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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 sea 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) analysis of sea use conflicts; 3) 3-D hydrodynamic modelling of nutrient dispersion (nitrogen and phosphorus) from riverine sources in the Adriatic Sea Basin and 4) marine ecosystem services capacity assessment from seabed habitats based on an ES matrix approach. Geospatial modelling results were illustrated and analysed for three biogeographic subdivisions, Northern-Central-Southern Adriatic Sea. The paper discusses model results for their spatial implications, relevance for sea planning, limitations and concludes with an outlook towards the need for more integrated, multi-functional tools development for sea planning.

1.Introduction

Maritime Spatial Planning (MSP) is a rapidly expanding approach for ocean and coastal management (Stamoulis and Delevaux, 2015). MSP is intended to be used 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 conduct 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 (MSP-Platform, 2017).

This paper presents a spatial toolset initially developed in the ADRIPLAN Project (2012-2015) and comprehensively extended through the RITMARE Project – Italian Research for the Sea (2012-2016), capable of addressing 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: (1) assessment of cumulative impacts (CI) from anthropogenic sea uses on 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 seabed habitats. The paper presents datasets and methodologies applied in the models and describes results for their geospatial implications, importance for sea planning and model limitations. The paper concludes with a discussion on the current specificities of the toolset and its future advancements towards more integrated and multi-functional modelling perspective.

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) and ggplot2 library of R programming language (R-Cran Project, 2017).

2.1. The Adriatic Sea

The Adriatic Sea (25,2191 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 borders 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; 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 (71,327 km^2) and Adige (12,417 km^2) in northern Italy, the Neretva river in Croatia (13,122 km^2) and the Drin river (13,067 km^2) in Albania.

The Adriatic Sea is heavily exposed to anthropogenic pressures (EC, 2011; Goffredo and Dubinsky, 2013) generated by 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 the 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), 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 = 44,434 km^2; 17.6 %) delimited by the Conero Regional Park to southern tip of the Istrian peninsula, covering the national sea boundaries of HR, IT and SL; 2) the Central Adriatic (CAd, area = 13,2610 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 = 75,146 km^2; 29.8%) delimited by the city of Otranto, covering the national sea boundaries of AL, HR, IT and MT.

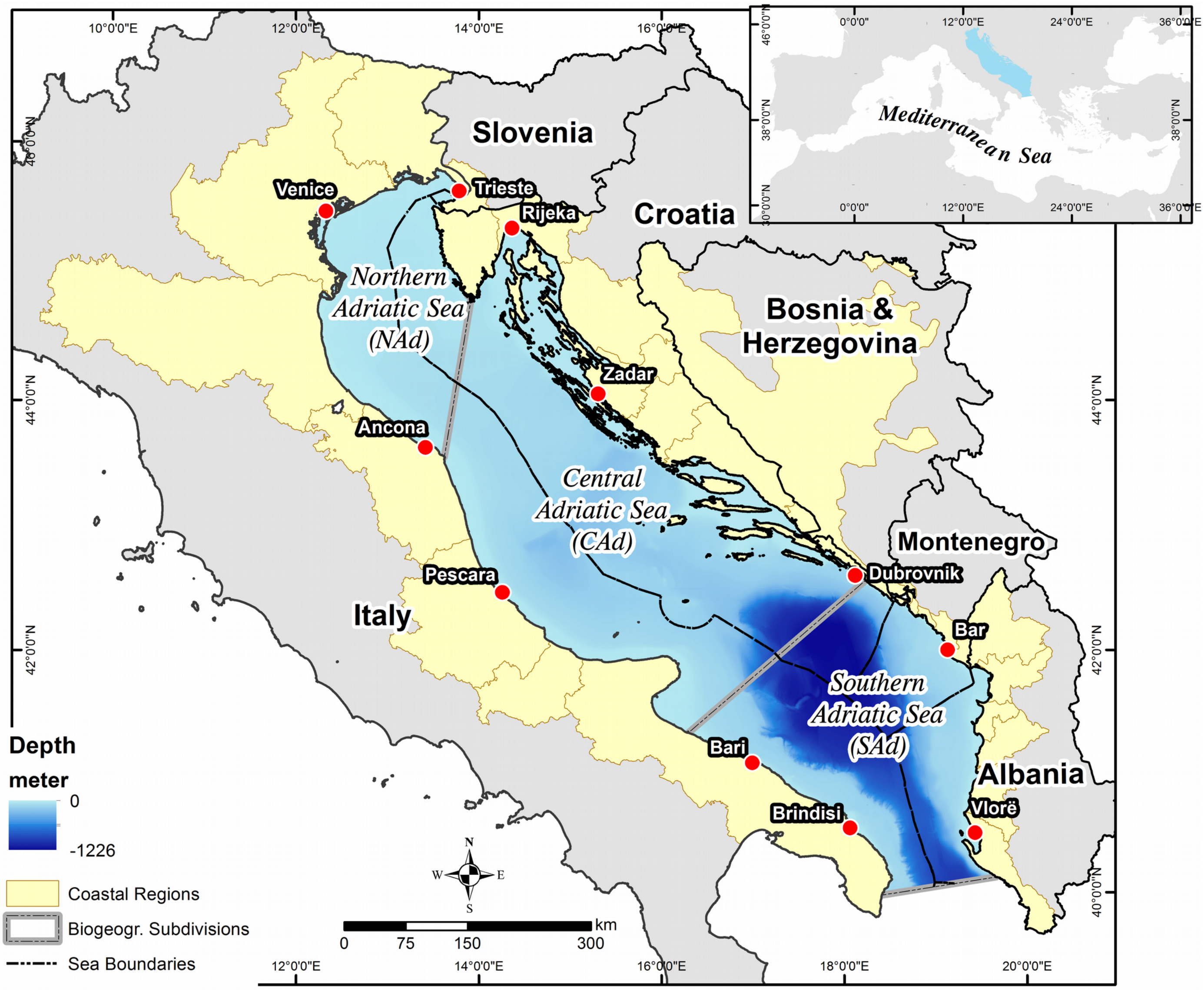

Figure 1. The Adriatic Sea with administrative boundaries of coastal regions, national marine boundaries and three biogeographic subdivisions (Northern-Central-Southern Adriatic Sea).

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 CI algorithm applied in this research is provided by Andersen and Stock (2013). For more detail on the CI assessment in the study area and the algorithm adopted we refer to the supplementary material (see Appendix S1). In Table 1 the MSP stocktake for CI assessment and the indictors used were presented. The MSP stocktake includes 28 environmental components (*E*) and 15 human uses (*U*) at sea. Moreover, the *U* stocktake includes 18 pressures (*P*) that are defined as disturbances causing temporary or permanent alterations to one or multiple ecosystem components. The *P* were adopted from the Marine Strategy Framework Directive (MSFD, 2008/56/EC, Annex III, Table 2). The units of measurement for the spatial indicators *E* and *U* include dummy indicators of presence/absence (*P/A*), weighted dummy indicators (*wP/A*) and intensity indicators (*I*) based on proxy indicators (*PR*). For intensity indicators, a *log[x+1]* transformation and a rescaling from 0 to 1 was used. Full *E* and *U* geospatial datasets can be downloaded under Menegon et al. (2017a). The sensitivity (*s*) is defined as the combination of the direct and indirect impact extent of a pressure generated by anthropogenic activities, its impact level defining the degree of disturbance and recovery time of environmental component subject to the pressure (Andersen and Stock, 2013). 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 over six buffer distances (local, 1 km, 5 km, 10 km, 20 km and 50 km). 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 (data.adriplan.eu) using the built-in tool with a resolution of 10 km x 10 km.

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) retrieved from Menegon et al., 2017a. Note: The seabed habitats include 23 layers as presented in the Table 2.

Dataset	Indicator
Aquaculture[1, 2, 3], Cables and Pipelines[2, 3, 4], Coastal Defence Work[2,5], Dumping area for dredging[2], LNGs[6], Military areas[2,8], Off-shore sand deposit [1, 7, 8, 10], Oil and Gas Extraction [2,11,12,13,14], Oil and Gas Research[2,11,12,13,14], Renewable Energy facilities (Offshore Wind farms)[3,6,15]	P/A
Coastal and Maritime Tourism[*]	I/PR – distance from the marinas and number of boats/marinas
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[7]	I – Traffic density (vessels/year)
Small Scale Fishery[7]	I – fishing effort expressed in 5 classes of intensity: from very low to high)
Trawling[16]	I – hours of activities calculate through Vessel Monitoring System (VMS)
Marine Mammals[17], Giant Devil Ray[17], Nursery Habitats[18], Turtles[17], seabed habitats[19]	P/A
Seabirds[17]	wP/A

[1] Veneto Region (www.regione.veneto.it); [2] SHAPE-Shaping a Holistic Approach to Protect the Adriatic Environment between coast and sea (www.shape-ipaproject.eu); [3] HCMR-Hellenic Centre for Marine Research (www.hcmr.gr); [4] OTE S.A.- Hellenic Telecommunication Organization (www.ripe.net); [5] SIT-Apuglia Region (www.sit.puglia.it); [6] OGS-Istituto Nazionale di Oceanografia e di Geofisica Sperimentale (www.ogs.trieste.it); [7] CNR-ISMAR-Italian National Research Council-Institute of Marine Sciences (www.cnr-ismar.it); [8] MIPAAF-Italian Ministry of Agriculture, Food and Forests (www.politicheagricole.it); [9] Emilia Romagna Region (www.regione.emilia-romagna.it); [10] Arenaria S.r.l. (www.arenariasabbie.com); [11] MEDTRENDS-The Mediterranean Sea, Trends, Threats and Recommendations (www.medtrends.org); [12] MESMGR-Ministry of Economy, Sector for Mining and Geological Research (www.petroleum.me); [13] CHA-Croatian Hydrocarbons Agency (www.azu.hr); [14] MISE-Italian Ministry for Economic Development (www.sviluppoeconomico.gov.it); [15] RAE-Regulatory Authority for Energy, (www.rae.gr); [*] modelled; [16] Blue Hub, JRC in-house platform to exploit big data in the maritime domain (www.bluehub.jrc.ec.europa.eu); [17] UNEP-MAP-RAC/SPA, Regional Activity Center for Specially Protected Areas; [18] MEDISEH MAREA Project (www.mareaproject.net/medviewer); [19] EMODnet Seabed Habitats (www.emodnet-seabedhabitats.eu).

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 15 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 open source geopython library freely available on GitHub (Tools4MSP, 2016). Cell grid resolution of the SUC model is 1 km x 1km (EEA, 2013). Customized SUC scenario runs can be run also from the ADRIPLAN Portal (data.adriplan.eu) on a 10 km x 10 km resolution. 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 dispersion (Nitrogen – N and Phosphorus – P) from rivers into the Adriatic Sea, considering a simple decay reaction to represent the first step dynamic 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 (Ghezzo et al., 2011), 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 (see Appendix S2). 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 in mg l^{-1}) to the Adriatic Sea are presented in Appendix 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). N 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 adopted. 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., 2017b).

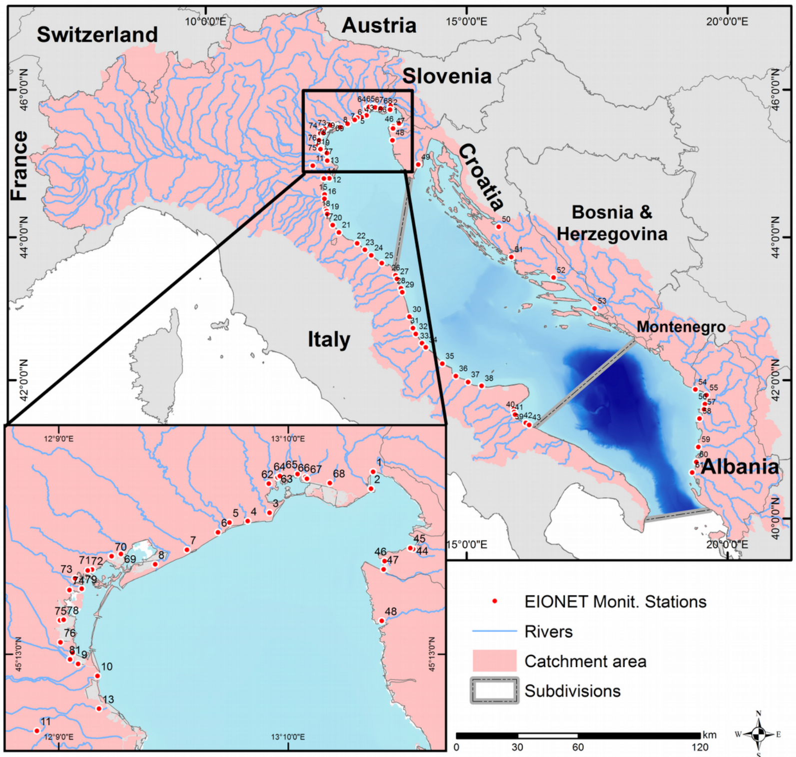

Figure 2. Riverine input dataset of Nitrogen and Phosphorus adopted from EIONET Water Quality monitoring stations applied for 3-D hydrodynamic modelling with SHYFEM. Rivers: 1 – Timavo; 2 – Isonzo; 3 – Tagliamento; 4 – Lovi; 5 – Nicesolo-Iemene; 6 – Livenza; 7 – Piave; 8 – Sile; Brenta/Bacchiglione/Gorzone – 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 marine habitats to provide marine ecosystem services (MES) was assessed using a MES matrix approach (Table 2). The capacity of marine habitats to provide ecosystem services is defined as the long-term potential of ecosystems to provide services that support directly and indirectly human wellbeing (Schröter et al., 2012). The MES matrix combines 13 MES on the x-axis defined according to Salomidi et al (2012) and 23 EUNIS (European Union Nature Information System) marine habitats for the Adriatic Sea retrieved from EUSeaMap (www.emodnet-seabedhabitats.eu/) on the y-axes. The matrix approach is a popular technique 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 seabed habitats.

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_{Sup}				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**

The MES capacity for EUNIS marine 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_{Pro}: 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_{Sup}: 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. The MES capacity (MES_{cap}) is the arithmetic sum of MES scores for each marine habitat. In the supplementary material (see Appendix S3) a detailed description of the algorithm used for MES_{cap} assessment is presented.

Results

Results of model application are illustrated in Figure 3 and 4. In Figure 3 (a-d) presents geospatial model results and Figure 4 (a-d) illustrates for each model, the variation of index scores as function of distance from coastline.

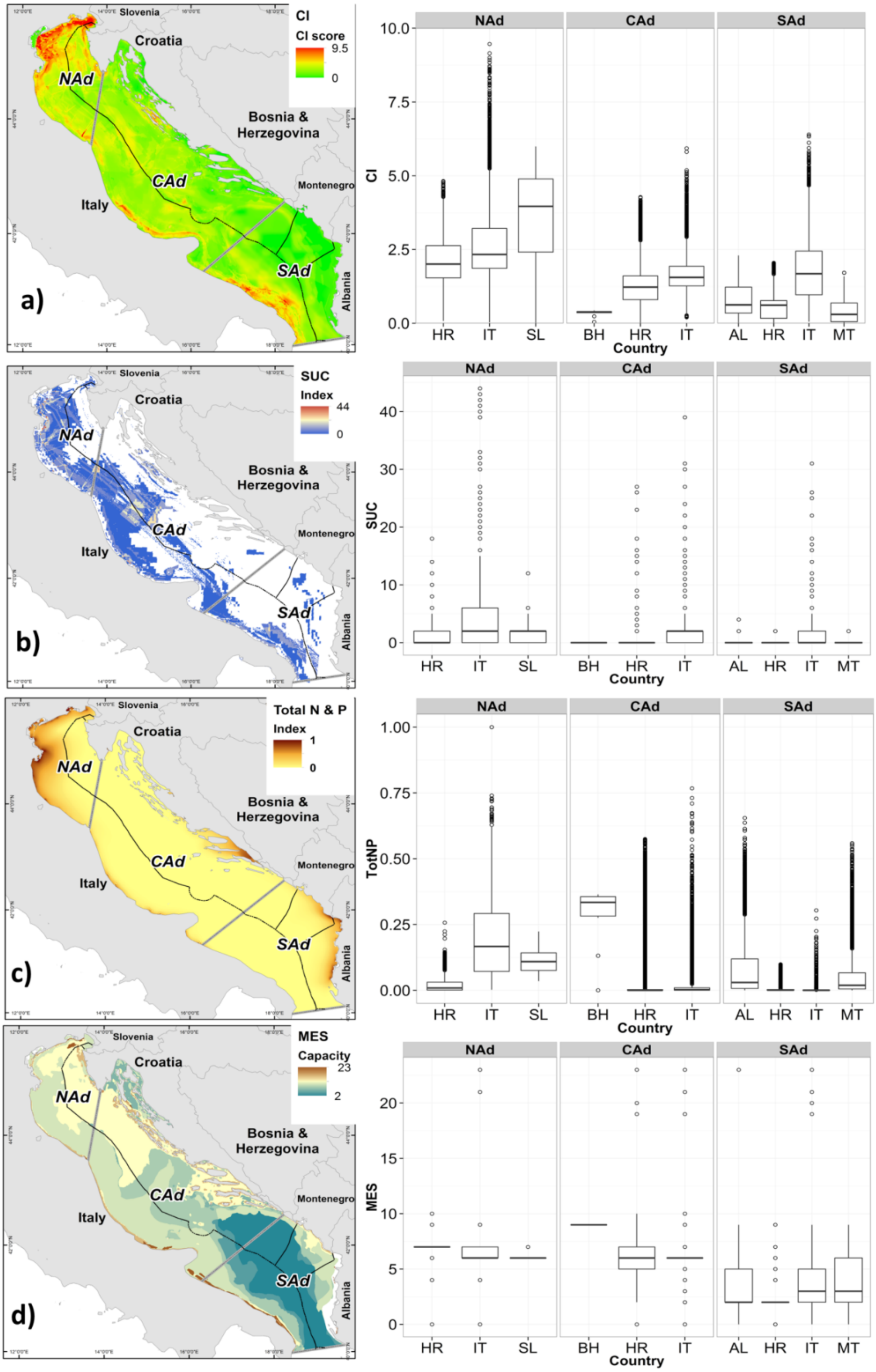

Figure 3. Left: Geospatial results of tools application for the study area: a) CI assessment; b) SUC analysis; c) TotN&P nutrient dispersion model and d) MES capacity from seabed habitats. Right: Comparison of model results for each subdivision. Boxplots show maximum/minimum outliers, boxes enclose first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

Geospatial results presented in Figure 3a indicate that high CI scores are dominant in the sea areas of Friuli-Venezia Giulia, Veneto and Emilia Romagna Region, located in the Italian 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 & Herzegovina has a negligible CI scores. On average, the Italian sea space has the highest CI score ($\tilde{x}$ = 1.6), followed by 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 the Apulia Region register highest CI scores in proximity of Bari and Brindisi ports. On average, the 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 to 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 & 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 model for riverine inputs of N and P are presented in form of TotN&P index. Maximum 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 0.2 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). Especially the coastal area of the 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 & 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 0.3). 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 the riverine dataset including discharge rate ($m^3 s^{-1}$), catchment area (km^2), river length (km), mean N and P concentrations ($mg\ l^{-1}$) is presented in supplementary material (see Appendix S3). In the NAd 49 (IT – 44; HR – 1; SL – 4) rivers were defined, in the CAd 23 (HR - 5; IT - 18) rivers and in the SAd 8 rivers (AL – 7; AL/MT – 1). In total, the drainage area of the Adriatic Sea covers 238,000 km^2. The rivers with biggest drainage area are the Po (74,000 km^2), the Neretva in Croatia (13,121 km^2), the Drini in Albania (13,067 km^2) and the Adige river in Italy (12,400 km^2). The total drainage area of those rivers covers 109,000 km^2, about 46% of the total drainage area of the Adriatic Sea. Other rivers of relevance are the Bojana river (6,056 km^2) at the border with Albania and Montenegro, Reno (5,912 km^2), Piave (4,433 km^2) in the Italian NAd, the Cetina river (3,869 km^2) in Croatia and the Ofanto river (2,777 km^2) in the SAd. The majority of the rivers coming from the Italian Apennines in the CAd and SAd and from the Dinaric Alps along the eastern Adriatic Sea catchment area have a torrential hydrological regime (Cosic et al., 2004; Guarnieri et al., 2016; Vollenweider et al., 1990).

In Table 2 the MES capacity matrix is presented along their spatial extent. The highest ES capacity scores provided by marine habitats 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, smaller than 0.0 %) and A4.26/A4.32 – Med. coralligenous communities (488.2 km^2, 0.2%). Marine habitats with low MES 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 (2,141.1 km^2, 0.4%); A6.4 – Deep-sea muddy sand (3,338.5 km^2, 0.7%), A6.51 – Med. communities of bathyal muds (45,403 km^2, 18.6%) and A6.511 – Facies of sandy muds with *Thenea muricata* (9,978.9 km^2, 4.1%).

Results in Figure 3d presents MES capacity map. The 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 located in Italy and Albania (score 23 respectively), followed by Croatia and Montenegro (score 9). On average MES capacity scores in the SAd are low compared to NAd and CAd ($\tilde{x}$ = 3 for Italy and Montenegro; $\tilde{x}$ = 2 for Albania 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 to the midline sea boundary for this reason Venice lagoon, the Grado-Marano lagoon and the aquifer of Comacchio in Italy were not included as the 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 offshore, 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 (μ = 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 in offshore areas located between 80-90 km from Croatian coasts (μ = 2.7). 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 TotN&P index scores are located in Italian NAd with mean values of about 0.4 within the 1 km distance from coast. Highest TotN&P scores for Slovenia (μ = 0.2) area are found at 11 km from coast. In the CAd, the highest TotN&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 TotN&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) and in Italy (μ lower than 0.1) 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).

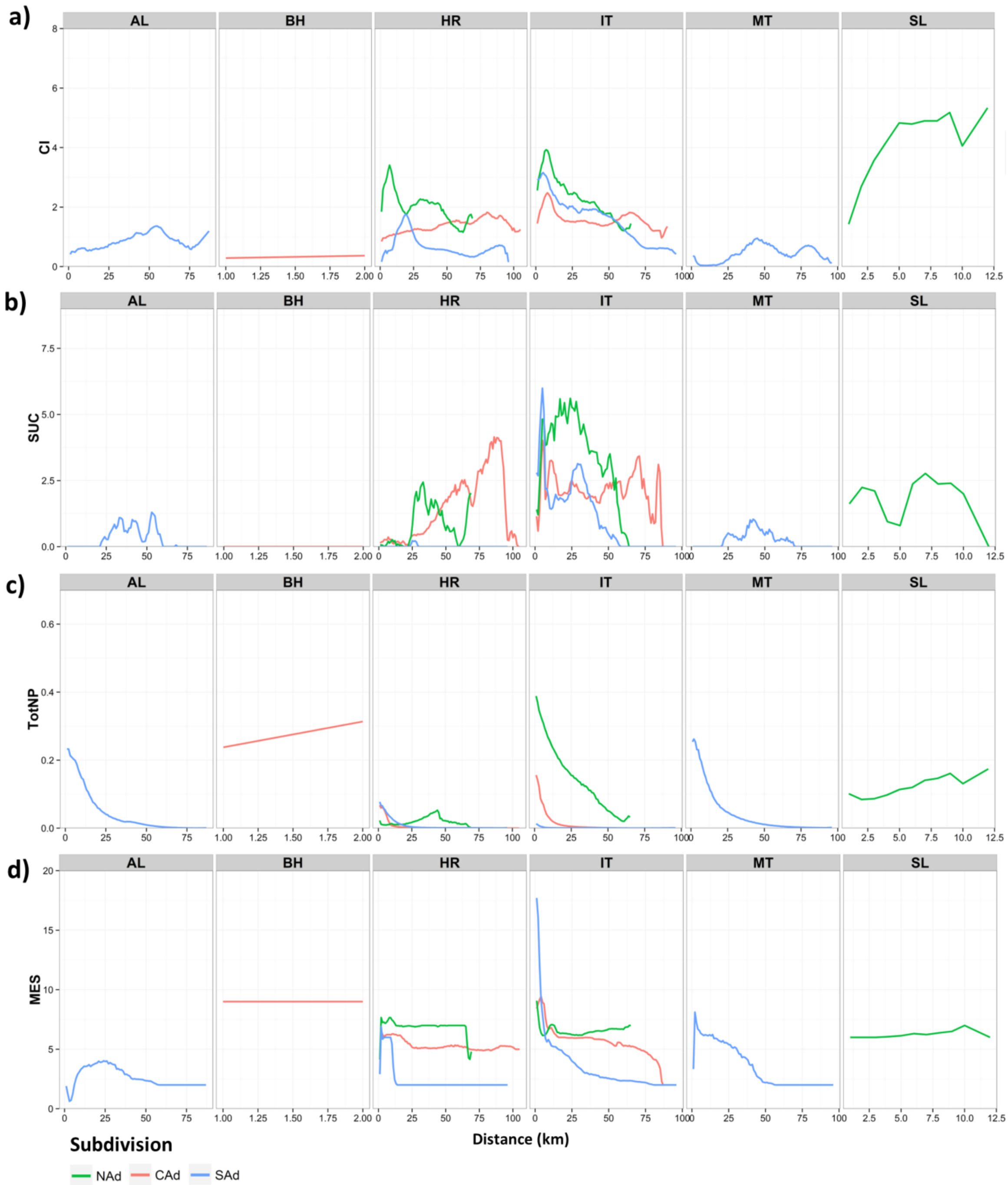

Figure 4. Mean index scores as function of distance from coast (in km), by country (AL – Albania; BH – Bosnia & Herzegovina; HR – Croatia; IT – Italy; MT – Montenegro; SL - Slovenia) and sea space segments (NAd = Northern Adriatic; CAd = Central Adriatic; SAd = Southern Adriatic).

3. Discussion

3.1. Overall spatial considerations

The NAd covers 25.2% of the total study area and can be considered as a regional hub. It is the smallest biogeographic subdivision, but is subjected to the most intensive anthropogenic pressures in its coastal and offshore areas, including 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 (Istria Region), the presence of mass tourism resorts (Veneto and Emilia

Romagna Regions) and considerable riverine inputs, which determine hydrodynamic and biophysical processes in coastal and offshore areas of the NAd. Among the river basins integrated in the database, the Po river basin has the biggest extension (71,137 km^2; see Appendix S3). The Po plain is subjected to intensive anthropogenic-driven modifications as it hosts 15.7 million 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). Anthropogenic influence in terms of cumulative impacts, sea use conflicts and inputs from riverine runoff is most evident in coastal areas at distance from 1 to 15 km (Figure 4a,b and c). The MES capacity in coastal area is among the lowest of the study area, rapidly decreasing from coastal areas and getting more stable towards offshore areas (Figure 4d). Exception is Slovenia, where MES capacity remains almost constant for the entire sea space.

The CAd covers 37.1 % of the total study area and can be considered a transitional sea area, because sea use conflicts are localized mostly offshore in proximity of intensive maritime traffic along the north-west and south-east axes with large patches of CI in proximity of major shipping route. Localized, high CI scores derive from small scale fishery and trawling in coastal areas.

In the CAd, the rivers with most extended catchment areas are the Neretva (13,122 km^2) and Cetina (3,869 km^2) in Croatia and the Pescara river (3,158 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. Rivers have mainly torrential character and therefore the area of influence is restricted to coastal areas (1 to 2 km from coastline, Figure 4c). The MES capacity for the CAd has slight decrease at distance of about 5 km from Italian coastal areas and then remains stable (Figure 4d).

The SAd covers 37.5 % and 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 at about 5 km distance from Italian coastal areas (Figure 4a and b) and more localized sea use conflicts due to 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. In the SAd rivers with most extended catchment area is the Drin river (13,067 km^2) in Albania and Buna/Bojana river (6,065 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). Coastal areas within 1 to 2 km from coast belong to coastal areas of highest MES capacity of the entire study area due to the presence of valuable *Posidonia oceanica* meadows, spread along the entire coastal length (Figure 4d).

3.2. Future developments

The peculiarities of anthropogenic uses, in combination with vulnerable ecological resources evidenced in the three biogeographic subdivisions, 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 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).

At the current stage the MSP stocktake applied in the CI and the SUC model need to be further extended including datasets on alien species, diving activities, underwater cultural heritage sites, artificial reefs or oil spill simulations for sea areas at highest oil spill risk. Moreover future development scenarios from new shipping routes, new port developments and extensions, coastal urban sprawl, tourism flow projections, detailed information on potential renewable energy sites (offshore wind energy or wave energy sites), oil & gas extraction sites, including their potential pressures on environmental components need to be included in the presented stocktake. In addition, the currently applied fishing effort datasets need to be integrated with quantitative spatial datasets on commercial fishery catch to better understand fishing fleet dynamics and the cumulative impacts generated for instance by multiple trawling activities over time (Foster et al., 2014). At the actual state, the SUC model only determines areas of conflict and does not identify areas of potential synergetic uses. Therefore, sea areas with SUC=0 need to be further investigated for their potential synergies and potential direct and indirect benefits they generate.

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; 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 (Micheli et al., 2013), is the comprehensive dataset of rivers, discharge rates and N and P concentrations coupled to the model that can be implemented as pressure from land-based activities into the CI model. This allows a flexible deployment of nutrient dispersion scenarios also on regional and local scales, considering anthropogenic activities, such as coastal tourism or aquaculture and the ecological components that 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 MES 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 NAd (e.g. Po and Adige river), the CAd (Neretva river) and SAd (Drin river), 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 model for the generation of indicators for microbial reduction and cycling of excess nutrients (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 in general seabed habitats in proximity of coastal areas provide the majority of MES (Table 2, Figure 3d and 4d). In particular marine habitats featuring seagrasses of *Posidonia* and *Cymodocea* spp. beds can be considered as coastal areas with high MES capacity, although relatively limited in space (0.5% of the total study area). 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. For marine conservation planning, the presented MES model requires further methodological and dataset integrations related to field measurements on benthic communities distribution coupled with predictive model to assess benthic community distribution (Puls et al., 2012), assessment of ecological multi-functionality through geostatistical techniques (Lefcheck et al., 2015; Schröter and Remme, 2016), development of habitat fragmentation models to better understand ecological resilience (Cognetti and Maltagliati, 2010), identification of socio-economic proxy indicators that link ecological functioning and services to human well-being and 5) extension of sensitivity analysis implemented in the presented CI model, by defining the sensitivity of a benthic habitat from anthropogenic pressures based on key stone species specific sensitivities and their ecological function (Depellegrin and Pereira 2016; Hooper et al., 2017).

The presented MES model is a first step towards a wider MES analysis in the Adriatic Sea. The ongoing MSP implementation process in the study area requires ES frameworks for trade-off and synergy analysis (Lester et al., 2013) on sea use sectors, to better understand the direct and indirect benefits provided by ecosystem services and their socio-economic dimension. This is especially important in the Northern Adriatic Sea, where space limitation induces trade-offs among environmental components and anthropogenic activities.

3.3. From multi-objective to multi-functional tools development

In future, the increasing demand for integrated planning tools in MSP will require an augmented availability of high quality datasets and improved methodological procedures. Similarly, the presented modelling framework needs to transit from its modelling specificities towards a more integrated and multi-functional perspective taking into account different stages of an MSP process (Pınarbaşı et al., 2017). In this context, the spatial data infrastructure (SDI) of the ADRIPLAN Portal (www.data.adriplan.eu; Menegon et al., 2016) is based on GeoNode software (www.geonode.org), an open source geospatial content management system, and the presented Tools4MSP python library (www.github.com/CNR-ISMAR/tools4msp) for geospatial modelling provide a favourable context for more integrated and multi-functional modelling objectives for sea use planning and environmental management: First of all, GeoNode eases geospatial data management and a high level of customization of the Portal to user needs by promoting data-sharing among its users and by integrating web mapping applications. Second, the design of the Tools4MSP library allows to extend the currently available modules (CI and SUC models) with additional analytical modules deployable to any study area. These modules can include scenario analysis, sector-oriented modules, socio-economic investigations, models for environmental economics or support stakeholder engagement through Public Participatory GIS (PPGIS) exercises. At the current stage, customized CI and SUC scenarios can be run from the ADRIPLAN Portal based on the Tools4MSP library functionalities. Third, the Tools4MSP modelling frameworks and SHYFEM are open source libraries. This has an essential role in the future improvement of the analytical tools, through sharing of codes, development of user/developer communities and enable critical reflection on conceptual and methodological constrains among expert. Forth, the combination of an integrated geospatial data platform and the modelling library ensures a high degree of interoperability among modelling components and datasets.

3.4. Model limitations

The results of the presented models are not free of limitations. At the current stage uncertainty analysis is performed as a three-levelled general uncertainty analysis for the CI model (Gissi et al., 2017) adopted from the typology development by Walker et al., (2003). In future a similar uncertainty analysis needs to be considered for the other models in order to increase the credibility of the modelling approach for stakeholders involved in the planning process.

All the presented datasets and model outputs are resampled on a 1 km x 1 km cell grid, that can be considered of acceptable resolution for the proposed macro-regional analysis, however for countries with small sea spaces, such as Slovenia and Bosnia & Herzegovina, regional/local scale analysis is required using high quality datasets and higher cell grid resolution. In the SUC model, the within-grid spatial uncertainty is particularly evident, as two or more sea uses within a 1 km x 1 km grid can potentially coexist, without creating conflicts. This can be source of artificial conflicts in the model output. The spatial extent of the study area required intensive data aggregation procedures to perform model runs, nevertheless modelling uncertainties related to limited data availability remain. The datasets on human uses and environmental components implemented for the CI and SUC model were based on a multitude of datasets from different spatial scales (macro-regional to national and regional/local level). In order to reduce this uncertainty, the amount of human and environmental datasets for CI and SUC implemented in the eastern segment of the study area need to be aligned with the more complete datasets of its western segment (Italian sea space). In the nutrient dispersion model additional datasets on N and P concentrations are lacking for torrential rivers of Apulia Region in SAd and need to be further complemented. The EMODnet (2016) seabed habitat map applied in the MES model is lacking spatial data coverage for Albanian coastal areas and needs to take into consideration the low habitat confidence level of the habitats, especially in the eastern segment of the study area (Populus et al., 2017) The nutrient dispersion model has limitation in the nutrient concentration datasets, as the applied dataset considers a combination of average discharge rates and modelled discharge rates based on timeseries (see Appendix S3). This does not allow to include seasonal overflow events in the model. Furthermore, a higher detail on nutrient transport and dispersion could be achieved through the implementation of a nearshore wave model. In the MES model limitations are mostly related to the three levels of information associated to the habitat (physical variables, habitat descriptors and habitat type), that determine the level of confidence and therefore the actual nature of the habitat (EMODnet, 2016). Other limitations are related to the lack of knowledge on ecosystem services provision in deep sea environments (Thurber et al., 2014), especially in the SAd subdivision and the application expert-based elicitation for the scoring of MES capacity (Hamel and Bryant 2013).

4. Conclusions

This research presents a set of geospatial models designed to address thematic objectives in sea planning and environmental management in the Adriatic Sea. In future, the development of tools need to shift from a multi-objective perspective, towards a multi-functional approach. In sense, that model functionalities and modelling processes need to become more integrative and interoperable among tools. In this context open source ADRIPLAN Portal and the Tools4MSP modelling framework can accelerate this multi-functional perspective as they enable sharing of codes, datasets, models and facilitate the knowledge exchange among expert communities. We conclude that a multi-functional approach includes, but is not limited to the following model integrations: *MES – CI integration.* MES capacity model can be used as initial step to extend the sensitivity analysis implemented in the presented CI model, by linking the sensitivity of a seabed habitat to single or multiple pressures as a function of the specific service it supplies. *CI – TotN&P integration.* This includes the integration of the CI model with N and P dispersion model to represent land-based activities and their pressures on target environmental components. Hydrodynamic models can easily feed CI models with spatial explicit indicators for anthropogenic pressures from other land based activities (e.g. toxic compounds, heavy metals or pathogens). *CI – SUC integration*. This includes the analysis of CI generated in high conflict sea areas or in areas of synergies among uses. *SUC – MES integration*. MES framework can provide methodological advancement and support a better understanding of human-nature interaction and support the analysis of trade-offs and synergies among uses concentrating in the same sea area. *MES – TotN&P integration*. Hydrodynamic models can be used to quantify regulating ES (e.g. water purification, waste treatment, coastal water quality).

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