocean and coastal management (Hall et al., 2011; Stamoulis and Delevaux, 2015). MSP is applicable on trans-boundary settings and across sectors to ensure efficient, safe and sustainable development of human activities at sea (EU Maritime Affairs, 2016). In order to practice MSP, decision-makers and planners require an increasing amount of spatial data and tools for archiving, managing and analysing datasets. Moreover, MSP frameworks have an iterative character (Ehler and Douvere, 2009), that requires tools, designed to address multiple challenges of ocean management, that can be flexibly deployed in different stages of the MSP process and that are capable to assimilate and process novel datasets, as they become available (Yee et al., 2015).

In 2014, the European Commission adopted the European Strategy for the Adriatic-Ionian Region (EUSAIR) as macro-regional strategy to create synergies and foster coordination among territories in the Adriatic-Ionian Region (AIR). The EUSAIR recognized the necessity of MSP as a planning framework to foster blue growth and sustainable use of marine resources in the Adriatic Sea, one of the most crowded European Seas (Barbanti et al., 2015; MSP-Platform, 2017).

This paper presents a spatial toolset developed in the ADRIPLAN Project (2012-2015) and further extended through the RITMARE Project - Italian Research for the Sea (2012-2016), capable to address multiple challenges for sea planning and environmental management in the Adriatic Sea. The toolset is developed within the Tools4MSP modelling framework, a regularly updated MSP-oriented open source software suite (Menegon et al., 2017) and the SHYFEM model (Shallow water Hydrodynamic Finite Model; Umgiesser et al., 2004). The toolset addresses four key challenges for the Adriatic Sea, one of the most industrialized sea areas of the Mediterranean: (1) assessment of cumulative impacts (CI) from anthropogenic sea uses on sensitive ecological components of the marine environment, (2) identification of sea use conflicts (SUC), (3) application of a hydrodynamic model for total Nitrogen and Phosphorus (N and P) dispersion mapping and (4) socio-ecological analysis of marine ecosystem services (MES) capacity from benthic habitats. Results from tools application are presented and discussed for their geospatial implications and importance for different regulatory frameworks in the AIR.

2. Materials and Methods

The following section describes the methodology and datasets involved in the development of the spatial tools. Geostatistical analysis and visualizations were performed in ArcGIS 10.1 (ESRI, 2017). Graphs were produced in ggplot2 using R programming language (R-Cran Project, 2017).

2.1. The Adriatic Sea

The Adriatic Sea (252191.4 km^2) is a semi-enclosed basin located in the North-Central Mediterranean Sea (Scheiber and Paik, 2013; Schofield and Townsend-Gault, 2011). It is connected to the Eastern Mediterranean Sea through the Strait of Otranto. The Adriatic Sea embraces six countries: Italy (IT), Croatia (HR), Montenegro (MT), Bosnia & Herzegovina (BH), Albania (AL) and Slovenia (SL). It is an extremely complex system due to its geomorphological and ecological characteristics: lagoons, estuarine areas, coastal high biodiversity habitats (e.g. *Posidonia oceanica* meadows, coralligenous assemblages; UNEP-MAP-RAC/SPA, 2010; Telesca et al., 2015), deep-habitats (e.g. canyons, seamounts, deep-sea corals; Danovaro et al., 2010; IUCN, 2016; Turchetto et al., 2007), with a high variability along its north-south gradient. Moreover it is populated by benthic, demersal and pelagic fish species of high ecologic and commercial value (Coll et al., 2010; DEVOTES-Project, 2016). The rivers with the most extended catchment area are the Po (71327 km^2) and Adige (12417 km^2) in northern Italy, the Neretva river in Croatia (13122 km^2) and the Drin river (13067 km^2) in Albania.
The Adriatic Sea is heavily exposed to anthropogenic pressures (EC, 2011; Goffredo and Dubinsky, 2013) from a complex suite of activities: maritime transport, port activities (Trieste, Venice, Koper, Rijeka, Ancona, Brindisi, Bari or Vlorë), commercial fishery, aquaculture, especially in the lagoons of the Northern Adriatic Sea and tourism (EC, 2011). In future, an intensification of human activities could be expected, leading to increased environmental pressures and sea conflicts: development of new port infrastructures in Ploce (Croatia), Bar (Montenegro) and Vlorë (Albania; Vidas, 2008), container traffic increase by 350% by 2020 (Barbanti et al., 2015), development of new cruising routes (Venice-Ravenna-Bari-Sivola and Kotor), increase of aquaculture activities (Brigolin et al., 2017; EUSAIR, 2017), increased grid connectivity through cabling and pipelines (IGI Poseidon Project, 2016; PCI Project, 2017), potential renewable energy development (Liščić et al., 2014; Schweizer et al., 2016; Vicinanza et al., 2011), new hydrocarbon concessions, establishment of LNG terminals and booming of coastal and cruise tourism (Caric and Mackelworth, 2014).
The spatial characterization of results was performed by dividing the Adriatic Sea into three biogeographic subdivisions according to Bianchi 2004 (Figure 1): 1) The Northern Adriatic (NAd, area = 44434 km^2; 17.6 %) delimited by the Conero Regional Park to Istrija, covering the national sea boundaries of HR, IT and SL; 2) the Central Adriatic (CAd, area = 132610.7 km^2; 52.6%) delimited by the Gulf of Manfredonia to the coastal city of Dubrovnik, covering the national sea boundaries of BH, HR and IT and 3) the Southern Adriatic (SAd, area = 75146.56 km^2; 29.8%) delimited by the city of Otranto, covering the national sea boundaries of AL, HR, IT and MT.

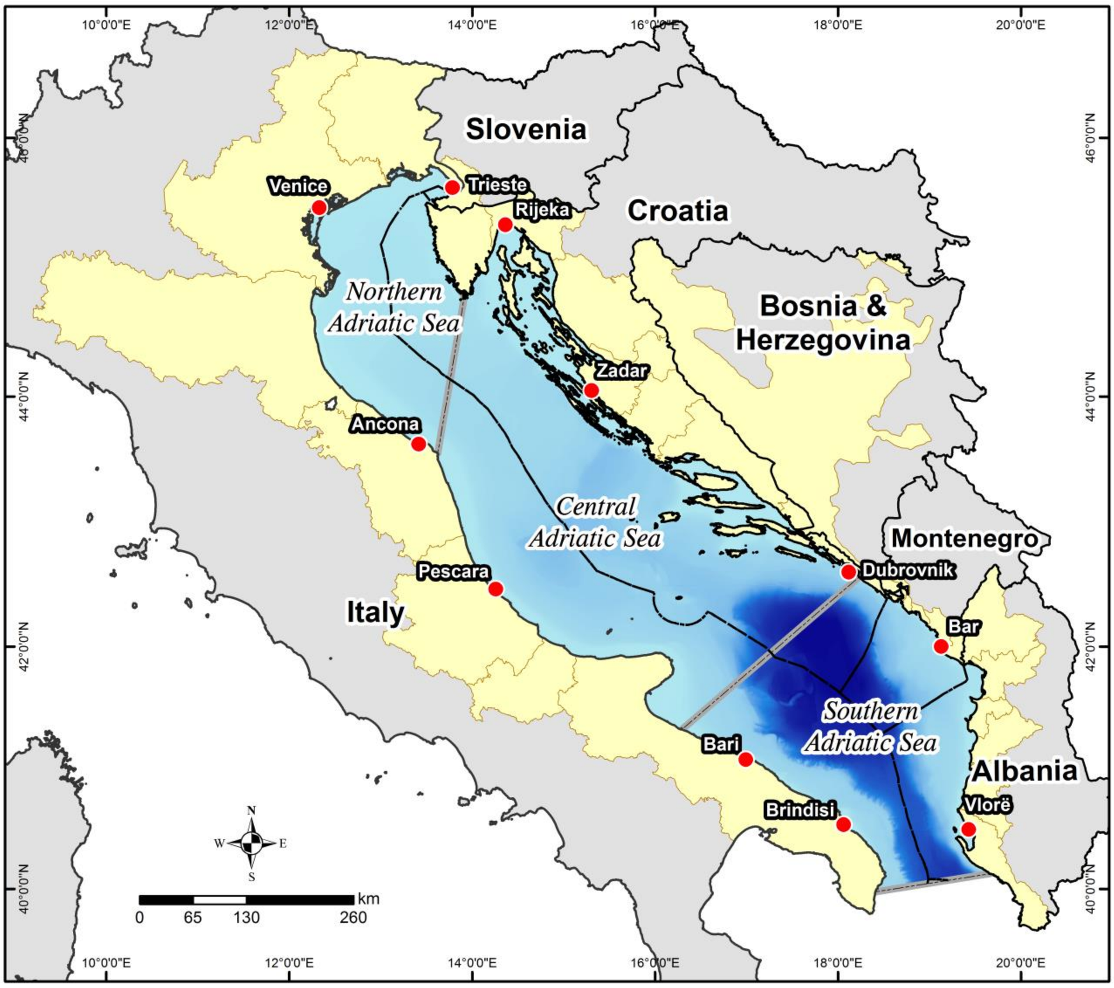

Figure 1. The Adriatic Sea with administrative boundaries of coastal regions, national marine boundaries and three subdivisions (Northern-Central-Southern Adriatic Sea).

2.2. Objective 1: Cumulative impact assessment

One of the first applications of CI occurred in 1980s for the Wadden Sea (Dijkema et al., 1985). Since then, its application has become a widespread modelling technique for cumulative impact assessment on global (Halpern et al., 2008), seabasin (Andersen and Stock, 2013) and regional (e.g. Holon et al., 2015) scale. The implemented CI assessment is composed by a MSP stocktake of 45 layers: 28 environmental components (*E*), 17 human uses (*U*) at sea. Moreover the *U* stocktake includes 18 pressures (*P*), defined as disturbances causing temporary or permanent alterations to one or multiple ecosystem components. The *P* were defined according to the Marine Strategy Framework Directive (MSFD, 2008/56/EC). The units for the spatial indicators *E* and *U* include presence/absence (P/A) (aquaculture, habitats) and, where applicable, intensity indicators were applied (maritime traffic, trawling and small scale fishery). For intensity indicators, a log[x+1] transformation and a rescaling from 0 to 1 was used. In Table 1, an overview of the MSP stocktake is presented. Full *E* and *U* geospatial datasets can be downloaded under Menegon et al. (2016b). At the current stage, the CI model incorporates 516 sensitivities $s(U_i, P_j, E_k)$. Each of the sensitivities includes a distance model $m(U_i, P_j, E_k)$. The distance model uses a 2D Gaussian spatial convolution to model isotropic propagation of impacts across the study area. The CI spatial model implemented can take into account the dispersion of the pressure generated by each single human use as a buffer distance. The CI model functions are available under the Tools4MSP modelling framework/toolbox, an open source geopython library available in its latest version on GitHub (Tools4MSP, 2016). The CI operates on a cell grid resolution of 1 km x 1 km using the standardized European Environmental Grid (EEA, 2013). CI scenario runs can be also performed from the ADRIPLAN Portal using the built-in tool with a resolution of 10 km x 10 km (data.adriplan.eu, 2017a). For more information on the CI assessment in the study and the algorithm adopted we refer to S1 and Barbanti et al. (2015).

Table 1. MSP stocktake for CI assessment and SUC analysis (P/A = presence/absence; I = normalized intensity indicator; PR = proxy; w P/A weighted presence/absence).

Dataset	**Indicator**
Human uses (U)	
Aquaculture, Cables and Pipelines, Coastal Defence Work, Dumping area for dredging, LNGs, Military areas, Off-shore sand deposit, Oil and Gas Extraction, Oil and Gas Research	P/A
Coastal and Maritime Tourism	I/PR - distance from the marinas and number of boats/marinas
Naval Based Activities	I/PR - distance from the cargo ports and port capacity
Maritime Transport	I - Traffic density (number of vessels/year)
Small Scale Fishery	I - fishing effort expressed in 5 classes of intensity: from very low to high)
Pair Pelagic Trawling, trawling	I - hours of activities calculate through Vessel Monitoring System (VMS)
Environmental components (E)	
Marine Mammals, Giant Devil Ray, Turtles, Marine habitats, nursery habitats	P/A
Seabirds	w P/A

2.3. Objective 2: Sea use conflict analysis

The analysis of SUC is important to locate conflict areas, setup conflict mitigation strategies and guide decision makers in the definition of planning processes that can aid sustainable ocean zoning concepts (Bruckmeier, 2005; Hadjimitsis et al., 2016; Moore et al., 2017). The methodology for sea use conflict analysis is based on 17 sea uses (Table 1) using the FP7 project methodology named COEXIST – Interaction in European coastal waters: A roadmap to sustainable integration of aquaculture and fisheries (COEXIST, 2013). The following operational steps were considered: (1) classification and assignment of numerical values to five traits (mobility, spatial (horizontal), vertical and temporal scale, location); (2) assignment of rules to calculate level of conflict for pairwise combinations and (3) calculation of total conflict score for each pairwise use combination within a single grid cell. Similar to the CI assessment, also sea use conflict analysis is implemented through the Tools4MSP modelling framework/toolbox (Menegon et al., 2016) on a 1 km x 1km grid cell resolution (EEA, 2013). For further details on the methodology we refer to Gramolini et al. (2010).

2.4. Objective 3: Nutrient dispersion model

The open source, 3-D hydrodynamic model named SHYFEM (Shallow water Hydrodynamic Finite Model; Umgiesser et al., 2004) was used to model total nutrient (Nitrogen and Phosphorus) dispersion from rivers into the Adriatic Sea, considering a simple decay reaction to represent the first step dynamico of substances in the water sea. A detailed description of SHYFEM equations can be found in https://sites.google.com/site/shyfem/. SHYFEM has been applied in several settings such as the Lagoon of Venice (Ferrarin et al., 2013), the Black Sea (Dinu et al., 2011) and the Curonian lagoon (Umgiesser et al., 2016). SHYFEM solves the shallow water equations in a 3D formulation, using a finite element technique (Bajo et al., 2014). The domain has been represented by a computational grid counting 87,016 nodes and 158,180 triangular elements deployed for the Adriatic Sea, including Venice and Grado-Marano lagoons and the Po deltaic system. The vertical discretization of the domain counts 33 z-layers of same thickness around 1.5 m (surface) until the depth of 100 m and progressively growing under this depth until 70 m depth. Climatic and hydrological conditions, such as wind forcing, precipitations and thermal conduction for the year 2014, were retrieved from the MOLOCH Model from the Institute of Atmospheric Sciences and Climate of the National Research Council of Italy (ISAC-CNR, 2017). Catchment area extension (km^2), river length (km), discharge rate (m^3s^{-1}) and mean riverine N & P inputs (N and P mg l^{-1}) to the Adriatic Sea are presented in S3. For each river a mean annual discharge rate was retrieved, whereas for lagoons and delta systems outlets a mean annual time series was adopted. In total, 80 rivers of the Adriatic Sea Basin (62 – IT; 7 – HR; 7 – AL; 1 – MT/AL; 3 – SL) were collected. Geospatial datasets for catchment area and river length were retrieved from the EEA dataset on large and other rivers (EEA, 2009a and 2009b) and from the European river catchment datasets (EEA, 2008; Figure 2). The total N and P load was retrieved from stations of the water quality monitoring system of the European Environment

Information and Observation Network (EIONET, 2008, 2010, 2011 and 2013) and regional environmental protection agencies (ARPA-FVG, 2013; ARPAE, 2013). Na and P concentrations were collected from monitoring stations in proximity of river mouths or, in absence of a monitoring station at the river mouth, the nutrient concentrations closest to the river mouth was retained. The bathymetry was retrieved from the European Marine Observation and Data Network (Emodnet, 2017) and from regional environmental protection agencies of Veneto and Friuli-Venezia-Giulia Region. Finally, a log normalization [Log (1 + NP_{Total})] of total N and P was performed in order to generate a Total N and P index (TotN&P; Menegon et al., 2017).

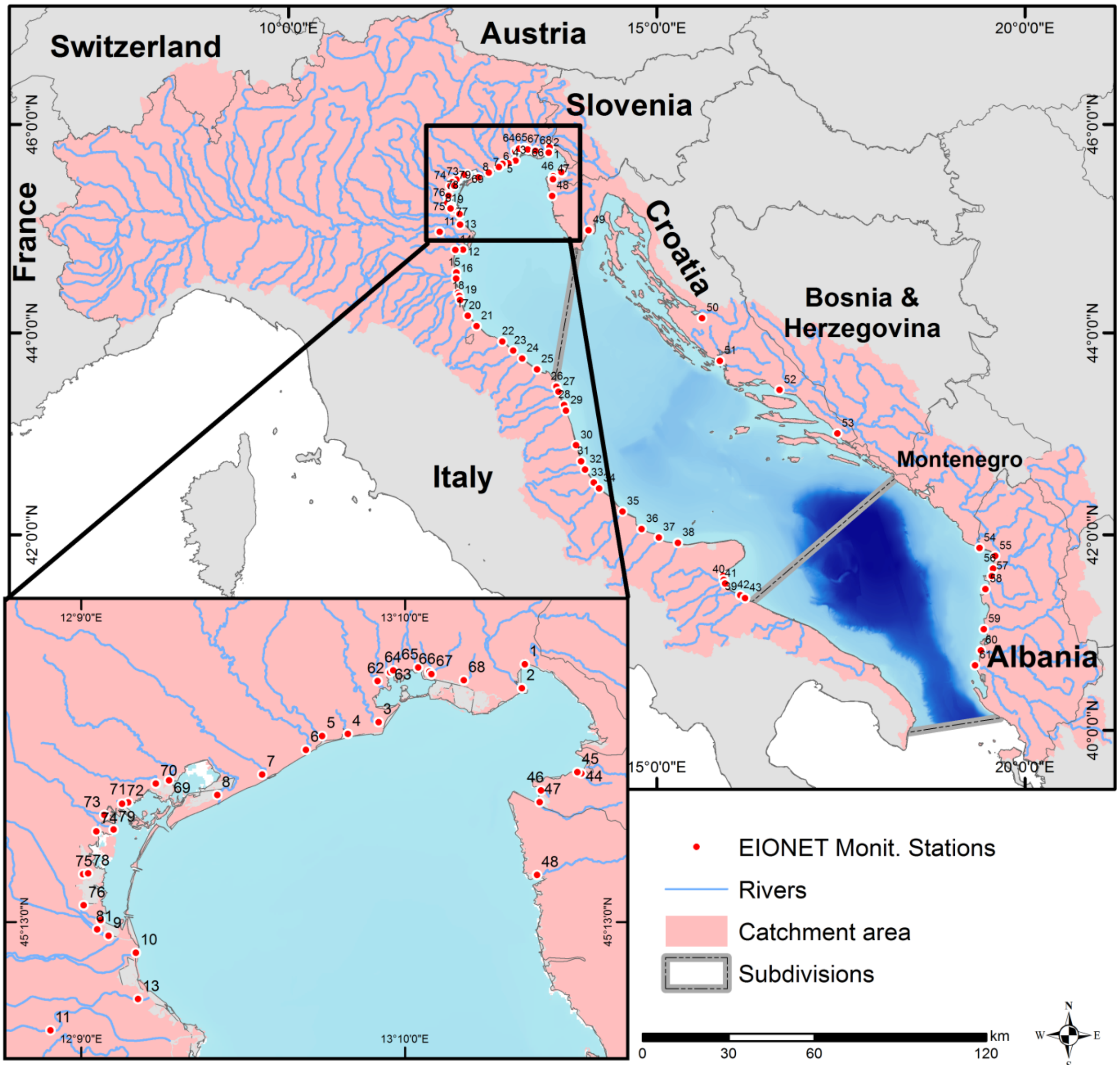

Figure 2. Riverine input dataset of Nitrogen and Phosphorus adopted from EIONET Water Quality monitoring stations applied for 3-D hydrodynamic modelling with SHYFEM. Rivers: 1 - Timavo; 2 – Isonzo; 3 – Tagliamento; 4 – Lovi; 5 – Nicesolo-Iemene; 6 – Livenza; 7 – Piave; 8 – Sile; Brenta/Bacchiglione/Gorzone – 9; 10 – Adige; 11 – Po-Venezia; 12 – Po-Goro; 13 – Po-Levante/Bianco/Tartaro; 14 – Po-Volano; 15 – Reno; 16 – Lamone; 17 – Fiume Unit; 18 – Bevano; 19 – Savio; 20 – Uso; 21 – Marecchia; 22 – Foglia; 23 – Matauro; 24 – Cesano; 25 – Esino; 26 – Musone; 27 – Potenza; 20 – Chienti; 29 – Tenna; 30 – Tronto; 31 – Tordino; 32 – Vomano; 33 – Salinello; 34 – Pescara; 35 – Sangro; 36 – Trigno; 37 – Biferno; 38 – Fortore; 39 – Celone; 40 – Cervaro; 41 – Carapelle; 42 – Candelaro; 43 – Ofanto; 44 – Rizania; 45 – Basadevica; 46 – Drinca; 47 – Dragonia; 48 – Mirna; 49 – Arsa; 50 – Zrmania; 51 – Krka; 52 – Cetina; 53 – Neretva; 54 – Bojana; 55 – Drin; 56 –Mat; 57 – Ishm; 58 – Erzen; 59 – Shkumbi; 60 – Seman; 61 – Vijuse; 62 –Stella; 63 – Turgnano; 64 – Cormor; 65 – Zellina; 66 – Corno; 67 – Aussa; 68 – Natissa; 69 – Silone; 70 – Dese; 71 – Scolmatore; 72 – Osellino; 73 – Lusore; 74 – Bondante; 75 – Lova; 76 – Taglio; 77 – Montalbano; 78 – Lugo; 79 - Naviglio/Brenta; 80 – Morto/Cuori.

2.5. Objective 4: Marine Ecosystem Services Capacity

The capacity of benthic habitats to provide marine ecosystem services (MES) was assessed using a *EUNIS x MES* matrix approach (Table 2). The matrix approach is a popular technique which has been applied in the Mediterranean (Salomidi et al., 2012), the North and Eastern Atlantic Sea (Galparsoro et al., 2014) and other European Seas (Tempera et al., 2016) for rapid assessment of MES capacity of benthic communities.

Table 2. MES capacity matrix including EUNIS habitats and 12 ES according to Salomidi et al (2012) and Galparsoro et al (2014).

				MES_{Prov}		MES_{Reg}			MES_{Cult}			MES_{Supp}				MES_{Cap}
Code	**Habitat Description**	**Area (km^2)**	**%**	**Food provisioning**	**Raw material**	**Air quality**	**Disturbance protection**	**Water quality**	**Cognitive benefits**	**Leisure**	**Feel good/warm glove**	**Photosynthesis**	**Nutrient cycling**	**Nursery**	**Biodiversity**	**Σ**
A3	Infralittoral rock and other hard substrata	254.2	0.1	2	2	2	2	2	2	2	2	2	1	2	2	**23**
A4	Circalittoral rock and other hard substrata	501.1	0.2	2	2	1	2	2	2	2	2	0	2	2	2	**21**
A4.26/32	Med. coralligenous communities moderately exposed to or sheltered from hydrodynamic action	488.2	0.2	2	1	2	0	2	2	2	2	0	2	2	2	**19**
A4.27	Faunal communities on deep moderate energy circalittoral rock	5.7	0.0	2	1	1	1	2	2	2	2	1	2	2	2	**20**
A5.13	Infralittoral coarse sediment	409.8	0.2	2	2	0	0	0	0	1	1	0	1	2	1	**10**
A5.14	Circalittoral coarse sediment	101.4	0.0	2	2	0	0	0	0	0	0	0	1	1	1	**7**
A5.23	Infralittoral fine sands	8836.1	3.6	2	1	0	0	0	0	1	1	0	1	2	1	**9**
A5.25	Circalittoral fine sand	5742.8	2.4	2	1	0	0	0	0	0	0	0	1	2	1	**7**
A5.26	Circalittoral muddy sand	10213.5	4.2	2	1	0	0	1	0	0	0	0	1	1	1	**7**
A5.33	Infralittoral sandy mud	1137.3	0.5	2	0	0	0	1	0	0	0	0	1	1	1	**6**
A5.34	Infralittoral fine mud	721.8	0.3	1	0	0	0	1	0	0	0	0	1	0	1	**4**
A5.35	Circalittoral sandy mud	17461.8	7.2	2	0	0	0	1	0	0	0	0	1	1	1	**6**
A5.36	Circalittoral fine mud	22474.0	9.2	2	0	0	0	1	0	0	0	0	1	1	1	**6**
A5.38	Med. biocoenosis of muddy detritic bottoms	5792.7	2.4	1	0	0	0	1	0	0	0	0	1	0	1	**4**
A5.39	Med. biocoenosis of coastal terrigenous muds	34218.9	14.0	2	0	0	0	1	0	0	0	0	1	1	1	**6**
A5.46	Med. biocoenosis of coastal detritic bottoms	39083.3	16.0	2	0	0	0	1	0	0	0	0	1	1	2	**7**
A5.47	Med. communities of shelf-edge detritic bottoms	38045.8	15.6	2	0	0	0	1	0	0	0	0	1	0	1	**5**
A5.531	*Cymodocea* beds	622.7	0.3	2	1	2	2	2	2	2	2	2	2	2	2	**23**
A5.535	Posidonia beds	413.8	0.2	2	1	2	2	2	2	2	2	2	2	2	2	**23**
A5.5353	Facies of dead "mattes" of *Posidonia oceanica* without much epiflora	17.4	0.0	2	1	2	2	2	2	2	2	2	2	2	2	**23**
A6.3	Deep-sea sand	1618.6	0.7	1	0	0	0	0	0	0	0	0	0	0	2	**3**
A6.4	Deep-sea muddy sand	499.3	0.2	1	0	0	0	0	0	0	0	0	0	0	2	**3**
A6.51	Med. communities of bathyal muds	45403.5	18.6	0	0	0	0	0	1	0	0	0	0	0	1	**2**
A6.511	Facies of sandy muds with *Thenea muricata*	9978.9	4.1	1	0	0	0	0	0	0	0	0	0	0	2	**3**

EUNIS benthic habitats were ranked based on their capacity to provide ES on a scale from 0 (absent/negligible) to 2 (very high). For the case study area, 12 marine ES were considered: two provisioning services (MES_{Prov}: food resources, raw material); three regulating services (MES_{Reg}: air quality, disturbance regulation, water quality); three cultural services (MES_{Cult}: cognitive benefit, leisure, feel good-warm glove) and four supporting services (MES_{Supp}: photosynthesis, nutrient cycling, nursery, biodiversity). MES capacity ranks were adopted from desk research as the studies of Galparsoro et al. (2013) and Salomidi et al. (2012) provide site specific MES capacity scores. In S3 a detailed description of the algorithm used for MES capacity assessment is presented.

Results

Geospatial and geostatistical model results are illustrated in Figure 3 (a-d), geostatistical results are presented in Figure 4. In Figure 5 (a-d) analysis of index scores as function of distance from coastline are presented.

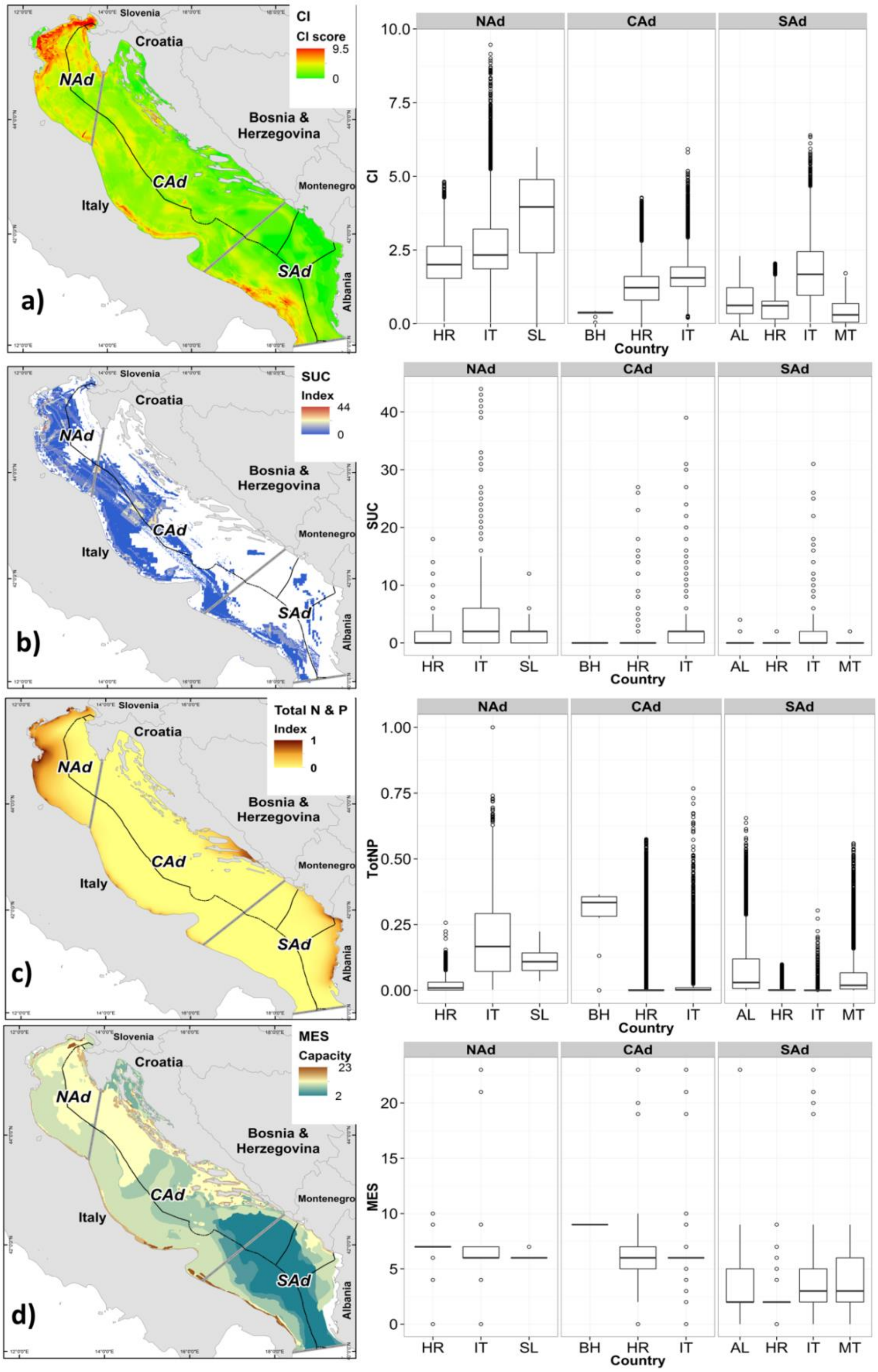

Figure 3. Left: Geospatial results of tools application for the study area: a) CI assessment; b) SUC analysis; c) SHYFEM nutrient dispersion model; d) MES capacity from marine habitats. Right: Comparison of model results for each subdivision. Boxplots show maximum outliers, minimum outliers, boxes enclose first and third quartiles and box centres define median.

Geospatial results presented in Figure 3a indicate that high CI scores are dominant in sea areas of Friuli-Venezia Giulia, Veneto and Emilia Romagna Region located in the NAd. Maximum CI scores reach 9.5. The Slovenian Coastal Karst Region has a maximum CI score of 6 and the Croatian Istria Region a CI score of 4.8. In proximity of the port of Ancona (Marche Region) in Italy more localized high CI scores are evident. On average the Slovenian sea space has the higher CI scores ($\tilde{x}$ = 4) compared to Italy ($\tilde{x}$ = 2.3) and Croatia ($\tilde{x}$ = 2). In the CAd, CI scores are highest in Italian sea areas with a range from 0.2 to 5.9. Especially in proximity of the port of Pescara (Abruzzo Region) CI scores are relevant. For the Croatian sea areas CI score range from 0 to 4.2, with high scores in proximity of Zadar port (Dalmatia). Bosnia and Herzegovina has a negligible CI score. On average the Italian sea space has the highest CI score ($\tilde{x}$ = 1.6), followed Croatia ($\tilde{x}$ = 1.2) and Bosnia & Herzegovina ($\tilde{x}$ = 0.4). In the SAd, the CI scores for Italian sea areas range from 0 to 6.4, followed by Albania (score 2.3), Croatia (score 2) and Montenegro (score 1.7). In particular coastal areas of Apulia Region register highest CI scores in proximity of Bari and Brindisi port. On average, CI score is highest in Italy ($\tilde{x}$ = 1.7) followed by Albania and Croatia ($\tilde{x}$ = 0.6 respectively) and Montenegro ($\tilde{x}$ = 0.3).

In figure 3b, results from sea use conflict analysis show that in the NAd the Italian sea space has the highest SUC score range, from 0 – 44, followed by Croatia (score 18) and Slovenia (score 12). Average SUC scores are equal in Italy and Slovenia ($\tilde{x}$ = 2). For Croatia SUC scores are negligible.

In the CAd, highest SUC score are located in Italy (score 39), followed by Croatia (score 27). Bosnia and Herzegovina has a negligible SUC score. The average SUC score is highest in Italian sea area ($\tilde{x}$ = 2). In the SAd Italy has the highest SUC score (score 31), followed by Albania (score 4) and Croatia and Montenegro (score 2).

In figure 3c, results from nutrient dispersion (N and P) are presented in form of TotN&P index. Highest nutrient loads are located in the NAd in proximity of the Po Deltaic System (score 1). Slovenian and Croatian sea areas have similar TotN&P score of o.2 and 0.3 respectively. In the CAd highest score are located in Italy (score 0.8) followed by Croatia (score 0.6) and Bosnia & Herzegovina (score 0.4). In particular coastal area of Dalmatia Region in Croatia and in localized areas of the Marche and Abruzzo Region coasts are affected. The highest average TotN&P score is located in Bosnia and Herzegovina ($\tilde{x}$ = 0.3). In the SAd the TotN&P index is highest in Albania (score 0.7), followed by Montenegro (score 0.6) and Italy (score 3.3). Croatia has negligible TotN&P scores. The highest average TotN&P score is located in Albania ($\tilde{x}$ = 0.7), followed by Montenegro ($\tilde{x}$ = 0.6) and Italy ($\tilde{x}$ = 0.3).

The spatial distribution of riverine input data applied for hydrological modelling is presented in figure 2 and a detailed overview of discharge rate (m^3s^{-1}), catchment area (km^2), river length (km), mean N and P concentrations ($mg\ l^{-1}$) is presented in supplementary material (S3). In the NAd 36 (IT - ; HR) rivers were defined, in the CA 18 (7 – HR; 11 - IT) rivers and in the SA 12 rivers (7 – AL; 1 - AL/MT; - IT). In total, the drainage area of the Adriatic Sea covers 23.8 x 10^4 km^2. The rivers with biggest drainage area and highest mean discharge rate are the Po (74000 km^2; m^3s^{-1}), the Neretva in Croatia (13121 km2; 378 m^3s^{-1}), the Drini in Albania (13067 km^2; 338 m^3s^{-1}) and the Adige river in Italy (12400 km^2; 200.8 m^3s^{-1}). The total drainage area of those rivers covers 10.9 x 10^4 km^2, about 46.1 % of the total drainage area of the Adriatic Sea. Other rivers of relevance are the Bojana river (6056.2 km^2; 00 m^3s^{-1}) at the border with Albania and Montenegro, Reno (5911.7 km^2; 00 m^3s^{-1}), Piave (4433.1 km^2; 87 m^3s^{-1}) in the Italian NAd, the Cetina river (3868.9 km^2; 32.0 m^3s^{-1}) in Croatia and the Ofanto river (2776.6 km^2 11.7 m^3s^{-1}) in the SAd. Other rivers coming from the Apennines in the CAd and SAd and from the Croatian Adriatic Sea catchment area have a torrential hydrological regime (Cosic et al., 2004; Guarnieri et al., 2016; Vollenweider et al., 1990).

Results in Figure 3d from MES capacity mapping indicate that highest capacity in the NAd is located in Italy (score 23), followed by Croatia (score 10) and Slovenia (score 7).Whereas average scores are similar for all three countries ($\tilde{x}$ ranges from 6 to 7). In the Cad, maximum MES capacity scores are located in Italy and Croatia (score 23 respectively). To notice is that Bosnia & Herzegovina has the highest average score of 9, followed by Italy and Croatia with 6 respectively. In the SAd maximum MES capacity scores are locate in Italy and Albania (score 23 respectively), followed by Croatia and Montenegro (score 9). Average MES capacity score are low compared to NAd and Cad ($\tilde{x}$ = 3 for Italya and Montenegro; $\tilde{x}$ = 2 for Albania and Croatia).

The marine ES capacity matrix is presented in table 3 while its geospatial representation is shown in figure 3d. Marine habitats with the highest ES capacity are as follows: A3 - infralittoral rock and other hard substrata (254.2 km^2, 0.1%), A5.535 - Posidonia beds (413.8 km^2, 0.2%), A5.531 - Cymodocea (622.7 km^2, 0.3 %), A5.5353 - Facies of dead "mattes" of *Posidonia oceanica* without much epiflora (17.4 km^2, 0.0%), A4 - Circalittoral rock and other hard substrata (501.1 km^2, 0.2%), A4.27 – Faunal communities on deep moderate energy circalittoral rock (5.7 km^2, 0.0 %) and A4.26/A4.32 – Med. coralligenous communities (488.2 km^2, 0.2%). Marine habitats with low ES capacity are related to deep sea environments: A6.1 - Deep-sea rock and artificial hard substrata (80.9 km^2, 0.0%); A6.2 - Deep-sea mixed substrata (82.3 km^2, 0.0%); A6.3 - Deep-sea sand (2141.1%, 0.4%); A6.4 - Deep-sea muddy sand (3338.5 km^2, 0.7%), A6.51 - Med. communities of bathyal muds (45403 km^2, 18.6%) and A6.511 - Facies of sandy muds with *Thenea muricata* (9978.9 km^2, 4.1%). According to table 1, max ES capacity (MES = 23) is located in coastal areas of Italy, Croatia and Albania. The highest mean capacity is located in the NAd (Italy and Croatia).

In figure 4 (a-d), the mean (μ) index scores as a function of distance from coastline (in km) are presented. Distance from coast was considered from the continental coastline. The lagoons of Venice, Grado-Marano and the aquifer of Comacchio in Italy were retained from this analysis.

In the NAd, the highest mean CI score (μ =5.3) is located in Slovenia at a distance of about 11 km from coast, whereas for Italy the highest mean CI (μ=3.9) is located at a distance of 8 km.

Similarly to the NAd, the highest mean CI score for the CAd is located at 10 km from Italian coasts (μ =2.5). For the Croatian CAd, the highest mean CI is located at 75-80 km distance from coast (μ = 1.8).

In the SAd, the highest mean CI scores are located at 6 km distance from Italian coasts (μ =3.2), whereas for Croatia at 20 km from coast (m=1.7). For Albania, the highest mean CI scores (μ =1.4) are located at 54 km from coast, while Montenegro mean CI scores (μ =1) occur at 44 km distance from coast.

In the NAd highest mean SUC score (μ =5.4) is located at about 15 km from Italian coasts, followed by Slovenia (μ =2.6) at 7 km distance and Croatia (μ =2.5) at about 30 km distance. On overall the CAd registers the highest mean SUC scores of the entire study area between 80-90 km from Croatian coasts (μ =27), whereas, for Italy, the highest SUC scores are located at 10 km (μ =3.2). In the SAd, the highest mean SUC scores (μ =6.2) are located at 5 km from Italian coasts, followed by Albania (μ =1.3) at 54 km distance, Montenegro (μ =1.1) at 42 km distance and Croatia (μ =0.4) at 25 km distance.

The highest mean Total N & P index scores are located in Italian NAd with mean values of about 0.4 within the 1 km distance from coast. Highest Total N & P scores for Slovenia (μ = 0.2) area are found at 11 km from coast. In the CAd, the highest Total N & P index scores were found in Bosnia & Herzegovina (μ =0.3), followed by Italy (μ ranging from 0.1 to 0.2) at 2 km from coast and below μ = 0.1 from coast in Croatia. In the SAd, the highest mean Total N & P index score are found in Montenegro (μ ranging from 0.2 to 0.3) at 3 km from coast, in Albania (μ =0.2) at 1 km from coast and in Italy (μ lower than 0.1) as well at 1 km from coast.

The highest mean MES capacity scores in the NAd are located at 1 km distance from coast in Italy (μ =15) and Croatia (μ =7.4) and at 10 km from coast for Slovenia (μ =6.7). In the CAd, the highest mean MES capacity scores are located within 5-10 km distance from coast in Italy (μ =9.8), Croatia (μ =6.5) and Bosnia & Herzegovina (μ =9). In the SAd, the highest mean MES capacity scores are located within 1-2 km from coast for Italy (μ =17.5), 1-2 km for Croatia (μ =7.5), at 25 km for Albania (μ =4) and 3-5 km in Montenegro (μ =8).

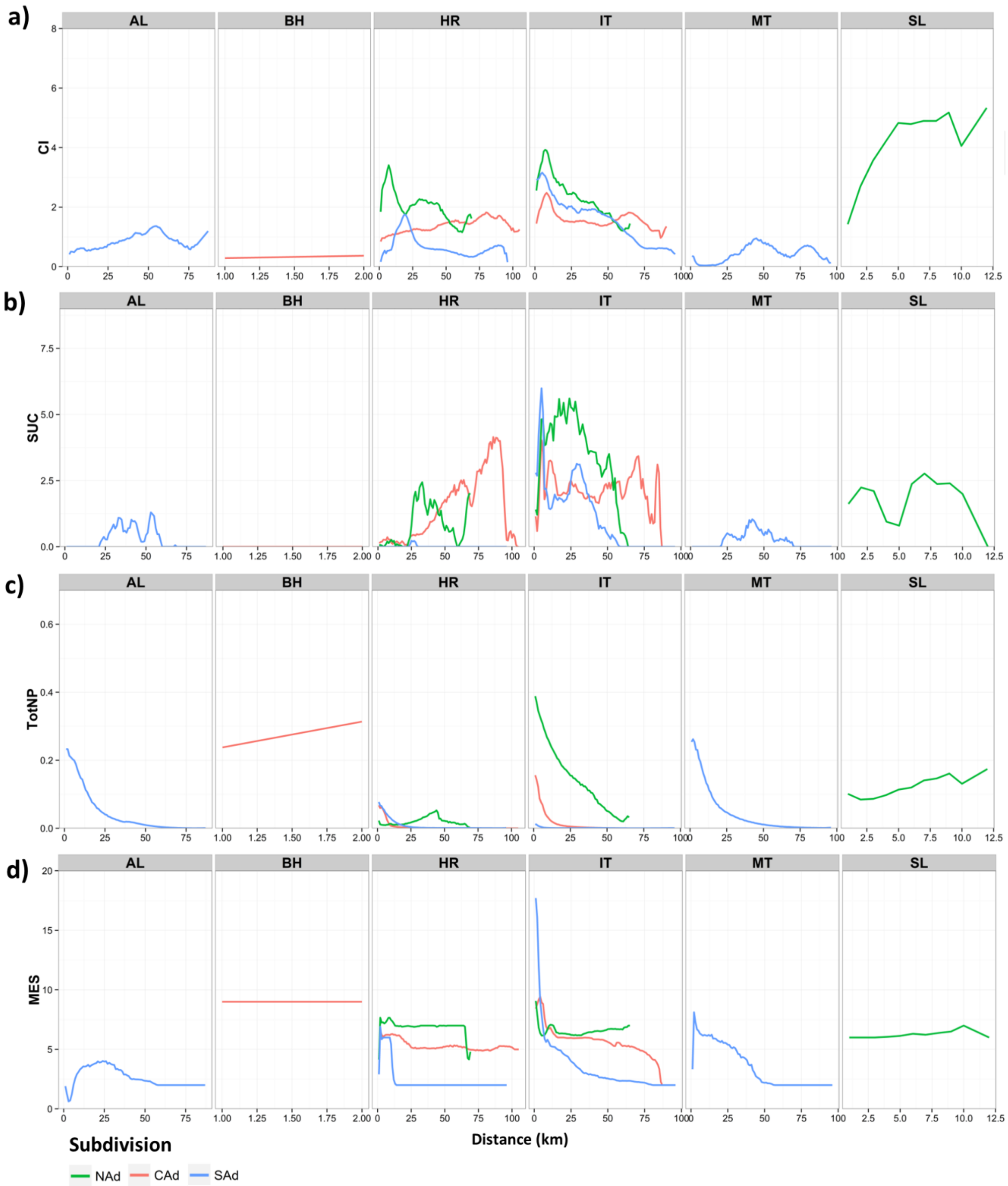

Figure 4. Mean index scores as function of distance from coast (in km), by country (AL – Albania; BH – Bosnia & Herzegovina; HR – Croatia; IT – Italy; MT – Montenegro; SL - Slovenia) and sea space segments (NA = Northern Adriatic; CA = Central Adriatic; SA = Southern Adriatic).

3. Discussion

The NAd covers 25.2% of the total study area and can be considered as a regional hub, as it is affected by intensive anthropogenic activities in its coastal and marine areas, such as shipping traffic, coastal and maritime tourism, oil and gas research and extraction, cables and pipelines, aquaculture, trawling and small scale fishery. Moreover, there is a considerable land-sea interaction deriving from commercial port activities such as Venice (Veneto Region), Trieste (Friuli-Venezia-Giulia), Ancona (Marche Region), Koper (Coastal Karst Region) and Rijeka (Istrija Region), the presence of mass tourism resorts (Veneto and Emilia Romagna Regions) and industrial and agricultural runoff from

NAd rivers, which have significant influence on coastal water quality this part of the study site (Della Croce et al., 1995; Bramwell 2004).

The CAd covers 37.1 % of the total study area and can be considered a transitional sea area. Sea use conflicts are localized mostly offshore, characterized by intensive maritime traffic along the north-west and south-east axes. In coastal areas, CI are dominated by small scale fishery and trawling. Land-sea interaction is more localized in proximity of Pescara port (Abruzzo Region). River input is important, as most of the rivers have torrential character.

The SAd covers 37.5 % of the total study area is the gateway connecting, through the Strait of Otranto, the Adriatic Sea to the Ionian Sea and the Eastern Mediterranean Sea. Similar to other straits in European Seas, such as Gibraltar (Oral and Simard, 2008), English Channel (OSPAR 2009) or Danish Straits (HELCOM, 2010), also the Otranto Strait is characterized by intensive maritime transport, especially near Italian coastal areas, determining high CI scores and increasing sea use conflicts with other more localized sea uses, such as coastal and maritime tourism in Apulia Region, intense port activities (ports of Bari and Brindisi) and small scale fishery activities distributed along the entire coastal area.

The peculiarities of anthropogenic uses, in combination with vulnerable ecological resources evidenced in the three subdivision, require an in depth analysis of trade-offs among competing sea uses and robust environmental impact assessment tools that can be deployed flexibly on site specific contexts. In the future, the implemented CI assessment will be further developed considering the (a) refinement of the spatial dispersion model to better understand specific spatial dynamics of pressures, (b) modulation of CI considering additive, synergetic or antagonistic impact phenomena, (c) implementation of a CI backtracking module for sourcing the human activities generating single or multiple pressures on an environmental component, (d) integration of land-based activities into the CI assessment model supported by hydrodynamic model functionalities, (e) modelling of non-linear response of environmental components to specific pressures (Halpern et al., 2015) and (f) assessment of cumulative impacts over ecosystem services provision (Hooper et al., 2017).

The development of CI and sea use scenario needs to be further integrated with MSP datasets of future planned shipping routes, new port developments, coastal urban development trends, tourism flow projections, detailed information on potential renewable energy sites, such as offshore wind energy (Schweizer et al., 2016) or wave energy (Vicinanza et al., 2013) sites including the potential environmental impacts performed and quantitative spatial datasets on commercial fishery catch to better understand fishing fleet dynamics and the potential cumulative impacts and conflicts generated.

The nutrient dispersion model evidenced that the NAd Sea is considerably influenced by riverine run off in coastal and offshore areas. Among the river basins integrated in the database, the Po river basin has the biggest extension (71.137 km^2; S3). The Po plain is subjected to intensive anthropogenic-driven modifications as it hosts 15.7 x 10^6 inhabitants and its industrial, agricultural and service sectors produce about 40% of the national GDP (ADPO, 2017). The basin plays a determining role in eutrophication phenomena in the Adriatic Sea especially in the coastal segment of 90 km from the Po Deltaic System to Ravenna, and it is subjected to seasonal eutrophication phenomena affecting coastal water quality (ADPO, 2006).

In the CAd, the rivers with most extended catchment areas are the Neretva (13121.9 km^2) and Cetina (3868,9 km^2) in Croatia and the Pescara river (3158,3 km^2) in Italy. The Neretva river is the largest river of the eastern part of the Adriatic with considerable freshwater inputs to the Moli Ston Bay (Bužančić et al., 2016). According to geospatial results presented in Figure 3c, the plume generated by the Neretva river has the highest area of influence in the CAd.

In the SAd rivers with most extended catchment area is the Drin river (13067.4 km^2) in Albania and Buna/Bojana river (6065.2 km^2) that partially forms the border between Albania and Montenegro. The plume of the latter has influence over 150 km northwards, along the eastern coast (Marini et al., 2010).

Hydrodynamic models are getting increased attention due to their potential support in MSP (Filgueira et al., 2014; Mohn et al., 2011), MSFD (Garcia-Gorriz et al., 2016; Hansen et al., 2015) and WFD (Tsakiris and Alexakis, 2012). The presented hydrodynamic model has capabilities to provide information in support of EU MSFD descriptors, as they can determine indicators for past, present and future conditions, estimate future impact scenarios, fill data gaps and support the design of monitoring campaigns (Mohn et al., 2011; MSFD Modelling Framework, 2017; Piroddi et al., 2015). In particular, hydrodynamic modelling capabilities can be important for addressing MSFD descriptors that are not place specific (Gilbert et al., 2015), such as eutrophication (D5; Umgiesser 2005), contaminants (D8; Periáñez, 2009), contaminants in seafood (D9; Pommepuy et al., 2006), marine litter (D10; Ballent et al., 2013; Krelling et al., 2017) and energy, in terms of noise pollution (D11; Menegon et al., 2017; Rossington et al., 2013). In support of MSP in the study area, the presented nutrient dispersion model is part of a comprehensive research effort for the integration of full range of pressures derived from land-based activities (e.g. urban cities, coastal tourism, catchment areas) into a socio-economic database. Similarly to other CI assessments, the results from the hydrodynamic modelling will be integrative component of the CI assessment in form of land based activities. A major advantage of the presented hydrodynamic model, compared to other CI assessments in the Mediterranean (Holon et al., 2015; Micheli et al., 2013) is the comprehensive dataset of rivers, discharge rates and N and P concentrations coupled to the model. This allows a flexible deployment of nutrient dispersion scenarios on different spatial scales, taking into account anthropogenic activities, such as coastal tourism (Guimarães et al., 2012) or aquaculture (Bannister et al., 2016) and ecological peculiarities that affect or can be impacted by coastal water quality. Moreover, the presented nutrient dispersion model is a valuable test case for ecosystem services research in the study area, as model results can be used as proxy for the analysis of three ES in particular: 1) regulation of water flows (e.g. water purification and mass transport of water) associated to river plume especially in coastal areas of the NA (e.g. Po and Adige river), the CA (Neretva river) and SA (e.g. Drin river) or 2) waste treatment and assimilation, due to dilution and dispersal of toxicants through hydrodynamics processes (Hattam et al., 2015) and 3) through the coupling of biogeochemical models model indicators for microbial reduction and cycling of excess nutrients can be generated (Liquete et al., 2013).

The presented MES capacity model is a rapid screening methodology for the analysis and mapping of marine ES on large spatial scale. Results show that coastal areas featuring seagrasses of *Posidonia Oceanica* meadows and *Cymodocea* spp. beds are high ES capacity areas. Seagrass meadows play an essential ecological role and are fundamental for supporting biodiversity conservation, nursery and habitat conservation, provision nutrient cycling and are responsible for photosynthesis processes (Campagne et al., 2015). In this context, the presented model can inform planners on the ecological functioning of coastal areas and provide baseline information for the development of ecosystem-based management strategies, required by the MSFD. From a planning perspective, the presented results can support MPA designation and management (Potts et al., 2013); however further datasets are required: 1) field measurements on benthic communities distribution coupled with predictive model to assess benthic community distribution are required (Colin et al., 2011; Puls et al., 2012), 2) ecological multi-functionality needs to be addressed using geostatistical techniques (Lefcheck et al., 2015; Schröter and Remme, 2016), 3) habitat fragmentation models are required to better address ecological resilience (Cognetti and Maltagliati, 2010) and 4) improved proxies for monetary and non-monetary benefits from ecological functioning are needed to better inform environmental managers. Moreover, the presented ES capacity model can be used as initial step to extent the sensitivity analysis implemented in the presented CI model, by linking the sensitivity of a benthic habitat to single or multiple pressures as a function of the specific service it supplies (Depellegrin et al., 2013; Hooper et al., 2017).

In the Adriatic Sea, the majority of marine ES research in the study area is focused on the Venice lagoon (Nunes et al., 2004 and 2008; Zanatta et al., 2005); we consider the presented mapping approach a first step towards a wider analysis of ES in the Adriatic Sea. Considering the ongoing MSP implementation process in the study, ES frameworks are particularly suitable for trade-off and synergy analysis in MSP (Lester et al., 2013; White et al., 2012) as they support the analysis of direct and indirect socio-ecological benefits from different conflict mitigation strategies. This is essential in high intensity sea use areas, such as the Northern Adriatic, where space limitation induces trade-offs among environmental components and anthropogenic activities. In the near future, ES capacity assessment will be further developed considering sea use specific supply/demand ES assessment.

4. Conclusions

Although the presented modelling approaches were designed in the context of specific objectives, they are highly interlinked through the dataset they process and through the environmental, planning and regulatory challenges they address. In the specific case of CI assessment, the MES framework can provide methodological advancement and support a better understanding of human-nature interaction, while hydrodynamic models, which are valuable tools for the analysis of MSFD descriptors, can be used to quantify regulating ES (e.g. water purification, waste treatment, coastal water quality) and feed CI models with spatial explicit indicators for anthropogenic pressures from land based activities (e.g. toxic compounds, heavy metals or pathogens). In the study area, the scale of analysis remains an essential factor, as it has implications on data availability and therefore on model results.

The Tools4MSP modelling frameworks and SHYFEM are open source software tools. This can have an essential role in the advancement of analytical tools as they enable sharing of codes, development of user/developer communities and enable critical reflection on conceptual and methodological constrains among expert communities.

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Supplementary material

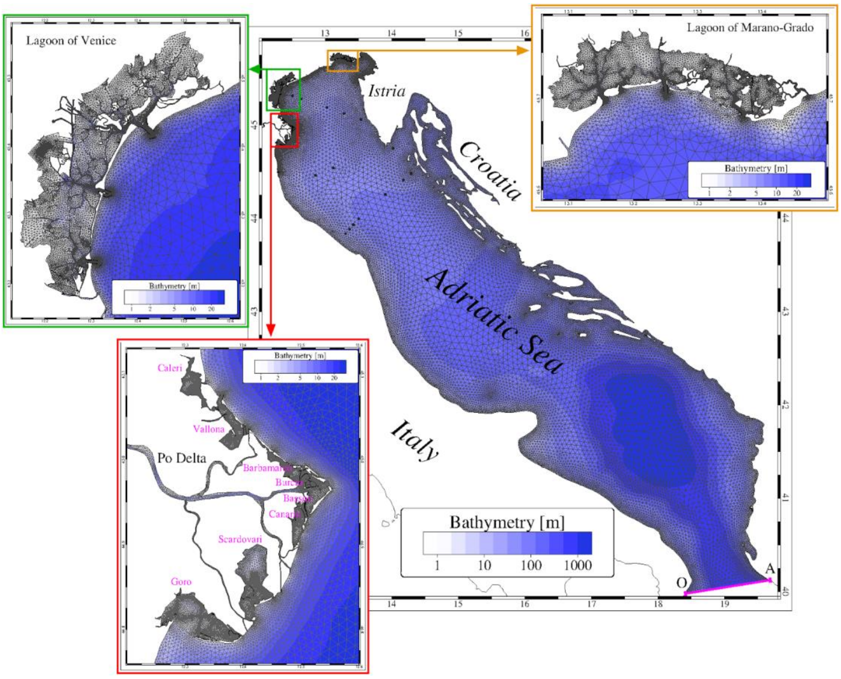
Supplementary material for this research includes the following items: CI assessment algorithm adopted from Andersen and Stock 2013 (Appendix S1), SHYFEM 3D Grid (Appendix S2), riverine database (Appendix S3), marine ES capacity algorithm (Appendix S4), marine ES capacity matrix (Appendix S5).

S1. CI assessment algorithm modified from Andersen and Stock 2013.

$$CI = \sum l_i \sum m_j \sum n_k \, s(U_i, P_j, E_k) i(U_i, P_j, E_k) d(E_k) \, w_i^U w_k^E$$

- *U* = Activities and uses
- *E* = Environmental components
- *P* = Pressures
- *s(U, P, E)* = Sensitivities
- *i(U, M)* = intensity *U* in the cell in question according to spatial model *M*.
- w^U *and* w^E = weights for human activities and ecosystem components

S2. SHYFEM 3D grid including Lagoon of Venice, Lagoon of Grado-Marano and Po Delta System. Author: M.Ghezzo.



S3. Input datasets for the hydrodynamic model including river length (km), catchment area (km^2) mean discharge rate (m^3 s^{-1}), mean annual nutrient concentration in mg l^{-1} for N and P.

River	Nation	Length (km)	Catchment (km^2)	Discharge rate (m^3s^{-1})	Ntot (mgl^{-1})	Ptot (mgl^{-1})
Tagliamento	IT	171	2610	timeserie	1.81	0.02
Lovi	IT	9	45	10	1.37	0.02
Livenza	IT	163	2503	timeserie	3.22	0.06
Piave	IT	228	4433	timeserie	2.00	0.03
Sile	IT	22	52	timeserie	3.50	0.07
Adige	IT	455	12417	timeserie	1.54	0.06
Po-Venezia	IT	699	71327	timeserie	2.70	0.13
Reno	IT	212	5912	timeserie	5.50	0.07
Bevano	IT	14	316	1.5	6.46	0.22
Savio	IT	97	643	timeserie	8.25	0.02
Marecchia	IT	70	2	timeserie	19.00	0.13
Cesano	IT	70	638	5	1.60	0.68
Tronto	IT	95	1258	8.6	1.60	0.13
Salinello	IT	72	617	18	1.60	0.15
Pescara	IT	158	3153	29.2	5.50	0.30
Sangro	IT	126	1743	21	0.33	0.07
Trigno	IT	91	1207	12.6	0.33	0.07
Fortore	IT	109	1595	13.5	1.60	0.15
Candelaro	IT	70	551	2.5	1.60	0.15
Ofanto	IT	163	2777	14.3	5.50	0.45
Basadevica	SL	9	39	0.22	7.22	0.08
Drinca	SL	3	14	0.22	4.20	0.16
Dragonia	HR	25	147	0.7	4.09	0.05
Mirna	HR	62	15	7.6	0.75	0.05
Krka	HR	98	2549	53.4	1.50	0.03
Mat	AL	111	2596	timeserie	4.33	0.05
Erzen	AL	97	904	timeserie	4.65	0.06
Vijuse	AL	248	6640	timeserie	5.40	0.07
Turgnano	IT	4	208	timeserie	3.43	0.06
Cormor	IT	11	208	timeserie	5.25	0.04
Zellina	IT	16	52	timeserie	5.43	0.03
Corno	IT	8	8	timeserie	8.25	0.03
Aussa	IT	15	203	timeserie	5.55	0.02
Natissa	IT	8	58	2	3.98	0.33
Dese	IT	37	390	timeserie	3.26	0.22
Osellino	IT	2	212	timeserie	2.80	0.18
Taglio	IT	2	156	timeserie	2.30	0.10
Montalbano	IT	5	156	timeserie	3.21	0.10
Timavo	IT	89	9	2	1.72	0.02
Isonzo	IT	146	36	timeserie	2.16	0.01
Nicesolo-lemene	IT	72	720	12	1.80	0.13
BrentaBaccGorz	IT	171	2261	timeserie	2.30	0.13
Po-Goro	IT	49	14	timeserie	2.70	0.13
Po-LevBiaTar	IT	187	2349	22	5.50	0.13
Po-Volano	IT	62	546	11	6.00	0.13
Lamone	IT	103	2	timeserie	5.50	0.03
FUniti	IT	101	1258	timeserie	5.95	0.02
Uso	IT	49	214	timeserie	13.51	0.17
Foglia	IT	85	702	7	5.50	0.32
Matauro	IT	101	1396	10.7	1.60	0.07
Esino	IT	84	955	15	1.60	0.06
Musone	IT	70	641	6.4	5.50	0.30
Potenza	IT	95	2	5.1	1.60	0.13
Chienti	IT	101	4	8.9	1.60	0.18
Tenna	IT	71	487	7	5.50	0.15
Tordino	IT	61	444	6	5.50	0.30
Vomano	IT	77	784	15	11.50	0.60
Biferno	IT	77	1316	25	8.81	0.14
Celone	IT	90	2149	2.5	13.35	0.85
Cervaro	IT	105	673	2.8	4.55	0.03
Carapelle	IT	94	1020	2.1	8.81	0.14
Rizania	SL	15	78	3.17	2.84	0.04
Arsa	HR	58	486	12.6	1.66	0.03
Zrmania	HR	88	853	37.6	0.33	0.07
Cettina	HR	196	22	32	0.37	0.01
Nereteva	HR	281	13122	timeserie	3.80	0.02
Bojana	AL/MT	229	6056	timeserie	4.12	0.09
Drin	AL	249	13067	timeserie	4.12	0.09
Ishm	AL	73	769	timeserie	4.37	0.53
Shkumbi	AL	175	12	timeserie	4.65	0.06

Seman	AL	86	59	timeserie	5.25	0.08
Stella	IT	69	675	timeserie	4.00	0.03
Silone	IT	70	534	timeserie	3.00	0.11
Scolmatore	IT	4	10	timeserie	2.30	0.19
Lusore	IT	6	14	timeserie	4.00	0.24
Bondante	IT	2	12	timeserie	3.13	0.15
Lova	IT	NA	NA	timeserie	3.00	0.14
Lugo	IT	NA	NA	timeserie	5.40	0.19
NavBrenta	IT	83	738	timeserie	2.80	0.16
MortoCuori	IT	178	2034	timeserie	4.70	0.14

S4. Algorithm applied for marine ecosystem services capacity assessment.

$$C_{MES} = MES_{Pro} + MES_{Reg} + MES_{Cul}$$

Whereas the capacity of MES to type *i* to provide ES can be described as follows:

$$MES_i = \sum ES$$