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Geospatial analysis for fish farming across Tyrrhenian coast (Tuscany, central Italy)

M. Manca Zeichen[a], G. Ciotoli[b,c,*], M. Archina[a]

[a] Istituto Superiore per la Protezione e la Ricerca Ambientale, via Vitaliano Brancati, 48 - 00144, Rome, Italy
[b] Consiglio Nazionale delle Ricerche, Istituto di Geologia Ambientale e Geoingegneria, via Salaria km 29.300 - 00015, Rome, Italy
[c] Istituto Nazionale di Geofisica e Vulcanologia, Sezione Roma 2, Rome, Italy

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ABSTRACT

Aquaculture represents an important source of food and it plays an important role in terms of contribution to economic development. Offshore farming offers considerable advantages, especially in terms of production costs (lower than those of onshore facilities) and of farmed product quality. Suitable areas for aquaculture activities are still available in Italy but are increasingly limited and the demand for new farms is high. The lack of coastal areas allocated to aquaculture and the complex regulatory and legal framework constitutes the major constraints for further development of the sector. Zoning is the process that can allow to sustainably identify and allocate suitable areas for aquaculture. Several aspects, such as effective legal framework and procedures, collection of bio-geochemical, physical and socio-economical information, are crucial for a correct aquaculture zoning process in order to identify the Allocated Zones for Aquaculture (AZAs). In the present work, a spatial multi-criteria decision analysis (SMCDA) was applied for the individuation of potentially suitable marine areas for fish farming across the southern Tyrrhenian coast of Tuscany (Italy). The spatial model was developed by collecting and processing Earth Observation (EO) data, oceanography *in situ* measurements, and infrastructural and environmental constraints. Excluding areas of constrains, obtained results highlight that 96% of the total investigated area is characterized by medium (62%) and high (34%) suitability. In particular, the highest suitability areas occur in the Talamone gulf and offhore the Argentario promontory at water depth between 15 and 30 m and 30 50m, respectively. Other high suitability areas occur northern of Piombino town between 30 and 100 m depth. Environmental data at higher spatial resolution are needed to improve aquaculture zoning and further process of site selection in order to ensure the sustainability of fish farming in the study area.

1. Introduction

The rising number of aquaculture facilities increases competition and conflicts between fish farmers and other coastal users, such as tourism, energy and established fish sectors. Marine aquaculture is one of the pillars of the European blue economy and the development of a modern sustainable, dynamic, competitive and integrated industry in European coastal waters is recommended by European Commission (2012) and European Parliament and the Council (2002) to promote socio-economic development in marine areas and meet the gap of farmed seafood for European consumers.

In this context, the identification of Allocated Zones for Aquaculture (AZAs) reflect the goals of the European Blue Growth strategy and framework polices (Regulation EU N. 508/2014, Directive, 2014/89/EU, Directive, 2000/60/EC, Directive, 2008/56/EC) that ask the member states to implement a coordinated Maritime Spatial Planning (MSP) and consider the potential of aquaculture needs by ensuring the allocation of adequate space for a sustainable development. MSP is necessary to ensure a sustainable management of oceans and seas. Satellite technology can enable the maritime operators to define a coordinated approach to the sustainable use of the marine resources. Advance planning of sustainable aquaculture activities using the techniques of geospatial analysis is fundamental to enhance the conservation status of coastal areas encouraging and applying sustainable production methodologies.

AZAs are marine areas where the development of aquaculture is prior to other uses. AZAs are defined as areas dedicated to aquaculture, recognized by physical or spatial planning authorities, that would be

* Corresponding author. Consiglio Nazionale delle Ricerche, Istituto di Geologia Ambientale e Geoingegneria, via Salaria km 29.300 - 00015, Rome, Italy.
E-mail address: giancarlo.ciotoli@igag.cnr.it (G. Ciotoli).

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considered as a priority for local aquaculture development, with environmental conditions suitable for fish farming. Their identification should be based on the best environmental, social and economic available information in order to prevent conflicts among different users for increased competitiveness, sharing costs and services and to ensure investments (FAO Regional Commission for Fisheries, 2013a; FAO, 2013b; FAO, 2013c; GFCM General Fisheries Commission for the Mediterranean, 2012). Identification of an AZA will result from zoning processes through a participatory spatial planning (Ross et al., 2013), whereby administrative bodies legally establish that specific spatial areas within a region have priority for aquaculture development (Sanchez-Jerez et al., 2016). The process of identifying areas for AZA takes into account (FAO, 1995):

- the aquaculture development goals, which aim at supporting the sector economy by increasing production in a sustainable way.
- the administrative and socio-economic context, optimizing the available space and minimizing the conflicts of use;
- the optimal environmental conditions for farms and for farmed species;

Zoning is the first operational step of the maritime spatial planning process to identify potential areas for the sustainable development of aquaculture (FAO & World Bank, 2015; Meaden et al., 2016). The main purpose of zoning process aims at the sustainable development of aquaculture, at increasing quality production and at promoting socio-economic development, at reducing environmental risks, conflicts of use and space and at maximising complimentary uses of land and water. The spatial scale of zoning process is subnational-regional, or moderate (Aguilar-Manjarrez et al., 2017). At this spatial scale, it may only be possible to define in very general terms where fish farms would most likely flourish so that the results obtained are moderately detailed. "Zone" is intended as a hydrological system deemed suitable for aquaculture activities as a result of a consultation and evaluation process among the different stakeholders.

Remote sensing and geographic information systems (GIS) are decisive for this kind of process, and are useful tools to support stakeholder opinions and awareness. In fact, zoning serves as a tool for the integration of aquaculture into coastal zone management. Zoning follows a participatory approach coordinated by the main authority responsible for marine spatial planning at local level (Ross et al., 2013), and carried out in cooperation with the different public authorities and stakeholders (Aguilar-Manjarrez et al., 2010; Regolamento (CE) n. 762/2008 MiPAAF/ISPRA, 2014); Chapela Pérez (2009). The use of GIS to work across multiple spatial scales is a major advantage for aquaculture planning and management as there are local and regional considerations that must be accounted for the zoning of new aquaculture farms (Dell'Aquila et al., 2008; Falconer et al., 2013; Malczewski, 1999; Valentini et al., 2016). GIS is capable to display, manage and investigate many layers simultaneously, and explore their spatial relationships. In most cases, raw or pre-processed data should be pass through some level of geospatial analysis. Geospatial analysis includes a number of techniquesfor the transformations and manipulations of raw data to produce useful information for decision-making purposes (Longley et al., 2015). GIS tools allow to produce cartographic maps that serve as a zoning and regulatory instrument for planning economic activities and to identify the different uses in the investigated area. This would help coastal planners and policy makers to make complex decisions within a short period considering sustainability.

In addition to environmental limiting factors, it is also important to consider the interactions with other human activities when aquaculture facilities are set up (IUCN and De Monbrison, 2004; IUCN, 2009). Zones to be allocated to aquaculture activities shall be classified as (GFCM General Fisheries Commission for the Mediterranean, 2012):

- "*suitable areas for aquaculture activities*", in which there is no interference with other uses and there are good environmental conditions;
- "*suitable areas for aquaculture activities with particular regulation and/or restriction*";
- "*unsuitable areas for aquaculture activities*" for infrastructural or administrative incompatibilities and for environmental unsuitability.

At Mediterranean Sea level, the process for creating AZA is promoted as part of the ICZM (Integrated Coastal Zone Management) process (European Parliament and the Council, 2002) and the EAA (Ecosystems Approach to Aquaculture) strategy (FAO, 2010; Soto et al., 2008). At this stage of the process, it is necessary to define the exclusion criteria, in respect of the rules and in relation to the uses and constraints occurring in the area (infrastructural, administrative, environmental and archaeological constraints, decrees, ordinances). In 2012, the General Fisheries Commission for the Mediterranean (GFCM) approved the Resolution on guidelines on AZA (GFCM General Fisheries Commission for the Mediterranean, 2012) outlining the basics. In particular, Italy identifies marine areas, through coordinated spatial planning, for the development of marine aquaculture as one of the four objectives of the multiannual strategic Plan for Aquaculture 2014–2020 (MiPAAF Ministero delle Politiche Agricole Alimentari e Forestali, 2014).

This work presents the application of GIS-based (Spatial) Multi-criteria Decision Analysis (SMCDA) (Malczewski, 2006; Shin, 2017; Francisco et al., 2019) to selected criteria (i.e., remote sensed data) for the identification of the most suitable zones for the establishment of new aquaculture marine farms along the Tyrrhenian coast of Tuscany, Italy. In particular, this process was carried out by collecting infrastructural and environmental data such as Earth Observations (EO) and *in situ* observations delivered through Geographic Information System (GIS) applications. During the zoning process, unsuitable areas were identified and excluded considering environmental and infrastructural constraints including conservation priority habitats, as well as synergies and conflicts between human activities and their spatial distribution. The major conflicts were likely to occur with protected species such as *Posidonia oceanica* meadows, military easements and Sites of National Interest (SIN). Analytical Hierarchical Process (AHP) was applied to calculate optimal weights for the selected criteria (Saaty, 1980). The final map of the suitable areas was obtained by weighted linear combination (WLC) of physical and biogeochemical parameters considered in this study.

2. Material and methods

2.1. Study area

The study area is located across the Tyrrhenian coast of Tuscany for about 285 km and covers approximately 1000 km^2 (Fig. 1). The selected area was limited between the bathymetry of 20 m, as necessary distance between the cages and the seabed, and that of 100 m. The boundaries of the study area follow the coastline from the southern Latium-Tuscany boundary, from the Chiarone river mouth, up to the gulf of Baratti, bordering the northern promontory of Piombino. The bathymetry of 100 m reaches the maximum distance from the coast within the gulf of Follonica and Talamone, while it approaches to the coastline across the Argentario promontory where the coastline records the maximum slope of the seabed, up to 4% (CNR, 1997; Ferretti et al., 2003).

The offshore bathymetry (100 m) cuts off the islands of the Tuscan Archipelago National Park which encompasses Elba, Giglio, Montecristo, Giannutri and Formiche di Grosseto islands (Fig. 1).

Across the coast, there are several rivers' mouths, (Cornia, Bruna, Ombrone, Albegna and Chiarone).

The study area is characterized by several human activities including shipping, industries, tourism, fisheries and aquaculture. Currently, there are some active concessions for cage farms in the gulf of Follonica,

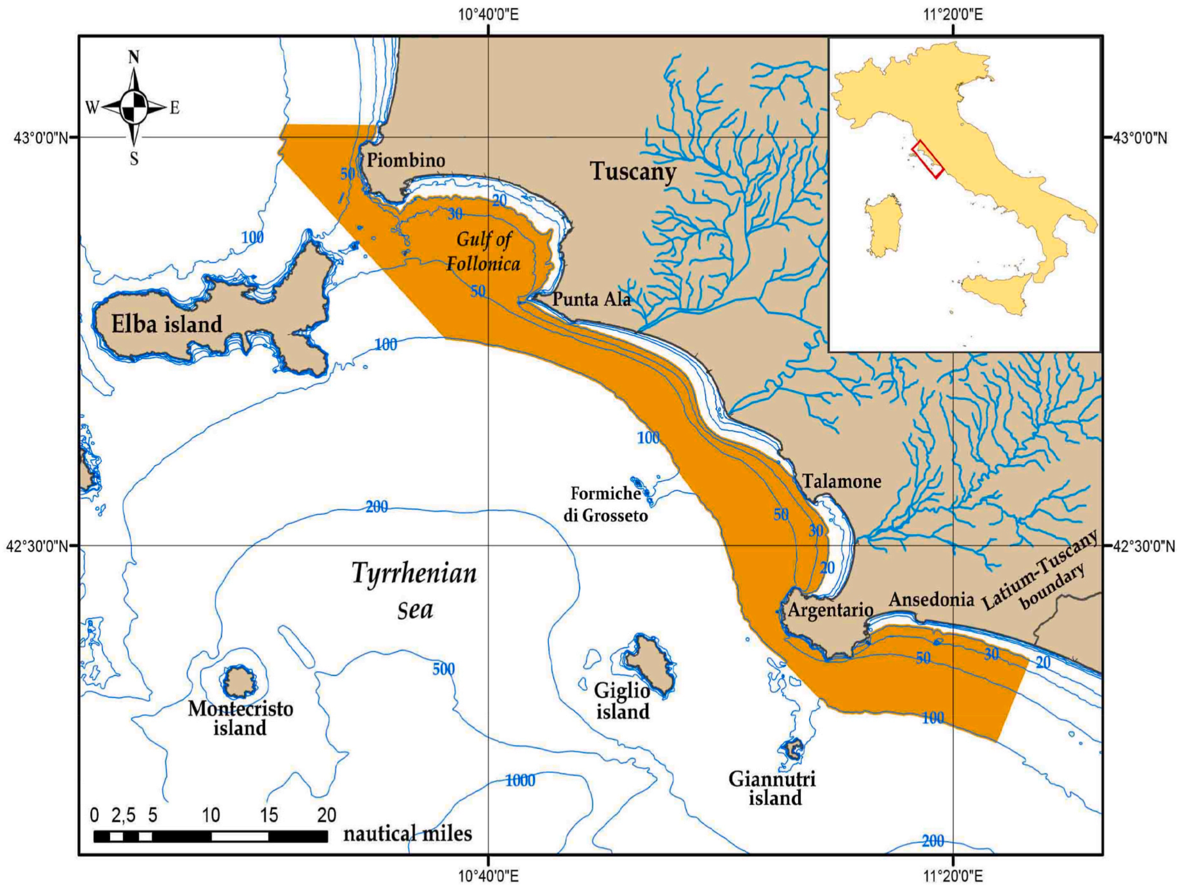

Fig. 1. Study area highlighted in dark yellow.

producing European seabass (*Dicentrarchus labrax*), Gilthead sea bream (*Sparus aurata*) and meagre (*Argyrosomus regius*) and two licenses for mussel farming.

2.2. Data description

Data collected for characterization of the study area were grouped into three main categories.

1. *Basic cartography,* including all information layers representing and describing the administrative boundaries and territorial components (e.g., municipal, provincial and regional administrative boundaries; morphology; bathymetry; location of port authorities and maritime offices, coastal hydrography);
2. *Environmental and infrastructural constraints* including restricted areas for environmental logistical, military and infrastructural reasons (Table 1): i.e., Sites of National Interest, *Posidonia oceanica* meadows, military easements, unexploded bombs zones, active fish farms, industrial sites, ports, wrecks, ferry routes, underwater cables and pipelines, emerged and submerged artifacts;
3. *Physical and biogeochemical parameters of interest for fish farming.*

2.2.1. Basic cartography

Coastline. The shapefile of the coastline was issued by ISPRA (Italian National Institute for Environmental Protection and Research) on 2006, and represents the coastline morphological structure and characterization at the 1:25000 scale of the entire Italian coastline. This shapefile has been carried out by means of photo-interpretation and on screen digitalization from digital colour orthophoto (Barbano et al., 2006a;b).

Bathymetry. The shapefile of the bathymetries was obtained by on-screen digitalization from the IIM (Military Navy Hydrographic Institute) maps at different scales.

Port authorities and maritime offices. The point shapefile, showing the location of the port authorities and maritime offices, was obtained starting from the information gathered from the decrees published in the Italian Official Gazette.

Hydrographic network. The shapefile of the hydrographic network at 1:250000 scale was realized by ISPRA in 2012. This shapefile was used to extract polylines of the rivers crossing the coastal territory.

2.2.2. Environmental and infrastructural constraints

Table 1 shows the main environmental and infrastructural constraints in the study area.

Posidonia oceanica and *Cymodocea nodosa* meadows. *Posidonia oceanica* is a protected species recognized as a priority habitat by the “Habitat” Directive (Directive 92/43/CEE of the Council of May 21, 1992).

Sites of National Interest (SNI). SNIs are large contaminated areas classified as hazardous at the national level, they need remediation of soil, groundwater and surface water to avoid environmental degradation and hazards for public health. They can be identified in relation to the characteristics of the site, the amount and the potential danger of the pollutants, the impact on the environment in terms of health and ecological risk;

Military easements. Military easements are areas with restrictions limiting the right of property in areas adjacent to military zones. In those areas military drills of various types are conducted; Port Authorities have jurisdiction over the marine areas affected by military exercises and issue orders to ban navigation, anchoring, fishing and other related activities.

Areas with discovered unexploded bombs, wrecks, emerged and

Table 1
Environmental and infrastructural constraints.

Constraints	Description	Data source	Regulatory reference
Posidonia oceanica and *Cymodocea nodosa* meadows	Protected species recognized as a priority habitat	GIS Natura (Ministry of Environment and Protection of Land and Sea - MATTM, 2005; European Commission, 2012).	Directive 92/43/CEE
Sites of National Interest (SIN)	Large contaminated areas classified as hazardous at the national level	MATTM (2005)	National Decree 22/97; National Decree 152/2006; MATTM Decree 471/99
Military easements	Areas with restrictions nearby military zones	Military Navy Hydrographic Institute	National Decree 898/1976 Bulletins of Notices to Mariners ("Avvisi ai Naviganti") 2009–2016
Other restricted areas	Areas with unexploded bombs, wrecks, emerged and submerged artifacts		Ordinances of the Maritime District Offices of Piombino (LI)
	Anchorage reserved areas for crafts and other particular restricted areas		Ordinances of the Maritime District Offices
	Main Ports	Corine Land Cover (CLC)	
Other marine uses	Main ferry routes	EuroGeographics's database	
	Submerged cables and pipelines	Greg's Cable Map	
Active fish farms concessions		Corine Land Cover (CLC)	Ordinance of the Maritime District Office of Porto Santo Stefano (GR) (23/1998) and Piombino (LI) (117/2014)

submerged artifacts (sunken boats and ships, statues, buoys, etc.), anchorage reserved areas for crafts and other particular restricted areas;

Main ports, port areas, urban coastal areas and industrial sites. A polygon shapefile of the Italian ports, urban areas and industrial sites was generated by extracting areas from the Corine Land Cover (CLC) 2012 starting from the information present on the ordinances of the port authorities.

Main ferry routes. Data of the main ferry routes (commercial and touristic maritime traffic) arriving and departing from the Italian coast were extracted from EuroGeographics's database (http://www.eurogeographics.org/products-and-services/euroregionalmap);

Submerged cables and pipelines. These data were obtained from "Greg's Cable Map" a free-to-use website (https://www.infrapedia.com/) that shows the location of undersea data cables.

Active concessions for fish farms. A polygon shapefile was created by using the coordinates of the vertices of the active concessions notified through the Ordinances of the Maritime District Office of Porto Santo Stefano and of the Maritime District Office of Piombino.

2.3. Integration of remote sensing and oceanography

The physical and biogeochemical parameters taken into account were those that could have an effect on fish biology and life cycles such as body size, metabolism, growth rate, population structure and sexual characterization, and those that could be have a negative impact on the fish cages system.

The parameters considered in this study were Sea Surface Temperature (SST skin), turbidity (Kd490), chlorophyll (Chl), pH and wave height Sea Surface Temperature and High turbidity could cause reduced fish visibility and feeding capacity and predisposes to pathologies; chlorophyll causes the risk of increased fouling whereas pH is necessary to monitor the acidification risk areas. The above-mentioned parameters were retrieved by Earth Observation (EO), *in situ* and modeled data at a suitable spatial and temporal resolution (Table 2).

2.3.1. Earth Observation data

Sea Surface Temperature (SST). The monthly SST data were obtained by averaging the Mediterranean Optimally Interpolated (OI) SST L4 products developed by CNR and distributed through the MyOcean Project. The monthly mean values were computed from the data covering the period July 2006/June 2012. The OISST L4 data consist in daily gap free SST fields at 1/16° resolution. They are obtained by combining and interpolating the night-time SST images collected by all available infrared sensors, and are nominally representative of the SST measured at 00:00 UTC. The sensors (and platforms) ingested in CNR system include: the Advanced Along Track Scanning Radiometer (AATSR) installed on the European ENVIronment SATellite, ENVISAT, the MODerate Resolution Imaging Spectroradiometer (MODIS) on both Aqua and Terra satellites, the Advanced Very High Resolution Radiometer (AVHRR) on METeorological Operational satellite (METOP) and National Oceanic and Atmospheric Administration (NOAA) satellites, Spinning Enhanced Visible and Infrared Imager (SEVIRI) installed on Meteosat Second Generation (MSG). The CNR processing chain includes several modules, from the data extraction and preliminary quality control, to cloudy pixel removal and satellite images collating/merging up to interpolation through statistical techniques (Buongiorno Buongiorno Nardelli et al., 2013). Four seasons were defined as in previous studies: January, February and March for Winter; April, May and June for Spring; July, August and September for Summer; October, November and December for Autumn. In order to evaluate the sea surface temperature in the Italian sea, the Mann-Kendall test (Kendall, 1975; Mann, 1945) was applied to the monthly Mediterranean product time series, spanning from 2006 to 2012.

Turbidity. Monthly climatological means of Kd490 coefficient derived from SeaWiFS data of diffuse attenuation coefficient at 490 nm (Kd490), collected from 2001 to 2009. The SeaWiFS Full resolution L0 data were acquired and processed by CNR-ISAC using the CNR Mediterranean Ocean Colour Observing system. The CNR processing chain includes several modules, from the data extraction and preliminary

Table 2
Earth observation (EO) and *in situ* and model data sources.

Parameters	Spatial Resolution (km)	Sources	Period
Temperature (SST)	6.0	CNR-ISAC/My Ocean, Level 4 SST from AATSR, MODIS, AVHRR and SEVIRI	2006–2012
Turbidity (Kd490) Chlorophyll (Chl)	1.1	CNR-ISAC from SeaWiFS	2001–2009
pH	1.0	ISPRA collected by national coastal tide gauge network, and Italian national programme of marine coastal monitoring (http://www.sidimar.tutelamare.it/index.jsp).	2006–2012
Wave height (Hs)	0.25	ISPRA	2006–2011

quality control, to cloudy pixel removal described in details in Volpe et al., (2012). The Mediterranean Sea high resolution (1.1 km) Kd490 data are mapped with equirectangular projection on Mediterranean Sea. Monthly climatology has been obtained by averaging all the daily Kd490 data acquired in the above mention period (Volpe et al., 2012).

Chlorophyll. Monthly climatological means of chlorophyll concentration derived from SeaWiFS data, collected from 2001 to 2009 (Santoleri et al., 2008). The SeaWiFS Full resolution L0 data were acquired and processed by CNR-ISAC using the CNR Mediterranean Ocean Colour Observing system. The Mediterranean Sea high resolution (1.1 km) CHL data are mapped with equirectangular projection on Mediterranean Sea. Monthly climatology CHL maps have been obtained from all the daily CHL data acquired in the above mention period.

2.3.2. *In situ measurements*

Ph. Data of pH were collected by sampling campaigns performed by ISPRA Environmental Monitoring Program, by national coastal tide gauge network and by Italian national programme of marine coastal monitoring. All data were collected in surface waters (<25 m) from 2006 to 2012.

2.3.3. *Ocean modeling products*

Wave height. Monthly mean data for the period 2006–2011, provided by the reanalysis of ECMWF numerical model ERA-Interim for the Mediterranean Sea, were used. These data are at a spatial resolution of 0.25 km for both latitude and longitude. The temporal variability was assessed through a statistical analysis providing the mean value of wave parameters in the area over the selected period. This analysis was repeated for seasonal data.

2.4. *Geospatial analysis and model development*

The building of a suitability zone map provides the assignment of a weight to the variables proportional to their contributions to the study phenomenon. Many spatial techniques are available to integrate space and relationships between variables that characterize spatial phenomena. For many spatial statistics, these spatial relationships are specified formally through a spatial weight's matrix. In general, weighing procedures of the variables are carried out by means of regressive or decisional techniques, e.g., spatial regression techniques and decision-making techniques.

Spatial regression techniques (e.g., multivariate and logistic regression, weighted geographical regression, machine learning, etc.) are certainly more statistically robust as they consent the construction of a model that can be replicated in other scenarios.

Instead, decision-making techniques (e.g., Spatial Multicriteria Decision Analysis, SMCDA), although they belong to a complex subject such as "decision theory" (Howard, 1966), include a series of tools that allow the weighing of the variables that frame the phenomenon without the need of a response variable, but through the use of an expert judgment. Multi-criteria decision making is indeed an approach that facilitates decision makers to considers multiple parameters (i.e., criteria), and to favor the criteria assessment and comparison in order to provide the best possible decision in a reduced time frame. Many environmental issues involve large set of multiple, conflicting criteria that can be combined and constrained only using the expert' opinions and literature surveying.

GIS makes possible to display and investigate as many layers as required, and visualize and simultaneously explore multiple layers and their spatial relationships. In most cases, raw or pre-processed data should be pass through some level of geospatial analysis. This step involves many possible techniques and approaches that depend on the data and on the overall objective of the work. Geospatial analysis is relevant for aquaculture spatial models and can be used to assess present conditions and future scenarios, thus providing stakeholders with significant information for planning and management.

In this work, a GIS-based (spatial) multicriteria decision analysis (SMCDA) was used to construct a map of the most suitable zones for fish farming along the southern coastal sector of the Tuscany (central Italy). Grid-based spatial coverage maps of the selected criteria (i.e., physical and biogeochemical parameters, see Table 2) are constructed at the grid resolution of $0.01^\circ \times 0.01^\circ$ (about 1×1 km). Moreover, all layers were snapped on the study area to be perfectly overlapped with each other, and were clipped by using the boundary of the study area. Original monthly and seasonal climatological mean values were converted into annual means. All the geospatial analyses and the suitability model were developed by using ArcGIS 10.8 (© 1999–2019 Esri Inc.) tools.

2.4.1. *Spatial Multicriteria Decision Analysis (SMCDA)*

Multicriteria decision analysis (MCDA) concerns the combination and the handling of different criteria by organising them into a hierarchical structure, as well as studying the relationships among the several components of a problem (Malczewski, 2006). Overlay processes in GIS applications give great opportunities to integrate MCDA within GIS environment. GIS-based (or Spatial) MCDA (SMCDA) is a set of a procedures can be used to combine criteria maps with respect to their relative importance and derive relative weights for the criteria (Zabihi et al., 2019; Malczewski 1999, 2006; Chakhar and Mousseau 2008; Greene et al., 2011).

One of the most widely used weighting technique is the Analytical Hierarchy Process (AHP) developed by Saaty (1977, 1980). AHP consists of specifying the hierarchical structure and determining the relative importance weights of the considered criteria (i.e., parameters) and determining the final suitability scores by using the weighted linear combination (WLC) of original criteria maps (Malczewski, 2000; Bagheri et al., 2013; Shin, 2017). Fig. 2 shows the main steps of the workflow of the SMCDA process used to construct the map of the suitable zones for aquaculture. .

Step 1 –Criteria Selection and environmental constraints

A first phase of "zoning" was aimed to identify and select criteria for fish farming in the study area, as well as to reclassify the selected criteria according to suitability levels. In particular, physical and biogeochemical parameters significant for Mediterranean aquaculture finfish, such as fish biology, and key parameters influencing fish life cycles (body size, metabolism, growth rate, population structure and sexual characterization) have been considered (Handeland et al., 2008; Person-Le Ruyet et al., 2004; Pavlidis et al., 2000; Sigholt and Finstad, 1990; Tandler et al., 1989; Jonsson and Ruud-Hansen, 1985). In particular, variables related to the environmental boundary conditions (i.e., physical and biogeochemical parameters) that might influence directly the technical feasibility of the aquaculture system were taken into consideration (IOCCG et al., 2009) (Table 2).

Moreover, a preliminary map of the constraints was also built for the identification of areas classified as (GFCM General Fisheries Commission for the Mediterranean, 2012): i) unsuitable, for infrastructural, administrative or environmental incompatibilities; ii) potentially suitable, where there are no interferences with other uses. All environmental and infrastructural constraints, in respect of current regulations, were considered and along with their related buffers were subtracted from the study area. In particular, the areas, including the buffer zones, precluded to new aquaculture facilities in respect of current regulations (i.e. active concessions for fish farms, *Posidonia oceanica* and *Cymodocea nodosa* meadows, ship routes, military easements, submerged cables and pipelines, Sites of National Interest) have been masked out. Buffer zones were constructed around the above-mentioned constraints (Table 3). Preventive buffer area of 1 km was then used as a minimum distance around particularly valuable and vulnerable habitats (Selkoe et al., 2015), such as *P. oceanica* and *C. nodosa* meadows. Regarding human activities, a precautionary buffer zone of 500 m was chosen. The final suitability map was masked by the map of the constraints.

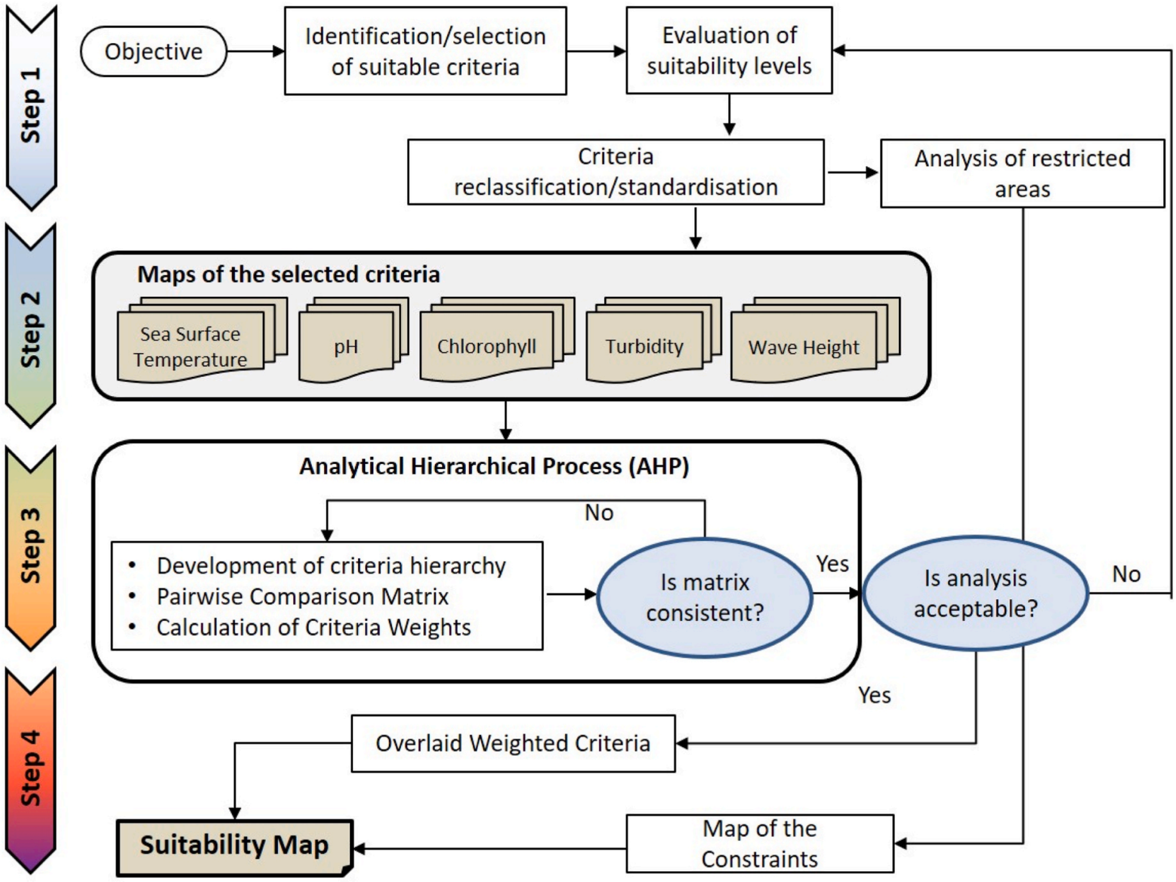

Fig. 2. Flow chart of the SMCDA decision process.

Table 3
Preventive buffer for main constraints.

CONSTRAINTS	PREVENTIVE BUFFER (m)
Sites of National Interest	5000
P. oceanica and *C. nodosa* meadows	1000
Military easements	500
Active concessions for fish farms	1000
Port areas, urban coastal areas and industrial sites	500
Areas with discovered unexploded bombs, wrecks, emerged and submerged artifacts, anchorage reserved areas for crafts and other restricted areas	Buffers enforced by any single ordinance of the Maritime Office of Piombino
Main ferry routes	500
Submerged cables and pipelines	500

Step 2 – Maps of the selected criteria

For each of the selected criteria, the range of suitability for fish cage site selection were defined and scored as low (1), medium (2) and high (3) based on literature (Table 4) (Forget et al., 2009; adapted from JACUMAR, 2008). Then, grid-based spatial coverage maps of the selected criteria (i.e., physical and chemical parameters, see Table 2) are constructed at the grid resolution of 0.01° × 0.01° (about 1 × 1 km). Raster were reclassified in three classes (low 1, medium 2, and high 3) according to the threshold values reported in Table 6 and on expert judgment. All grid cells show integer values on the basis of an ordinal scale of suitability increase (Ciotoli et al., 2011, 2013, 2016; Kendall, 1975).

Step 3 – Analytical Hierarchical Process (AHP)

Table 4
Classification of suitability criteria and scores for fish cage site selection and environmental monitoring, in Spain, in the Mediterranean Sea (JACUMAR, 2008).

Variable	good	medium	low
Coastal exposition	Partial	Sheltered	Non-sheltered
Wave height (m)	<1	1–3	>3
Water depth (m)	>30	15–30	<15
Water current speed (cm s-1)	>15	5–15	<5
Pollution level	Low	Medium	High
Max. temperature (°C)	22–24	24–27	>27
Min. Temperature (°C)	12	10	<8
Salinity (average)	25–37	15–25	<15
Salinity fluctuations	<5	5–10	>10
Dissolved Oxygen (%)	100	70–100	<70
Turbidity/Suspended solids	Low	Moderate	High
Sediment type	Sand or gravel	Mixture	Mud
Water classification	Oligotrophic	Mesotrophic	Eutrophic
Fouling	Low	Moderate	High

The calculation of the weights for the selected criteria has a crucial role in the production of suitability maps by applying GIS-MCDA methods. After the reclassification and generation of the criteria grid maps, the relative importance weight (RIW) of each criterion, taken two at time, was determined based on the expert opinion, analysis of inventory maps and literature knowledge. An importance scale from 1 to 9 is proposed for the comparisons through the AHP approach (see Table 5).

The basic input is the reciprocal pairwise comparison matrix, A, of n criteria, established on the basis of Saaty's scaling ratios, which is of the order (n x n) as defined in the equation, $A = [a_{ij}], i, j = 1, 2, 3, \ldots, n$, where A is a matrix with elements a_{ij}.

Table 5
Scales for the relative importance of two criteria.

Intensity of importance	Description	Intensity of importance
More important criterion		Less important criterion
1	Equal importance	1
3	Slightly importance	1/3
5	Strong importance	1/5
7	Very strong or demonstrated importance	1/7
9	Extreme importance	1/9
2,4,6,8	Intermediate values	1/2, 1/4, 1/6, 1/8

Table 6
Suitability model criteria for fish cage site selection.

Suitability model criteria	Suitability Classification and Scores		
	Low (1)	Medium (2)	High (3)
SST (°C)	–	–	19.1–18
pH	–	8.1–8.2	8.2–8.3
chlorophyll (mgm^{-3})	1.2–0.5	0.5–0.2	0.2–0.01
turbidity (m^{-1})	0.34–0.10	0.10–0.07	0.07–0.01
wave height Hs (m)	–	0.4–0.6-	0.4–0.01

The matrix A is then normalised as a matrix B:

$$B = [b_{ij}], i, j = 1, 2, 3, \ldots, n \tag{1}$$

With elements b_{ij} defined as:

$$b_{ij} = a_{ij} \Big/ \sum_{i=1}^{n} a_{ij} = 1, 2, 3, \ldots, n \tag{2}$$

Each weight value w_i is computed as:

$$w_i = \frac{\sum_{j=1}^{n} b_{ij}}{\sum_{i=1}^{n} \sum_{j=1}^{n} b_{ij}} \text{i, j} = 1, 2, 3, \ldots, \text{n} \tag{3}$$

The relationships between the largest Eigenvalue ($\lambda_{\max}$) and corresponding Eigenvector (W) of the matrix B is represented by the equation (4) (Xu, 2002; Feizizadeh and Blaschke, 2013):

$$\text{BW} = \lambda_{\max}\text{W} \tag{4}$$

Through the solution of pairwise comparison matrix, the AHP calculates the weights for each criterion (w_i) by taking the eigenvector corresponding to the largest eigenvalue of the matrix, and then normalizing the sum of the weights to unity as:

$$\sum_{i=1}^{n} w_i = 1 \tag{5}$$

In the AHP method the calculated weights need to be consistent. The degree of the weight consistency or inconsistency is defined by the Consistency Ratio (CR), that indicates the probability that pair comparisons of the matrix judgments have been generated randomly. The CR=CI/RI where RI is the random index, the average of the resulting consistency index depending on the matrix order by Saaty (1977) and CI is the consistency index defined by the equation (6):

$$CI = \frac{(\lambda_{max-n)}}{n - 1} \tag{6}$$

where $\lambda_{\max}$ is the largest eigenvalue of the matrix, and n is the order of the matrix. A CR approximately of 0.10 or less gives a reasonable level of consistency (Saaty, 1977). Otherwise, if the CR $\geq$ 0.10 then the pairwise comparisons are lacking consistency and the matrix needs to be adjusted by modifying the element values. The AHP method, used to construct the pair comparison matrix and calculate the weights for the analysed criteria, was performed by using the extAhp 2.0 (2014, developed by Ostwald Marinoni) plugin in ArcGIS.

Step 4 – Weighted Linear Combination (WLC) of the criteria and calculation of the suitability map

Finally, the overlay process of the weighted linear combination (WLC) of the criteria maps is applied to construct the final suitability map of the fish farming in the study area. The WLC is performed in ArcGIS to obtain the output grid that combines and overlays the input layers (criteria maps) multiplied by their respective calculated weights. The overlay procedure is mathematically defined as:

$$SLI_{yj} = \sum W_y {*} SL_{yi} \tag{7}$$

A total score for each 1 × 1 km grid cell is then obtained by multiplying the importance weight calculated for each criterion (GIS layer) by the score value given to the reclassified criterion and then by summing the calculated products for all considered criteria. The higher is the weight of the criterion, the more influence that factor has on the final suitability map. The final suitability map is then masked with the map of the constraints.

3. Results

3.1. Zones potentially available for aquaculture

The map of Fig. 3 shows the uses of the maritime space, such as the considered portion of sea along the coast from the Argentario Promontory to Piombino and the constraints imposed by current uses that cannot coexist with novel fish farms (Table 1).

The 22% of the study area (i.e., 248 km^2) is not available for aquaculture activities, for infrastructural, administrative or environmental incompatibilities.

The remaining 78% (i.e., 874 km^2) is available. Unavailable areas due to infrastructural, administrative and environmental constraints (including the buffer zones) were subtracted from the study area (Fig. 4).

3.2. Suitability analysis based on physical and biogeochemical parameters

Table 6 shows the suitability classification and scores of the aforementioned environmental parameters.

The mean annual SST falls within the class with the highest score or between 18 and 19.1 °C (Fig. 5) across the whole area.

pH values between 8.1 and 8.2 (medium class, highlighted in green) occur from Talamone up to Piombino in the northern sector of the study area and pH values ranging from 8.2 to 8.3 (high class) (Table 6) occur in proximity of the Latium-Tuscany boundary to the South up to the Argentario Promontory (Fig. 6). No values were registered within the low class (Table 6).

Chlorophyll values between 0.5 and 0.2 mg m^{-3} (medium class) occur from the bathymetry of 30m to the bathymetry of 100m from the Argentario promontory towards Piombino on the northern border encompassing the Gulf of Follonica (Fig. 7), whereas values between 0.5 and 1.2 mg m^{-3} (low class, Table 6) occur inshore at a bathymetry of 20m from Latium-Tuscany boundary to Ansedonia and southern Talamone village. High values (between 0.01 and 0.2 mg m^{-3}) were found offshore the bathymetry of 100m from Latium-Tuscany boundary to Argentario promontory, offshore the Gulf of Follonica and offshore the northern side of Piombino promontory.

The analysis carried out on turbidity shows values ranging from 0.01 to 0.07 m^{-1} (high class, Table 6) starting from the bathymetry of 50m across the whole study area, whereas values ranging from 0.10 to 0.34 m^{-1} (low class) occur inshore, across the bathymetry of 20m from Latium-Tuscany boundary towards north up to Punta Ala (Fig. 8). Across the bathymetry of 30m and 50m values ranging from 0.07 to 0.10 m^{-1}

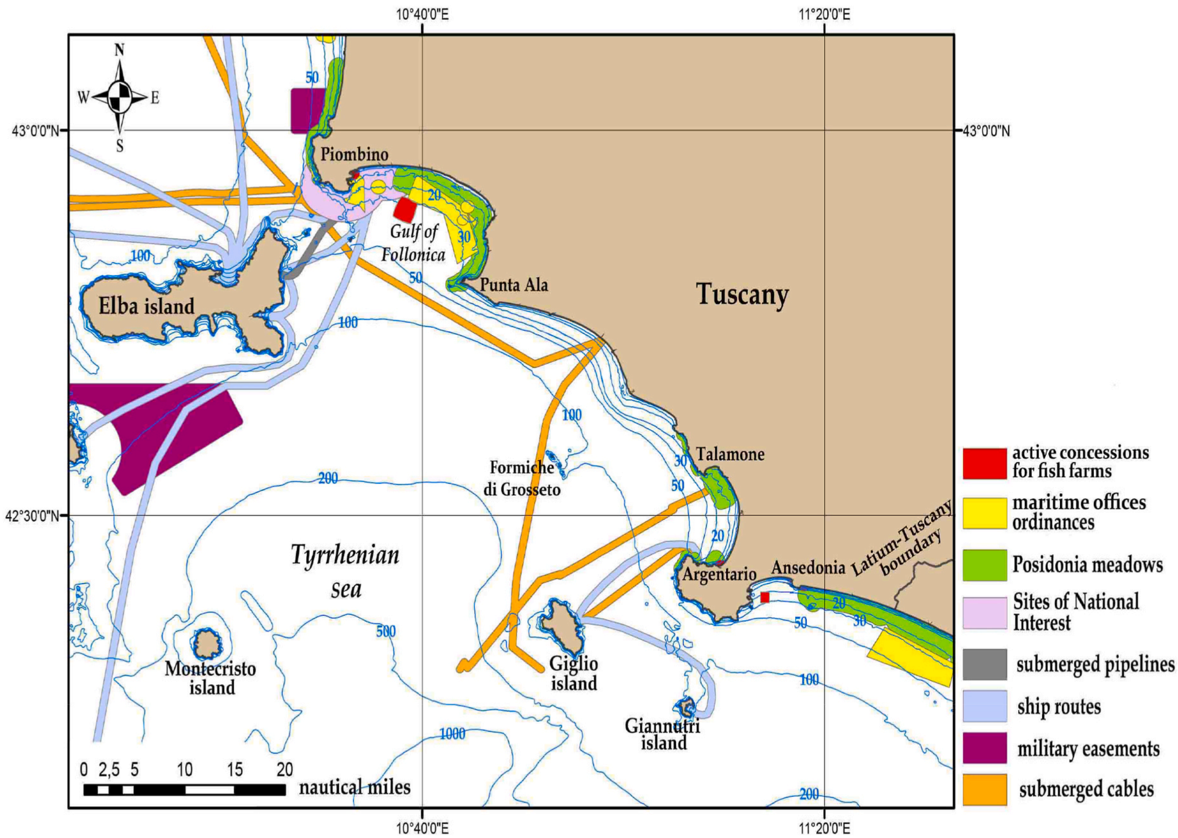

Fig. 3. Current maritime uses and constraints.

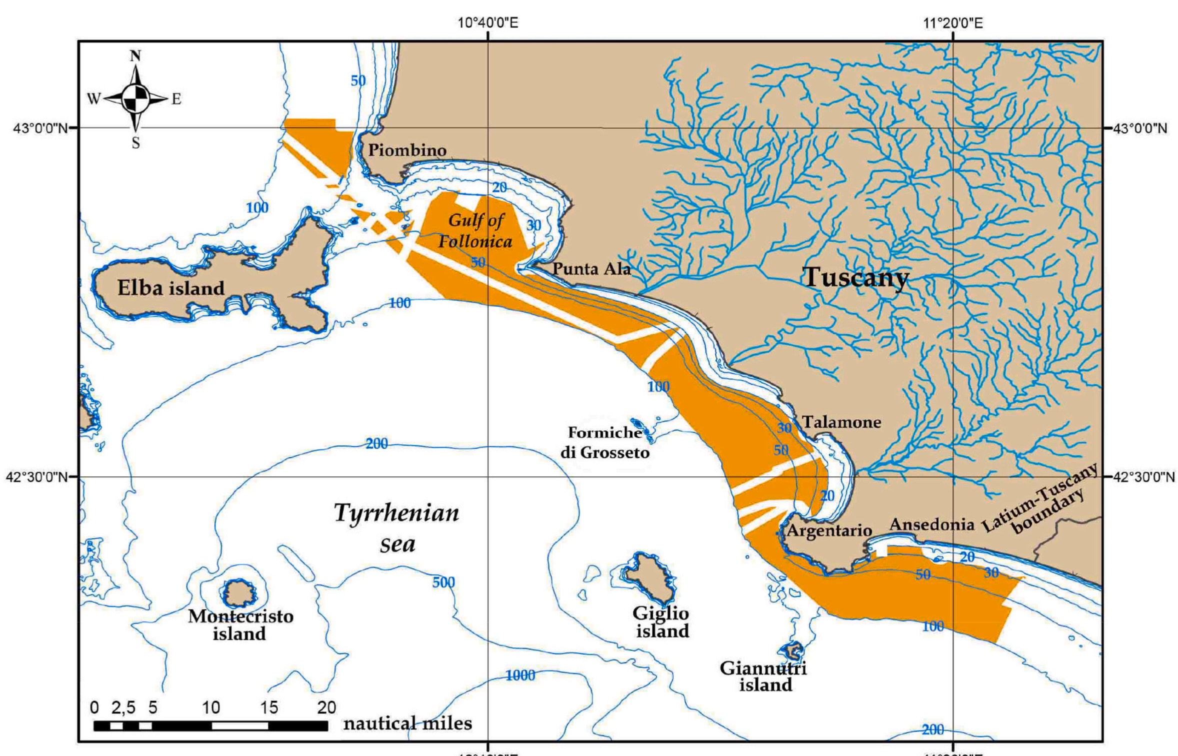

Fig. 4. The portion of sea potentially suitable for aquaculture (874 sq. km.).

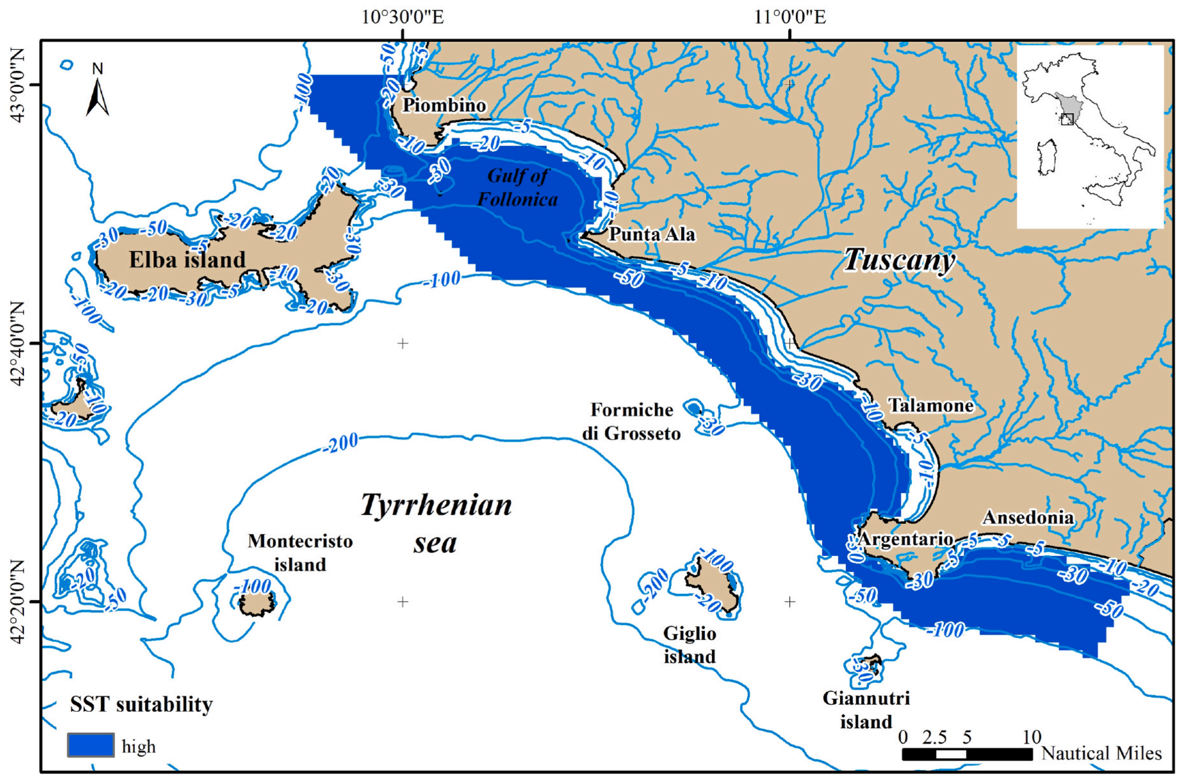

Fig. 5. SST within the study area. pH values between 18 and 19.1 °C 8 (high suitability class) highlighted in dark blue.

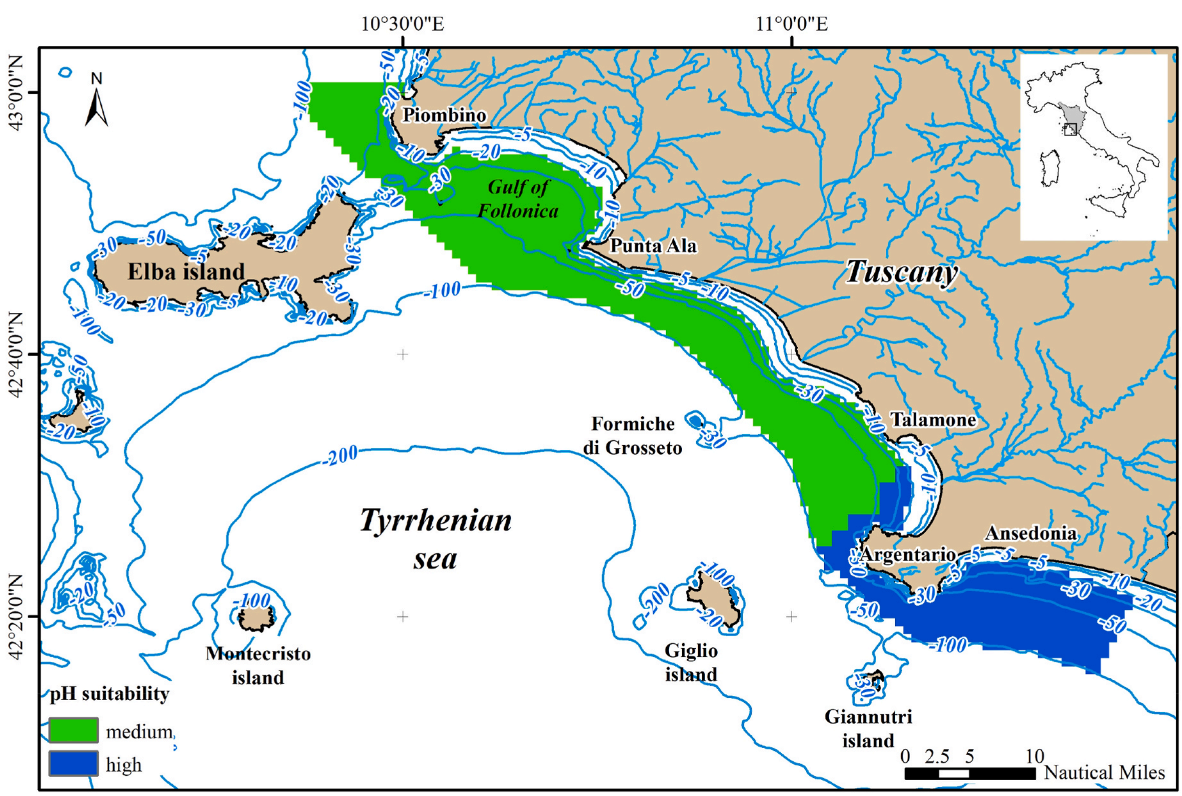

Fig. 6. pH within the study area. pH values between 8.1 and 8.2 (medium class) highlighted in green and between values of 8.2 and 8.3 (high suitability class) highlighted in dark blue.

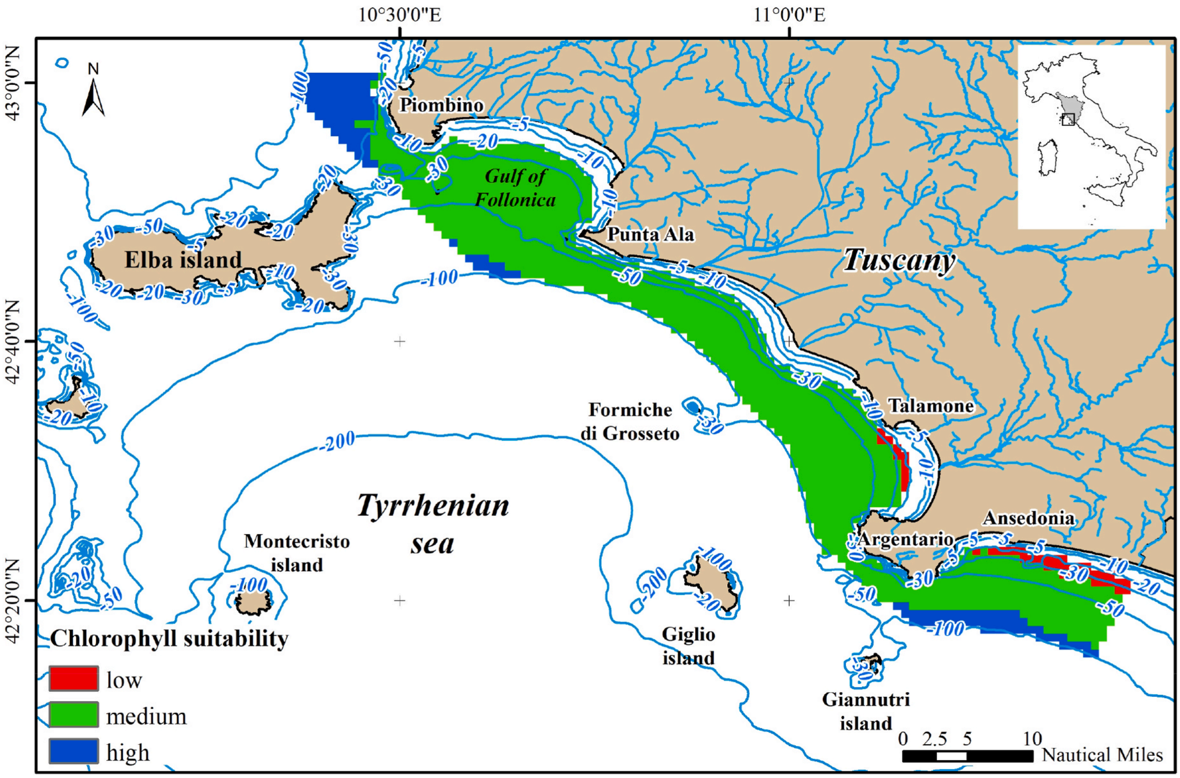

Fig. 7. Chlorophyll (*chl*) values between 0.5 and 0.2 mg m^{-3} are highlighted in green (medium class); whereas values between 0.5 and 1.2 mg m^{-3} (low suitability class) are highlighted in red. High suitability values (between 0.01 and 0.2 mg m^{-3}) are shown in dark blue.

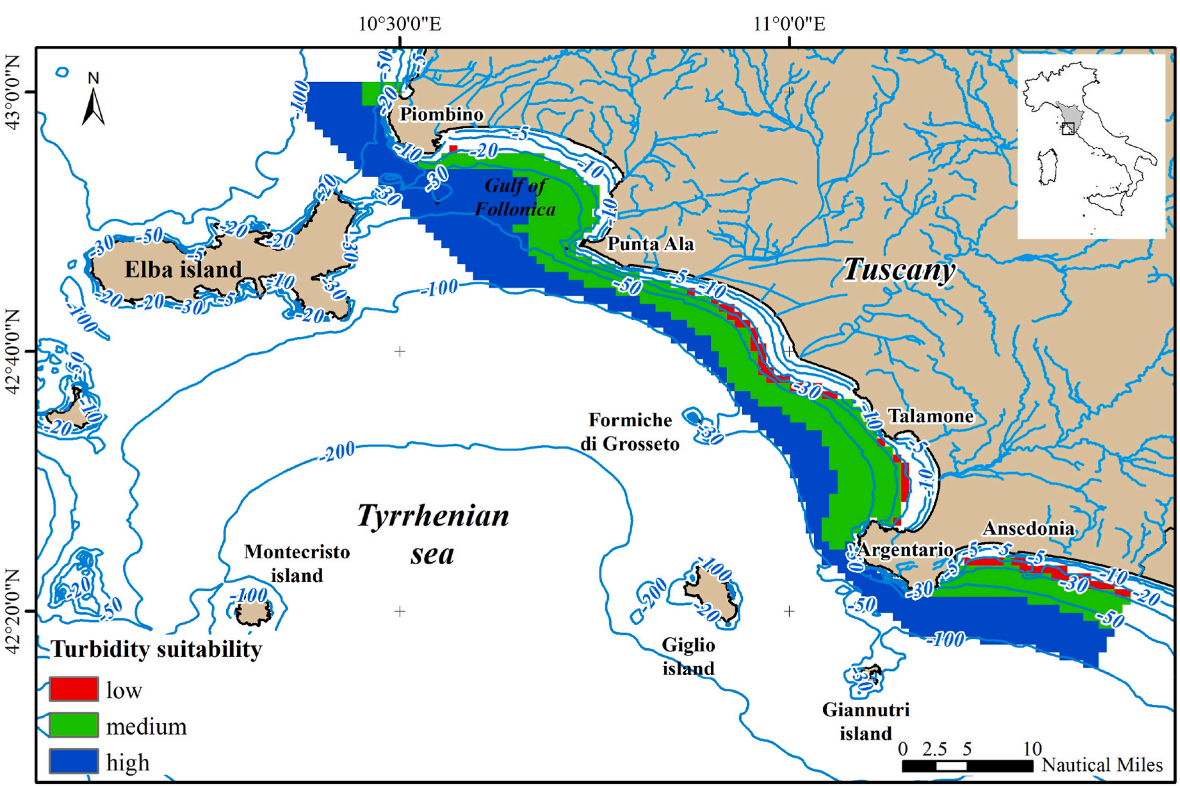

Fig. 8. Turbidity values ranging from 0.01 to 0.07 m-1 are highlighted in dark blue (high), whereas values ranging from 0.10 to 0.34 m^{-1} (low) are shown in red. Values ranging from 0.07 to 0.10 m^{-1} (medium) are highlighted in green.

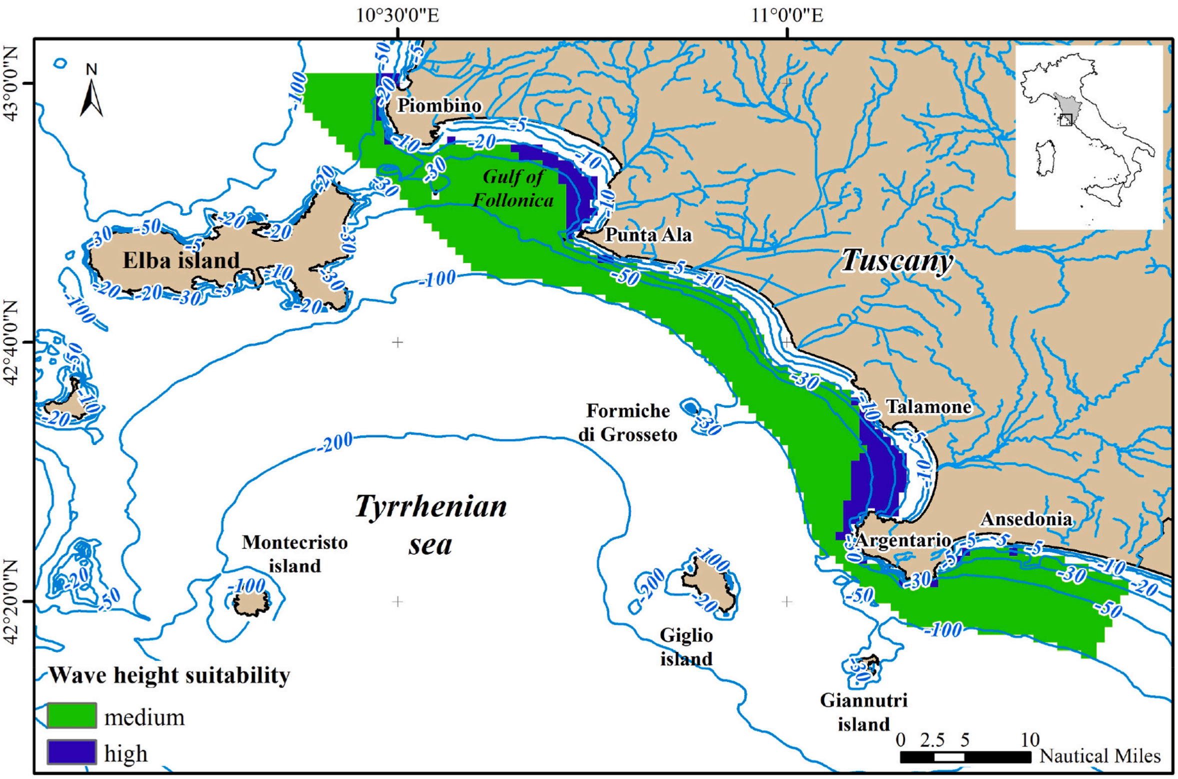

Fig. 9. Wave height values ranging from 0.01 to 0.4 m are highlighted in dark blue (high), values between 0.4 and 0.6 m (medium) are shown in green.

(medium class) were recorded up to Piombino Promontory.

The analysis carried out on wave height shows values ranging from 0.05 to 0.4 m (high class, Table 6).

Onshore between Argentario Promontory and Talamone and inshore the Gulf of Follonica and between the bathymetry of 20 and 50m and 20 and 30m. The remaining portion of the study area offshore the showed values between 0.4 and 0.6 m (medium class) (Fig. 9). No low class values were recorded within the study area.

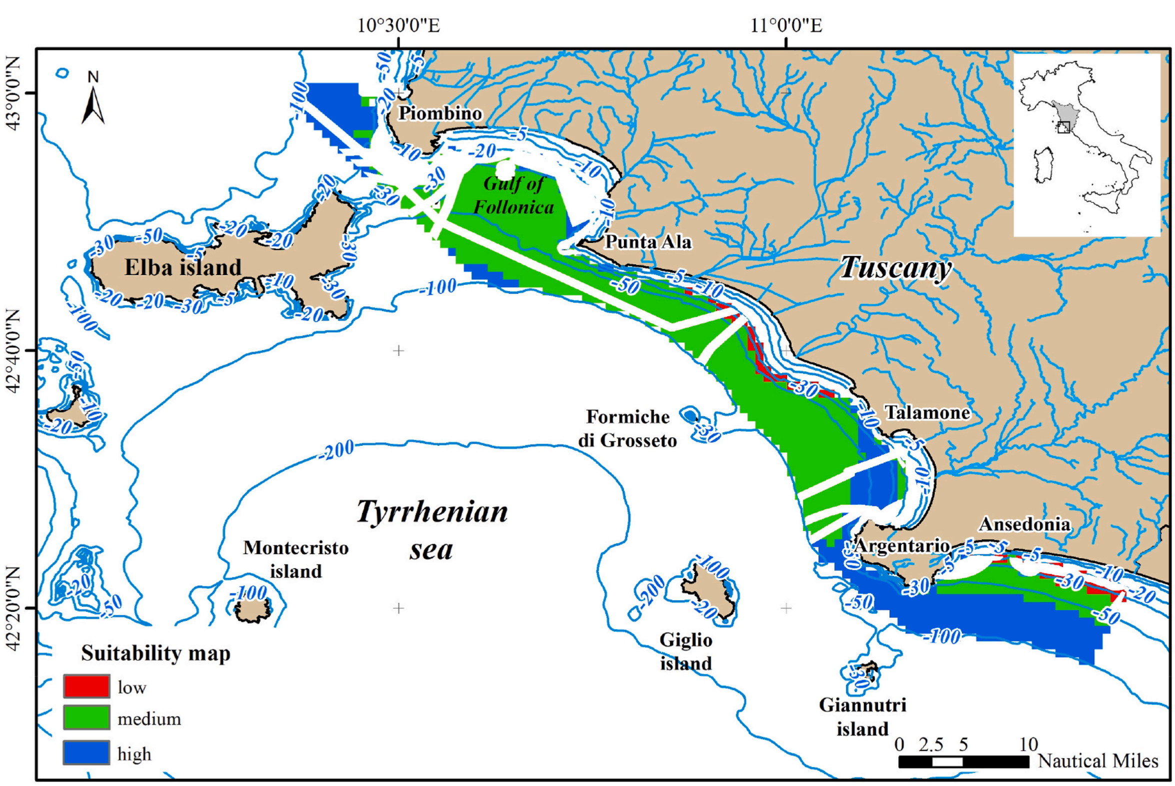

Fig. 10. Suitability map for marine aquaculture produced by SMCDA.

3.3. Ranking the suitability of potential available areas

The output map shows the level of suitability of potential available areas (total available area about 874 km^2) in which to set up novel aquaculture (in dark blue) to low suitable areas (in red) (Fig. 10).

Results suggest that nearshore coastal areas are not highly suitable for fish aquaculture across the southern-central portion of the study area, from Latium-Tuscany boundary to Punta Ala. In fact suitability level increases with rising of depth from Latium-Tuscany boundary to Piombino. Nearshore coastal areas from Latium-Tuscany boundary to Ansedonia and from Talamone to Punta Ala, between the 20m and 30m, were classified as low suitable. The highest suitability areas occur in the Talamone gulf and offshore the Argentario promontory at water depth between 15 and 30 m and 30 50m, respectively. Other high suitability areas occur northern of Piombino town between 30 and 100 m depth. . However, in correspondence of the Argentario promontory, shoreline is rocky, the sea slope is steep and the bathymetry of 50m skirts the promontory, thus making difficult to install aquaculture farms.

Between 30m and 50m the suitability level slightly increases (medium suitability) from Latium-Tuscany boundary to Ansedonia.

Beyond 30 up to 100m, from Talamone to Piombino the suitability level increases again (medium suitable).

In the northern sector of the study area, nearshore coastal areas show medium suitability level within the Gulf of Follonica. Here, the morphological characteristics of the sea floor are more favourable due to a less steep slope, a wider continental shelf and a more sheltered exposure to the prevailing winds. Towards the northern sector of Piombino promontory, although there is a high suitability level offhore, the sea slope is very steep and exposed to the open sea.

4. Discussion

In this work, we prefer to use the decision-making technique approach and fixed threshold values because of:

- the lack of a response variable (that prevent the application of regressive techniques);
- the fuzzy membership classification (Zadeh, 1965) and regression techniques are not easy to apply for stakeholders and they do need a deep knowledge of statistics.
- the rapidity of the setting up of a spatial model using variables that can be easily found in the several public available databases and due to the relatively ease of obtaining suitability maps in a short time, as often required by public administrations to make preliminary decisions.

In our approach, we have considered that the physical and biogeochemical characteristics of the water column represent the conditioning factors for the zoning process. For example, in future site-selection process, it is important that those parameters show low variability so as to not affect the growth and well-being of farmed fish.

Remote sensing and EO technology can be a valuable source of data and cost-effective technique for water quality monitoring which is particularly useful for aquaculture. The key strength of using EO data is the ability to efficiently investigate spatial and temporal scales that would be difficult to achieve by only *in situ* measurements. Short-term time series can be used to investigate seasonal or annual changes, whereas longer-term assessment can encompass more permanent changes and such as interannual changes.

The bottom type, with reference to the trend of continental shelf inclination, is a crucial element for the choice of the areas to be used for mariculture. Often sea bottom is noticeable sloped near the Tyrrhenian continental coast, reaching quickly depths ranging between 30 and 50 m. This allows the placement of cages relatively close to the landing sites, with consequent economic benefits. This depth range is very suitable for the setting up of cage farms providing an easy anchoring and shelter from the typical drizzle phenomena of the shallow bottoms. The proximity of the continental shelf to the coast favours greater circulation of water masses, due to the presence of surficial currents and to upwelling phenomena. This characteristic provides a benefit of the bred species that can live in a higher water supply environment and where greater is the dispersion of the organic waste from the cage production.

Surficial current velocity data are extremely important to site selection. However in this study those data were not used due to the fact that the data available were the monthly mean data for the period 2001–2010, provided by the reanalysis of MyOcean's numerical model for the Mediterranean Sea on a regular grid with a cell size of $1/16^{\circ}$ or at a spatial resolution of around 6 km. This resolution useful at regional scale (100 s km) was too coarse to the investigation of the local scale (10 s km).

Information on meteorological conditions is critical to describe extreme situations that could occur near the cages. As far as the submersible cages are a proved viable rearing system, they are not particularly sensitive to wave motion. However, it is preferable that the atmospheric conditions of areas concerned with breeding are not adverse for too long in order to allow continuous access and assistance to the facilities at sea.

The use of climatological series of remote-sensed physical, chemical and biological data could provide the initial state of seawater properties. Remote-sensed derived information can support aquaculture farmers and policy makers by issuing warnings on potential water quality threats and monitoring climate change taking into account the seasonal and annual variations, which can impact the sea farms.

A possible application of a GIS spatial analysis model, to support decision making for aquaculture, has been illustrated. The strengths of GIS include the ability to handle a wide range of datasets and resolutions, speeding up work allowing for easy updating of databases and handling of time series analysis in order to generate high-quality outputs. The ranking model developed in this study integrates different data sources as well as different products (EO, *in situ* and numerical modeling) generating added value products, which can foster the aquaculture sector contributing to the implementation of spatial planning processes.

The use of climatological series of remote-sensed physical, chemical and biological data provides the initial state of seawater properties.

In accordance with the model results, most eligible areas are located between Argentario Promontory and Talamone the Gulf of Follonica, at a water depth between 30m and 50m, and this is consistent with the general settings of aquaculture farm practice, which usually places the cages at a depth between 25m and 40m.

Results also suggest that the study area may be broadly suitable for fish aquaculture, in terms of physical, chemical and biological parameters. The model outputs indicated that there was little potential for the nearshore aquaculture development in the study area. In fact, nearshore coastal areas encompassed between Ansedonia and Punta Ala at the bathymetries of 20 and 30m are not suitable sites for fish farming, mainly due to the occurrence of high turbid waters caused by river discharge and seafloor sediment resuspension at the shallower bathymetries and high values of chlorophyll. The amount of suspended solid material at the mouth is predominantly coarse for the Ombrone river, while it is predominantly fine sand for the other rivers (Barbano et al., 2008; Ferretti et al., 2003). The net sediment local transport along the shore is mainly directed northbound between the Ombrone river mouth and Follonica. On the other hand SST skin within the study area is not a limiting factor to exclude a priori nearshore or offshore areas as unsuitable. The model used had a range of applications, but one of the key outcomes for aquaculture was an assessment of how physical and biogeochemical parameters could potentially affect aquaculture.

The limits selected for the study area were due to the high management costs of fish cages increasing with depth and distance from the coast, which can make the activity non profitable (CEFAS, 2014; IREPA Istituto di Ricerche Economiche per la Pesca e l'Acquacoltura, 1998;

Andersen, 2002, IUCN and De Monbrison, 2004; IUCN, 2009; Perez et al., 2005).

The analysis of suitability level of potential new sites for aquaculture should be evaluated also on the basis of the distance from the coast (Ross et al., 2013). The effective and sustainable management of an aquaculture site requires continuous monitoring. The selection of the best areas where new aquaculture fish farms can be allocated must lead to profits, that is to say that the profits arising from the exploitation of the farms must be higher than the costs incurred to reach them and for their maintenance. Indeed, the facilities should not be too far away from the ports, but, since in this part of the study area the highest suitability levels are placed far from the coast, the installation of new aquaculture plants beyond the 50m bathymetry requires a further detailed cost-benefit analysis. However, the presence of already almost three active operating farms in the area identified in this analysis supports the effectiveness of the method applied in the study.

5. Conclusions

- An increase in competing marine uses and users requires a holistic approach to the planning of allocated zones for aquaculture (AZA) has to be within a framework of Maritime Spatial Planning (MSP) that considers the environmental, economic and societal impacts of all activities;
- The zoning process is fundamental for the identification of potential areas for the sustainable development of aquaculture prior to the realization of any anthropic artefact;
- The present study uses open source remote-sensed and *in situ* derived information of the physical and biogeochemical characteristics of the study area to develop a decision model where suitability criteria for marine aquaculture are applied;
- The developed spatial model is based on GIS decision-making approach (Spatial Multicriteria Decision Analysis, SMCDA) by using the Analytical Hierarchical Process (AHP);
- The obtained suitability map, as the output of a zoning process, enables the individuation of the most suitable aquaculture zones in the study area and constitutes a useful tool for regional regulators engaged in the process of MSP and in the allocation of zones for a suitable development of aquaculture;
- The availability of a reliable and verified geospatial dataset might be a relevant issue in the implementation of spatial analysis process (i.e., site selection process);
- This study has predominantly a preparatory value, but further studies are needed to model and integrate data on a finer spatial scale for further site selection process;
- Finally, the socio-economic analysis of the study area, considering the potential environmental impacts and possible conflicts with artisanal fisheries, trawling and with tourism activities, should be investigated.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

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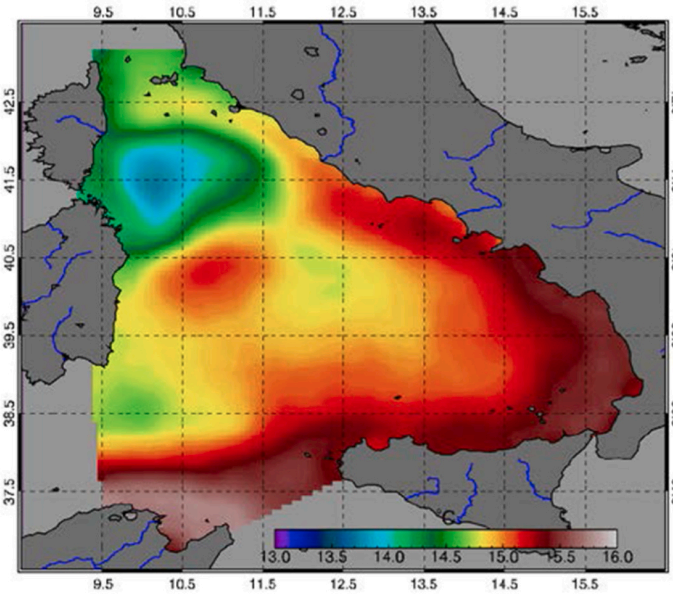
APPENDIX. SEA SURFACE TEMPERATURE (SST) seasonal climatological means 2006–2012 (source CNR-ISMAR)



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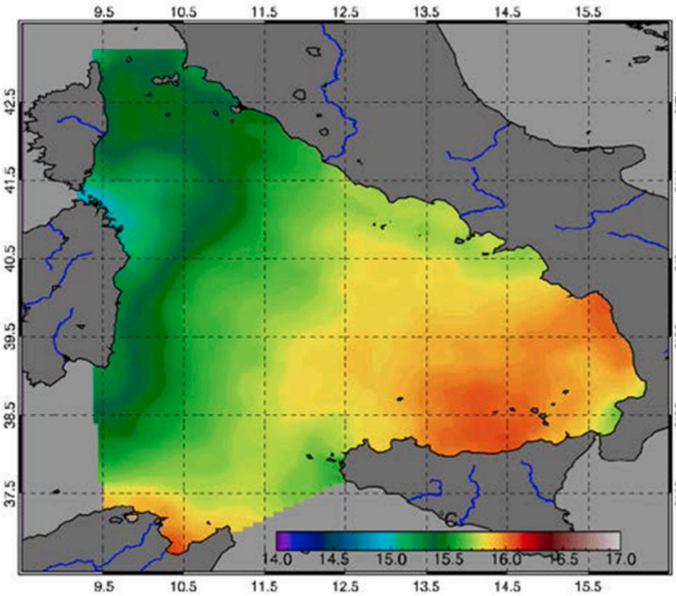

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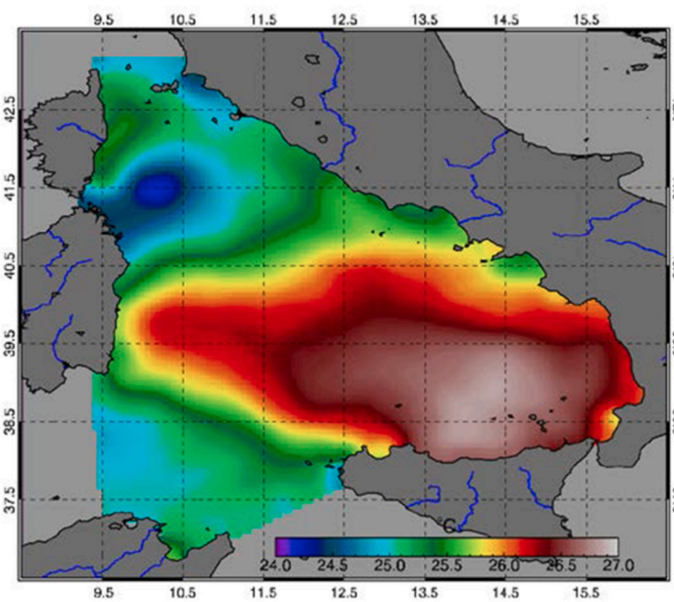

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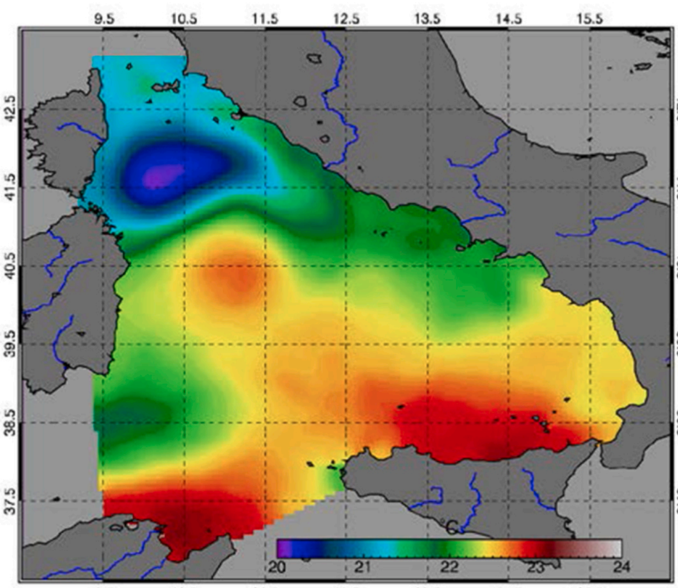

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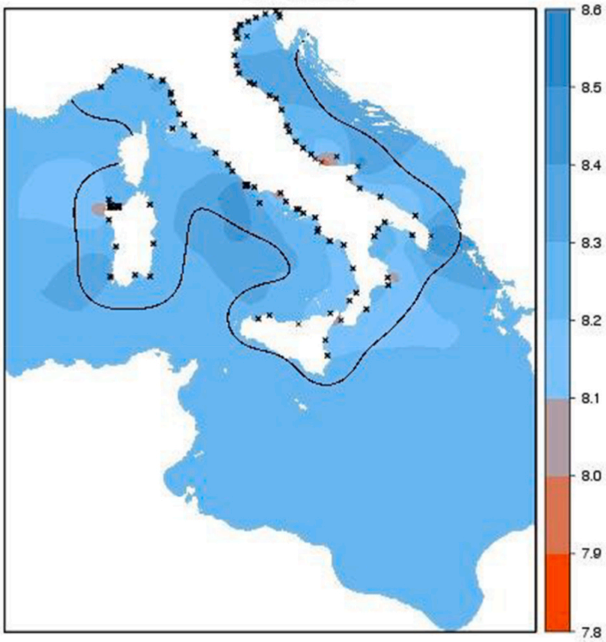
APPENDIX. SURFICIAL Ph 2006–2012



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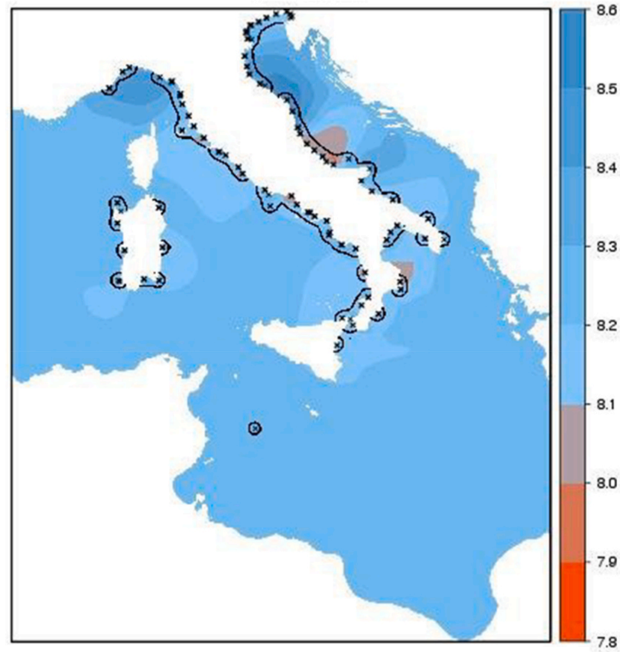

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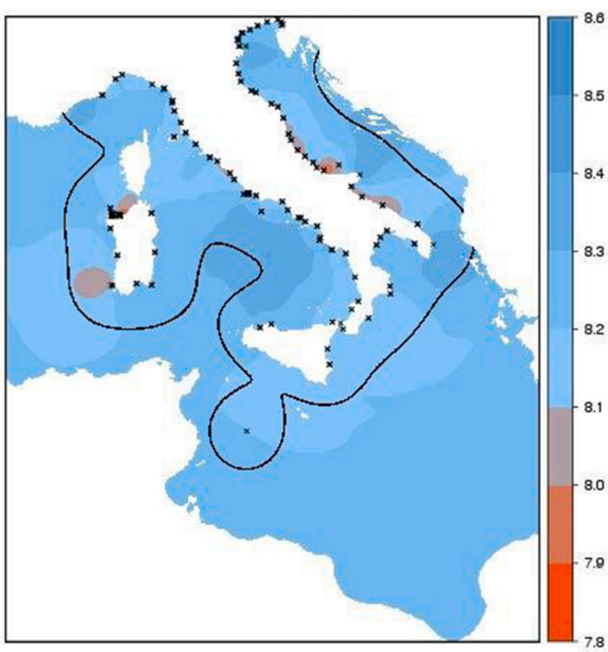

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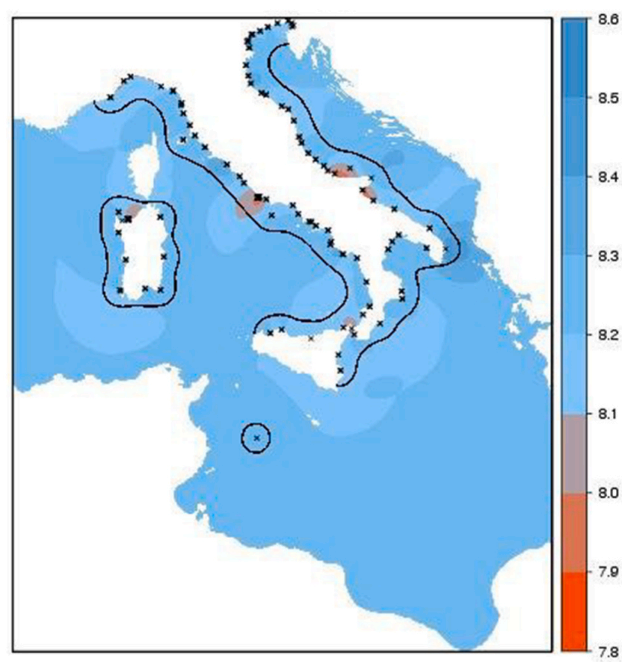

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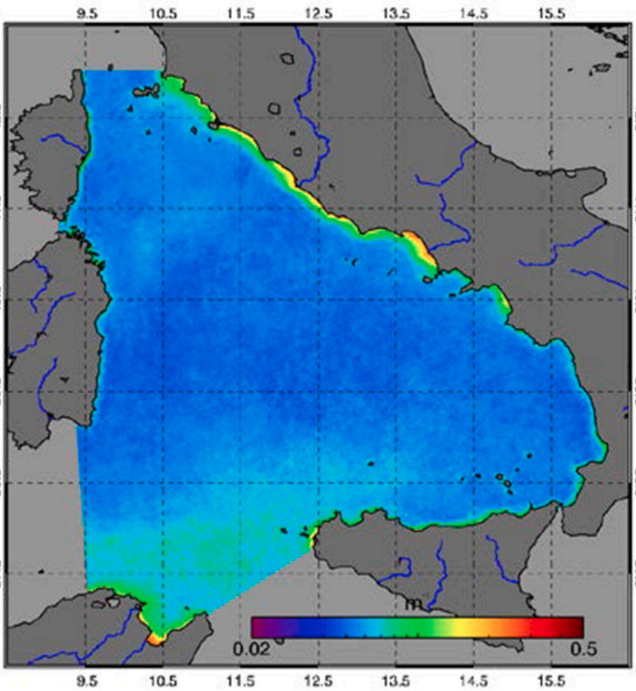
APPENDIX. TURBIDITY (KD490) seasonal climatological means 2001–2009 (source CNR-ISMAR)



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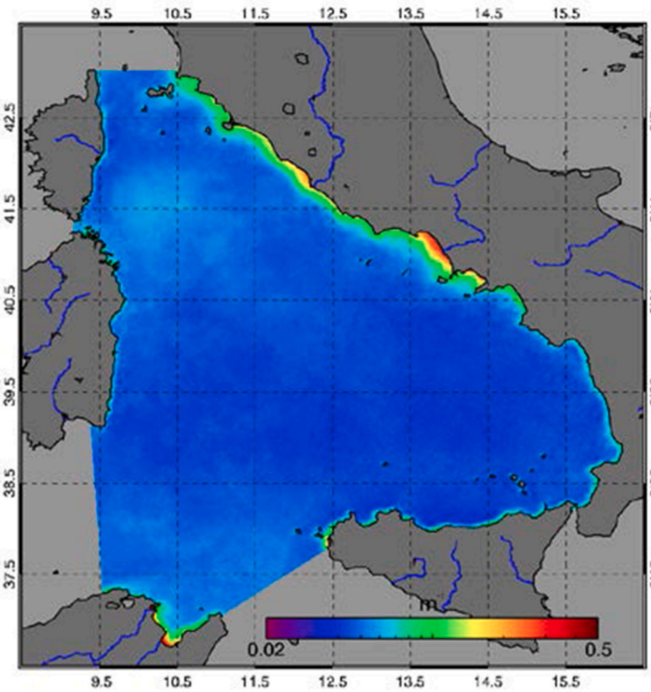

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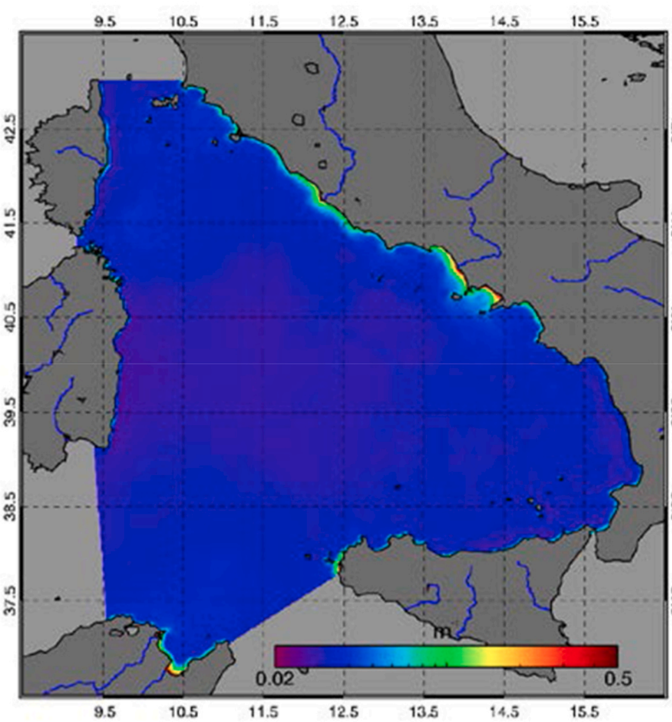

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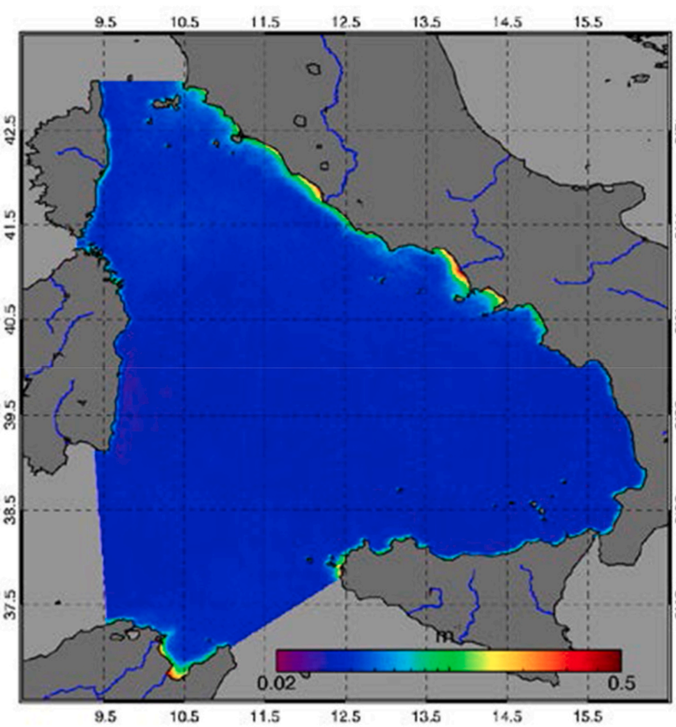

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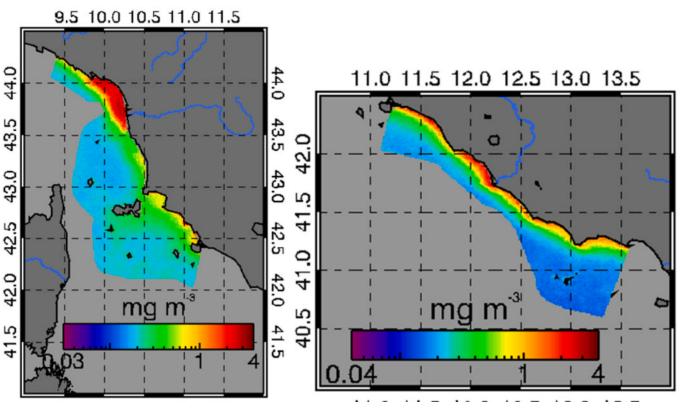
APPENDIX. CHLOROPHYLL (chl) seasonal climatological means 2001–2009 (source CNR-ISMAR)



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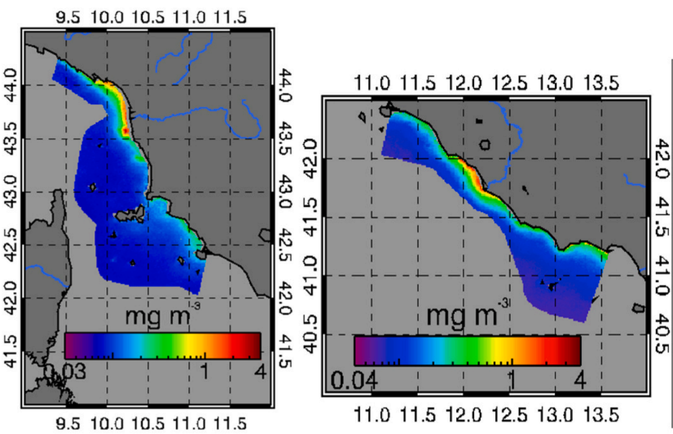

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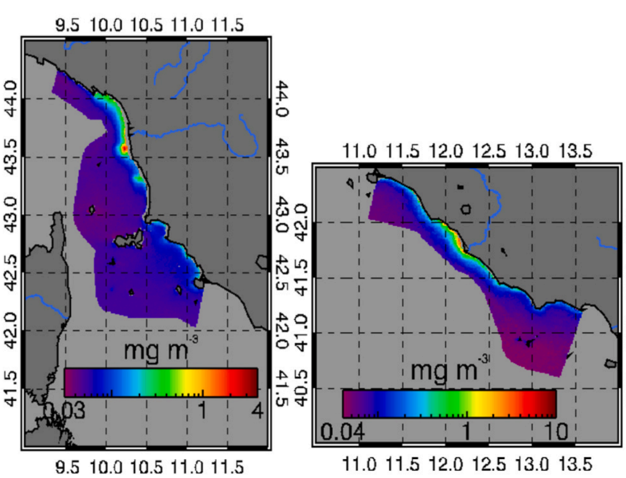

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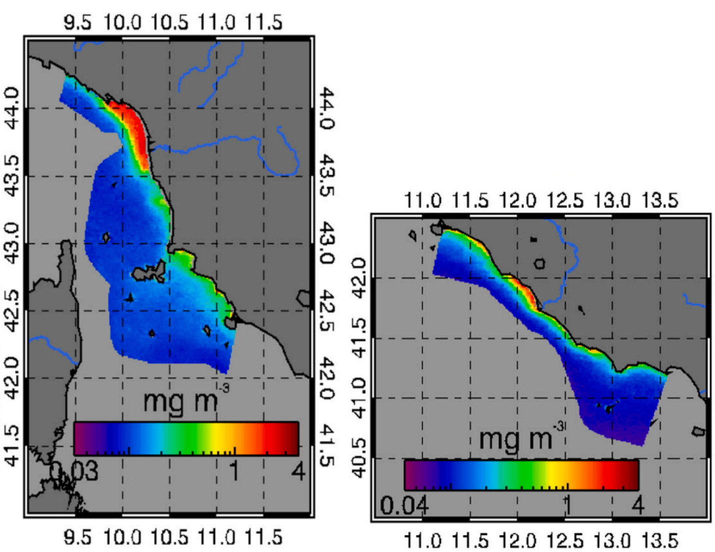

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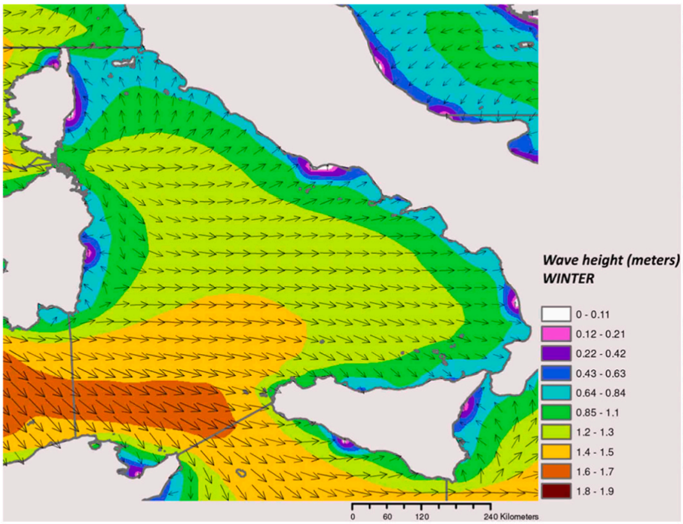
APPENDIX. WAVE HEIGHT seasonal climatological means 2006–2011



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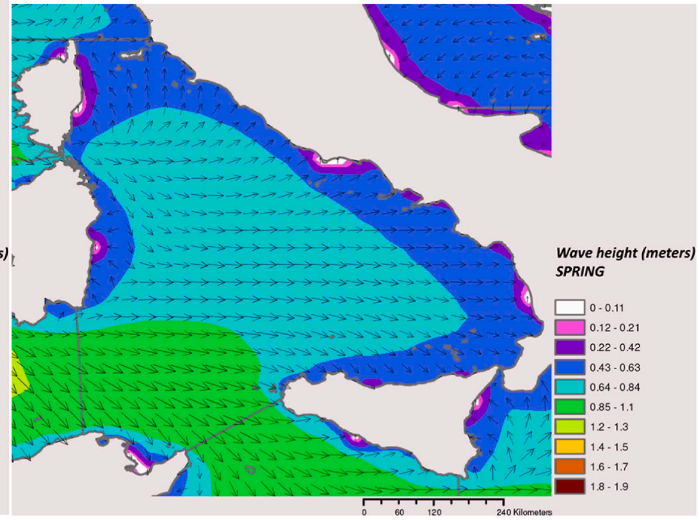

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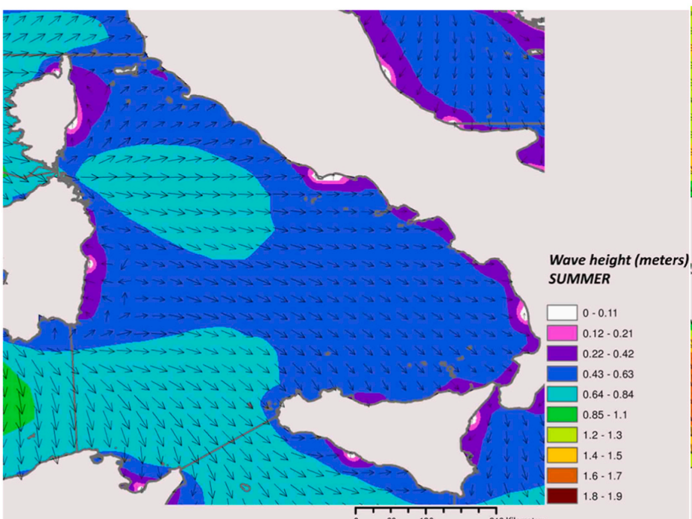

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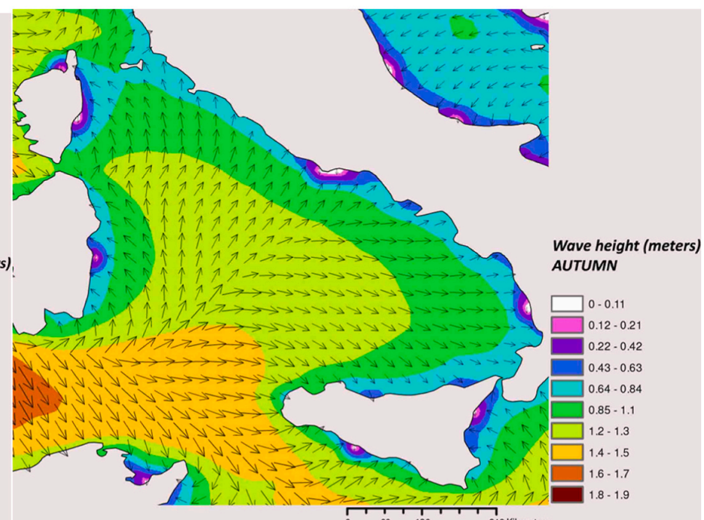

Autumn

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