

Article

# Earth Observation for Maritime Spatial Planning: Measuring, Observing and Modeling Marine Environment to Assess Potential Aquaculture Sites

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**Abstract:** Physical, chemical and biological characteristics of seawaters are primary descriptors for understanding environmental patterns and improving maritime spatial planning for potential aquaculture uses. By analyzing these descriptors in spatial and temporal dimensions, it is possible to characterize the potential productivity performances of different locations for specific aquaculture species. We developed a toolbox that, starting from the actual competing uses of the maritime space, aims at: (a) identifying sites with conditions feasible for aquaculture fish growth (feasibility scenario); and (b) assessing their different productivity performances in terms of potential fish harvest (suitability scenario). The toolbox is being designed in the Mediterranean, northern Adriatic Sea, but because of its modularity / multi-stage process, it can be easily adapted to other areas, or scaled to larger areas. The toolbox, representing a pre-operational Copernicus downstreaming service that integrates data and products from different sources (*in situ*, Earth Observation and modeling), is innovative because it is based more on parameters relevant for fish vitality than on those oriented to farm functioning. Stakeholders and farmers involved in the maritime spatial planning can use resulting scenarios for decision-making and market-trading processes.

**Keywords:** maritime spatial planning; aquaculture; Earth Observation; sea surface temperature; Copernicus downstream

## 1. Introduction

The EU Commission has prioritized the “blue economy” as a key focus area in terms of growth and job creation to support economic recovery and sustainability. Maritime economic activities alone are expected to increase to an estimated gross value added (GVA) of €590 billion and 7 million persons by 2020. Aquaculture, in particular, is expected to grow by 100%, offshore wind energy exploitation by 30% and the cruise sector by 60% [1]. As outlined in the Blue Growth Communication of 2012, there are a number of potential synergies to be created among maritime economic activities.

Similarly, the European Parliament and the Council adopted a framework for Maritime Spatial Planning in Europe (MSP) [2] that recognizes the importance of rationalizing competing uses of the marine environment, guarding its quality but also providing a greater confidence and certainty for investors in order to exploit the full potential of the blue economy [3,4]. With the purpose of creating synergies among different activities for multiple uses of space, this directive increases the cross-border cooperation to plan sustainable growth of marine aquaculture [5].

The numerous generic conflict matrixes developed for the purpose of MSP show more “spatial compatibilities” between uses than spatial non-compatibilities [6], making evident the need for specific decision support systems tool that can be based on Earth Observations (EO)’s synoptic mapping [7]. The modern remote sensing methods of space oceanography coupled with more classical *in situ* techniques constitute the most efficient and low-cost way for cost-effective planning, management and rational exploitation of marine resources [8–12]. Moreover, the Strategic Guidelines of Common Fishery Policy (CFP) 2014–2020 [5] identifies for the aquaculture sector the following priorities: reducing administrative burdens; improving access to space and water; increasing competitiveness; exploiting competitive advantages due to high health, quality and environmental standards.

The Food and Agriculture Organization of the United Nations (FAO-UN), states that the most common native species in European marine aquaculture are *Dicentrarchus labrax* (Linnaeus, 1758) (common name: sea bass), *Sparus aurata* Linnaeus, 1758 (common name: sea bream) for the Mediterranean Sea and *Salmo salar* (Linnaeus, 1758) (common name: Atlantic salmon) for the northern seas [13]. In 2007, the European production of Atlantic salmon (142,350 tons) represented 10% of global production, while the sea bass and the sea bream production represented 92% (57,893 t) and 67% (84,590 t), respectively, of global production [5]. According to the Federation of European Aquaculture Producers (FEAP), the European aquaculture fish production of 2014 for Atlantic salmon was 1,554,061 t; sea bass was 148,367 t and sea bream was 146,467 t. It is worth noting that this data includes Turkey, which is the second largest producer after Greece even if it is not a EU member [14].

Many parameters of seawater affect the conditions of fish growth [15] and, according to Swann [16], seawater properties determine the success or failure of an aquaculture activity. The assessment of water properties accounts for several parameters related to the chemical and biological characteristics, some of which are also individually considered in evaluating the feasibility of an aquaculture facility [17].

Among these parameters, temperature is the key descriptor because it influences the variation of many other physical and biochemical seawater properties as well as the entire life cycle in terms of fish size, metabolism, sex determination, growth and, in the natural environment, the population structure [18–23]. Parameters such as dissolved oxygen (DO), chlorophyll-a (Chl-a) and nutrient compounds are necessary for an early stage evaluation of an aquaculture productive process [24–26]. According to Kapetsky *et al.* [27], parameters such as bathymetry, sea surface temperature and chlorophyll are of equal importance for aquaculture production and adequate for estimating potential offshore aquaculture sites. Water current speed is a limiting factor for the maintenance of minimal water turnover in the farm cages, whereas a minimum water depth for the installation of an aquaculture plant is strongly dependent on the specific design selected [17,28].

EO products allow the assessment of the spatial and temporal distribution of many water quality parameters [29,30], including sea surface temperature (SST) [31,32] and chlorophyll. Statistical analyses of EO products also allow the delineation and tracking of possible anomalies [33].

The *in situ* data, along with data derived from EO, comprise the foundation of the toolbox proposed in this article for selecting aquaculture sites.

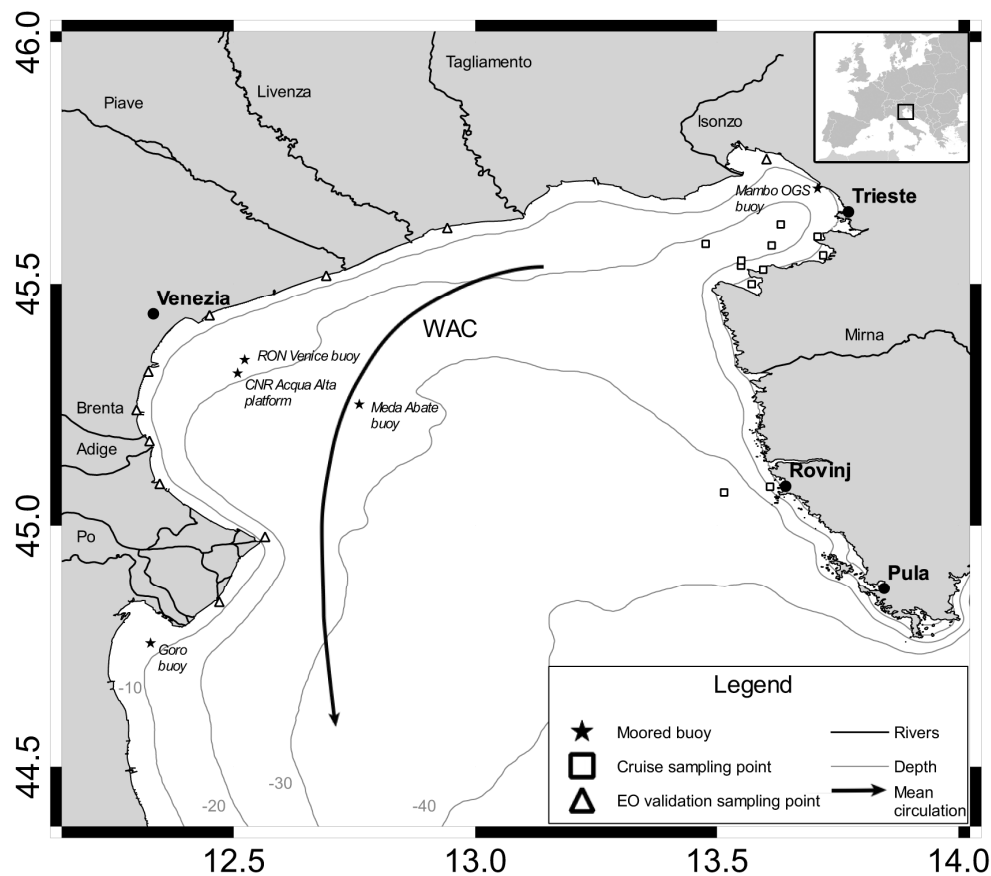
The toolbox proposed here assesses the feasibility of fish aquaculture and the suitability of specific sites by integrating *in situ* data, Earth Observation and modeling products through:

- the analyses of biologically, chemically and physically relevant seawater parameters to verify that values are within the vitality ranges of fish species;
- a spatial simulation of a harvesting model to evaluate aquaculture potential productivity performances.

## 2. Northern Adriatic Sea

The Adriatic Sea is a shallow semi-enclosed shelf sea located between the western and eastern parts of the Mediterranean Sea. It is about 800 km long and 150 km wide. The study area is the northern and shallower portion (depth < 100 m) of the Adriatic Sea, characterized by a gentle slope (about 0.02°). One of its major features is a coastal current along the western side of the basin, the Western Adriatic

Coastal Current (WAC), driven by wind and thermohaline forcing (Figure 1). The main components triggering the alternation of stratification and mixture of the water column are the river outflows and metocean forcing factors, such as the wave-supported turbidity flow during intense wind events or the high sediment and nutrient concentrations during periods of high river discharge [34]. Suspended materials (organic and inorganic) and chlorophyll concentrations in the basin are influenced by plume extent and content. Po River constitutes the main freshwater discharge in this area, collecting the runoff of a 71,057 km<sup>2</sup> drainage basin with a resident population of 16 million inhabitants [35].



**Figure 1.** Northern Adriatic Sea map showing the Western Adriatic Coastal Current (WAC) direction (solid arrow) and the available *in situ* measurement locations.

The temperature of the surface waters in northern Adriatic Sea shows a seasonal cycle, with fluctuations of more than 10 °C due to atmospheric heat transfer. In the summer, when a thermocline at a depth of 30 m clearly separates the upper layer from the bottom layer, the surface temperature is uniform throughout the entire basin with average values of 23–24 °C in the open sea [36,37].

Riverine freshwater inputs affect the productivity of certain areas, especially in the proximity of delta [28] where the nutrient levels are inversely related to the salinity [38] and the highest rate of oxygen consumption due to biochemical processes is recorded [37]. *In situ* measurements pointed out an increasing occurrence of frequent, short-lived hypoxic events along the northwest coasts even in periods of relatively low discharge, water stratification and/or temperature [39].

Among the Italian seas, the Adriatic and Ionian Seas account for over 40% of the overall national fish production. This high production level is partially related to the use of traditional fishing equipment [40]. Since 1987, containment measures for trawling were established and, later in 1992, the Italian government set up the temporary suspension of fishing to reduce pressure [41]. Even though statistics regarding fishery capture production show a reduction for the period between 2001 and 2013,

there is still evidence of overfishing: in 2014, 94% of all commercial species fish stock is still considered overexploited in the northern Adriatic Sea.

During the FP7-EU-funded MERMAID project (5th meeting March 2014—Athens, Greece), the Kefalonia Fisheries aquaculture company developed a site potential outcome scenario for the northern Adriatic area in terms of sea bass and sea bream aquaculture production and sales. The major evidence of the scenario was that the best economic return in the site can be obtained by lowering “normal”-sized fish production (200–400 g) at low market price and favoring the “larger” sized fish (600–800 g) at a higher market price.

### 3. Data and Materials

#### 3.1. In Situ Measurements

The *in situ* data sources used within this research (Figure 1) are reported in Table 1 with the recorded parameters and the period they refer to.

**Table 1.** *In situ* data sources.

Type	Name	Property	Parameter	Period
Oceanographic Platform	Acqua Alta	CNR	seawater temperature	2002–2013
Buoy	the Italian Data Buoy Network (RON): Venice	ISPRA	seawater temperature	2010–2012
Buoy	Goro buoy (located southern of the Po Delta)	Province of Ferrara	seawater temperature, salinity and DO at different water depth (1, 3, 6 m)	2009–2011
Buoy	MAMBO buoy (located close to Trieste)	OGS	seawater temperature, DO, turbidity, wind field, wave field	1999–2013
Station	Pontelagoscuro (located 90 km from Po river mouth)	ARPA EMR (Emilia Romagna Regional Agency for Environmental Protection)	freshwater discharge of Po river	2003–2012
Water samplings acquired during oceanographic cruises	EMODnet	Various data sources	chlorophyll-a, DO, pH, salinity, nitrate, nitrite, orthophosphate, temperature, total ammonium, total phosphorus, total alkalinity, total inorganic nitrogen, total nitrogen	1999–2012
Water quality measurements	ARPAV database	ARPAV (Veneto Regional Agency for Environmental Protection)	chlorophyll-a, total suspended matter	2008–2011

#### 3.2. Earth Observation Data

For the assessment of the SST, we selected gap-free SST maps at 1 km horizontal resolution, estimated from different satellite sensors in order to obtain two different datasets (Table 2). Both datasets were validated with *in situ* data measured by Acqua Alta CNR oceanographic platform and ISPRA RON Venice buoy (Figure 1).

The northern Adriatic Sea, a shallow semi-enclosed shelf sea, is optically characterized by turbid “Case 2” waters because of the vertical mixture of coastal and sea waters, the presence of suspended inorganic materials, and biogenic particulate material [42]. The retrieval of water quality parameters from absorption and scattering properties of seawater was achieved using the processing chain described in [42] for Case 2 Ocean Color products, applied to the MERIS sensor full-resolution products. As a proxy to identify the inter- and intra-annual patterns of seawater turbidity, we used estimates of: photosynthetic pigment chlorophyll-a (Chl-a), colored dissolved organic matter (CDOM) and total suspended matter (TSM) concentrations.

The EMODnet database and the ARPAV water quality measurements (Table 1) were used to validate Ocean Color products. As the measurements are not contemporary with the satellite



acquisitions, only qualitative comparisons were performed for Chl-a and TSM products while CDOM was not validated at all, due to the lack of *in situ* data measurements available for this parameter.

**Table 2.** Earth Observation data sources.

Parameter	Spatial Resolution	Source/Sensor	Period	Processing
Temperature	1 km (horizontal resolution)	OceanColor archive: daily Level 2 SST from MODIS	2000–2011	corrected for the bowtie effect and quality flags were used to remove all bad pixels. Finally binning process allowed to reproject and resample Level 2 pixels to a fixed Level 3 grid at 1 km resolution.
	1 km (horizontal resolution)	Copernicus Marine Environment Monitoring Service (CMEMS): daily SST products	2012–2014	none
Chlorophyll-a, Colored Dissolved Organic Matter, Total Suspended Matter	300 m	MERIS sensor aboard ENVISAT satellite (from European Space Agency)	2002–2012	Chl-a, CDOM, TSM obtained by applying processing chain described in [42] for Case 2 Ocean Color product

### 3.3. Ocean Modeling Products

The modeled daily current velocity products collected from CMEMS for the period April 2010–March 2012 (e.g., MEDSEA\_REANALYSIS\_PHYS\_006\_004) are modeled using the Mediterranean Forecasting System (physical reanalysis component), which is a hydrodynamic model supplied by the Nucleus for European Modeling of the Ocean (NEMO) [43] that provides the average current for each grid cell at 300 m spatial resolution.

### 3.4. Fish Harvest Modeling Products and the Potential Outcome

Daily maps of SST are the main input for the generation of potential fish harvest (expressed as  $t\ yr^{-1}$ ) for sea bass and sea bream. In the toolbox implementation, the authors used the harvest output from the InVEST FinFish model for aquaculture [44], run in consideration of each grid cell of the area as an aquaculture cage. Results from this model are the productivity performances at different locations with the assumptions that harvest practices, prices, and costs of farm production are constant over the selected periods. The quantitative parameters we used to setup the model are 2,700,000 juveniles, initial fish weight of 20 g, target fish weight of 1200 g, natural daily mortality of 0.000137 for a total of 6 years of simulation according to the parameterization used in the Northern Adriatic site potential outcome scenario described in Section 2.

According to the EC Regulation 1967/2006 [45], the market minimum size for sea bass and sea bream is respectively of 25 cm and 20 cm, which correspond to approximately 350 grams. This market size is generally reached/achieved with modern farming techniques after 2 years from time of hatching.

The use of the parameterization for the harvest aimed at reaching larger sizes/weight than those typical in the market is only due to the existence of a preliminary economic assessment. Nevertheless, in real aquaculture activity, there would be no reason to aim for weight and size targets different from commercial ones, but rather to aim for more value from products from an economic point of view (*i.e.*, recovery of the farm installation costs in a minimum period). Any kind of weight, size or time horizon could be set, and the selection of the FinFish Invest model choice can be substituted with other scenario generators.

## 4. Methods

The following paragraphs present: (i) the role of the actual competing maritime uses; (ii) the parameters relevant for aquaculture in terms of seawater properties and fish vitality and the constraints they generate (*i.e.*, the threshold values); and (iii) the processes governing toolbox functioning.

### 4.1. The Existing Competing Maritime Uses

Whilst planning is often cited as a priority for aquaculture development [46], the identification of sustainable aquaculture sites is a complex spatial problem requiring in-depth knowledge of the marine environment as well as an understanding of numerous social and civil factors [47]. As the aim of the toolbox is supporting farmers and policy makers in the identification of sustainable aquaculture sites, the current, official uses of the maritime space are used to mask the competing spaces in order to reduce potential planning conflicts. Among the most common competing maritime uses of the area, transportation (marine traffic routes), economic activities (platform for drilling extraction and for energy processing), nature protection (Natura2000 sites, Special Protection Areas, Sites of Community Importance, nationally designed protected areas, Important Bird Areas, geosites, *etc.*), infrastructure facilities (submarine cable, pipeline), and restricted areas (dumping sites, military zones, buffer area in the surroundings of platforms and pipelines, main maritime routes), are considered.

### 4.2. Criteria, Requirements and Constraints for the Selected Species

Temperature is the key parameter in selecting sites for aquaculture as it influences both fish biology and the ecology of the marine environment. The fish farming temperature is the temperature that allows the best cost/benefit ratio to obtain the highest fish quality and quantity.

The sea bass vitality temperature in aquaculture farms ranges between 2–3 °C and 30–32 °C. Sea bream has a minimum vitality temperature of 5 °C (lower temperatures cause permanent physiological damages until death) and a maximum of 34 °C. Rapid and significant changes of temperature close to the growth and breeding thermal limits are likely to lead to poor fish welfare [48,49]. According to the vitality temperature ranges of the two species, threshold values selected by the toolbox are: 5 °C (the highest value among the vitality minimum temperature of the two species) and 30 °C (the lowest value among the vitality maximum temperature of the two species).

The two species for aquaculture in the Mediterranean Sea have almost identical temperature vitality ranges and, in line with the scope of aquaculture, they could be reared together, allowing lower farming costs and consequently reduced environmental pressure.

Besides temperature, Table 3 lists other seawater biochemical parameters considered for the assessment and the related ranges for fish vitality conditions. These parameters depend on site-specific conditions and can be altered by the mass reared in cages, type of food and metabolic degradation products. For example, pH values can determine a poor welfare condition for both sea bass and sea bream, and this risk increases at pH values below 6.5 and above 8.5 [48,49].

**Table 3.** Seawater parameter ranges for vitality of the two selected fish species.

Parameters	Min	Max	Reference
NH <sub>4</sub> -N (μmol·L <sup>-1</sup> ) Ammonium	0	5	Directive 2014/101/EU [50]
NT (μmol·L <sup>-1</sup> ) Total Nitrogen	0	100	Directive 2014/101/EU [50]
PT (μmol·L <sup>-1</sup> ) Total Phosphorous	0	2.5	Directive 2014/101/EU [50]
pH	6.5	8.5	Panel EFSA, 2008 [48,49]
Dissolved Oxygen (mL·L <sup>-1</sup> )	3	–	Mallya, 2007 [51]
Salinity (PSU)	0–5	40–50 <sup>1</sup> (*)	Jensen <i>et al.</i> , 1998 [52]

\* Up to 50 *Dicentrarchus labrax*; (32–40) *Sparus aurata*; 30 Spawning *Sparus aurata*. <sup>1</sup> Panel EFSA, 2008 [48,49].

It is necessary to consider that water density is a function of pressure, salinity and temperature, and it fluctuates especially between 0 and 4 °C. Although euryhaline species are able to tolerate wide salinity ranges, they are sensitive to rapid changes of this parameter, which may occur near freshwater discharges and/or during cold season. We took into account that oxygen depends in different ways on the following rules:

- when the temperature rises, the solubility of oxygen decreases;
- when the salinity increases, the solubility of oxygen decreases;
- when tidal currents and wave motion increase, the solubility of oxygen increases;
- when the presence of aquatic plants varies, the solubility of oxygen varies.

In a marine environment, changes in water temperature may generally imply variations of dissolved oxygen (DO) as one of the most important parameters for welfare conditions in fish aquaculture [51,53]. DO represents a limiting factor because when DO concentration decreases, respiration and feeding activities also decrease and fish are not able to assimilate the food consumed.

Moreover, also phytoplankton cycle and oxidative decomposition of organic matter are related to DO variations.

As the physiological stress for sea bass occurs for DO concentrations lower than 3 mL·L<sup>-1</sup> [51], we assume this value as threshold for anoxia conditions. In fact, for sea bass, good levels of DO are above 5 mL·L<sup>-1</sup>, while its activity is totally inhibited below 2 mL·L<sup>-1</sup> and results in death [53].

Furthermore, seawaters characterized by high turbidity level are a limiting factor for aquaculture farms. Turbid waters are thus identified by applying threshold concentrations (Table 4) to average values of Chl-a, colored dissolved organic matter (CDOM) and total suspended matter (TSM).

**Table 4.** Thresholds to define high turbid waters.

Parameter	Threshold Value	Reference
Chl-a	2.0 mg·m <sup>-3</sup>	Hopkins <i>et al.</i> , 2013 [54]
TSM	3.0 g·m <sup>-3</sup>	Petus <i>et al.</i> , 2014 [55]
CDOM	0.6·m <sup>-1</sup>	Authors' estimation *

\* CDOM threshold concentration was statistically estimated by correlation analysis on the basis of TSM and Chl-a concentrations.

Current velocity is another parameter considered in the feasibility scenario (Table 4) as it represents a constraint for an aquaculture plant: the presence of minimum water turnover conditions is fundamental to maintain clean waters in the aquaculture cages. Rate of organic waste accumulation and its resuspension is a direct function of current speed: low current speed causes waste accumulation, mostly if the aquaculture fish farm is at low bathymetries, on the contrary, high current speed lowers local organic enrichment [56]. Furthermore, high current speed increases the oxygen supply that facilitates the aerobic decomposition of organic matter [57]. The minimum current speed threshold value we selected is 0.02 m·s<sup>-1</sup> [58].

#### 4.3. Toolbox

The toolbox generates the feasibility scenario to identify the feasible and unviable locations for aquaculture (Figure 2) and, by adding a species-specific harvest model, it provides the suitability scenario in terms of potential fish mass production for each location (Figure 3).

The decision process and the rules for the feasibility scenario are summarized in Figure 2 and Table 5, while the suitability scenario process is shown in Figure 3. The harvest model settings are reported in Table 6.

First, the toolbox verifies the existence of maritime space available for aquaculture by excluding the existing maritime uses. This analysis generates a mask that does not influence and is not influenced by any kind of valuation on potential competing uses.

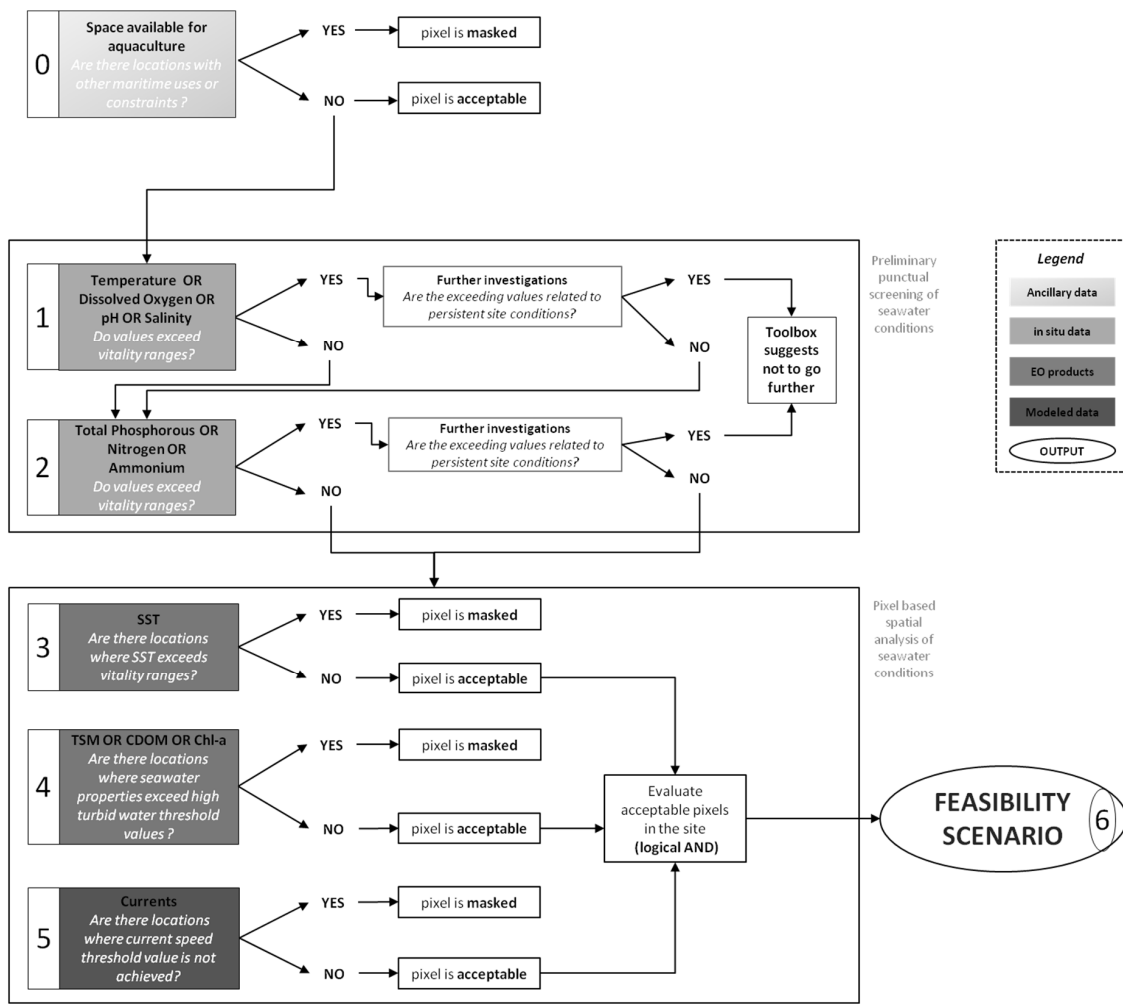


Figure 2. Toolbox feasibility scenario decision process.

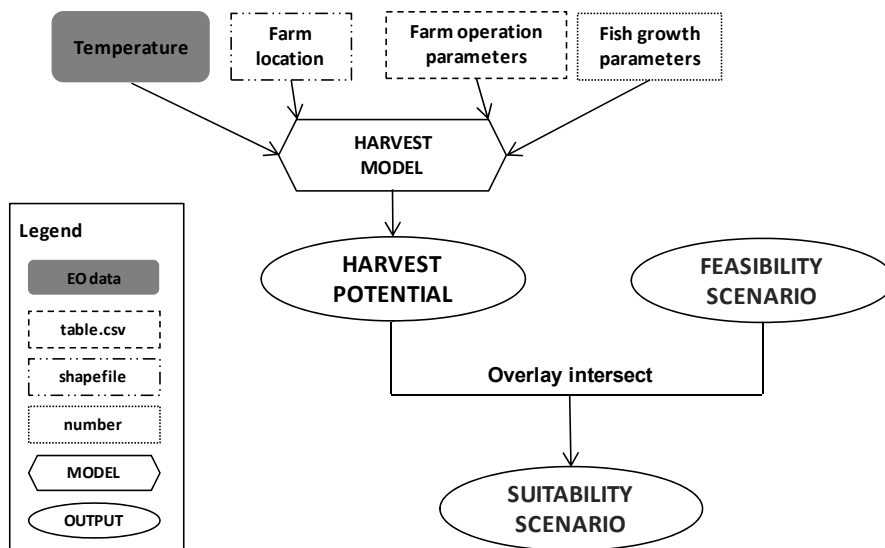


Figure 3. Toolbox suitability scenario process.

**Table 5.** Summary of feasibility scenario decision rules.

Step	Parameters	Input	Decision Question	RULE	Further Investigation
0	Space available for aquaculture	Current maritime uses	<i>Are there locations where competing maritime uses are present?</i>	IF competing maritime uses are present THEN the pixel IS masked, otherwise IS acceptable → go to STEP 1	—
1	Temperature OR Dissolved Oxygen OR pH OR Salinity	T: buoy hourly measurements; DO, Salinity and pH: buoys hourly measurements and cruise single measurements	<i>Do values of any of these parameters exceed vitality ranges?</i>	IF the exceeding values are present THEN further investigations are needed, otherwise parameters ARE acceptable → go to STEP 2	If the further investigation shows that exceeding values are not relevant (e.g., related to an episodic climatic event) → go to STEP 2 Otherwise → STOP
2	Total Phosphorous OR Nitrogen OR Ammonium	Cruise single measurements	<i>Do values of any of these parameters exceed vitality ranges?</i>	IF the exceeding values are present THEN further investigations are needed, otherwise parameters ARE acceptable → go to STEP 3	If the further investigation shows that exceeding values are not relevant (e.g., related to an episodic event) → go to STEP 3 Otherwise → STOP
3	Sea Surface Temperature	Daily observations from satellite radiometer	<i>Are there locations where SST exceeds vitality ranges?</i>	IF exceeding values are present THEN the pixel IS masked, otherwise IS acceptable → go to STEP 4	—
4	Total Suspended Matter OR Colored Dissolved Organic Matter OR Chlorophyll-a	Daily observations from satellite multispectral images	<i>Are there locations where seawater properties exceed high turbid water threshold value?</i>	IF frequency of exceeding values occurrence is higher than 40% THEN the pixel IS masked (turbid water), otherwise IS acceptable → go to STEP 5	—
5	Currents	Daily average products from numerical model	<i>Are there locations where current speed threshold value is not achieved?</i>	IF the minimum speed (average of daily products) IS NOT reached THEN the pixel IS masked, otherwise IS acceptable → go to STEP 6	—
6	<b>Generation of Aquaculture Feasibility Scenario</b> Feasibility scenario is obtained by overlaying (logical AND): pixels in which SST does not exceed threshold values (STEP 3) pixels not characterized by high turbid water conditions (STEP 4) pixels in which average current velocities are higher than the minimum threshold value (STEP 5)				



**Table 6.** Harvest model settings.

Required Information	Model	Parameters	Standard Input	Customization
Potential Harvest	Harvest Model	Temperature at farm	Time series of daily water temperature (°C) for each farm	Earth Observation-derived data
		Farm location	A user-defined vector polygon or point dataset, with a latitude and longitude value and a numerical identifier for each farm	Latitude and longitude value of all the pixels (grid cell)
		Fish growth parameters	Weight is a function of growth rate and temperature (Stigebrandt 1999) [59]	Function of growth adapted for seabass and seabream
		Farm operation parameters	User defined: Weight of fish when they are outplanted, Target weight of fish at harvest, Number of fish in farm, Length of fallowing period	Weight of fish when they are outplanted (20 g), Target weight of fish at harvest (1200 g), Number of fish in farm (2,700,000 juveniles), Length of fallowing period (6 years)

The approach of the toolbox for the feasibility scenario (Figure 2 and Table 5) considers the available *in situ* measurements (from buoys and cruise campaigns) because they can provide continuous measurements at high temporal resolution (e.g., hourly/daily).

The occurrence and the frequency of exceeding values for T, DO, pH, salinity and nutrients suggest further investigation of the relevance of these cases. When no technical solutions are available to overcome the critical conditions determined by these cases, or they are not due to episodic conditions, the toolbox suggests not proceeding with the analysis. If the result of this preliminary assessment—based on direct continuous *in situ* measurements in point locations—is positive (*i.e.*, no exceeding values or no relevant exceeding values), the toolbox goes ahead performing pixel-based spatial analysis on EO and model data.

The next steps follow a spatial-based approach operating in parallel, which means that the result of the previous does not influence the opportunity to pass through the following step.

Step 3 analyzes the SST, as daily observation from satellite radiometer, in order to verify if the temperature is within the vitality values (5–30 °C) over the entire basin.

Step 4 aims to detect high turbid water conditions on the basis of TSM, CDOM, Chl-a in order to exclude them from the final scenario. EO, indeed, enables turbidity condition detection, due to, for example, riverine freshwater inputs showing high concentrations of suspended sediments, colored dissolved organic matter and Chl-a.

Step 5 is the current speed evaluation in order to check that minimum speed is achieved: pixels not achieving the minimum value of  $0.02 \text{ m} \cdot \text{s}^{-1}$  are masked.

The toolbox's first output is the feasibility scenario, which is the result of a spatial combination (overlay logical AND) of the acceptable pixels of steps 3, 4 and 5 (Figure 2) *i.e.*, pixels in which temperature, turbidity and current thresholds are not exceeded.

In order to generate the suitability scenario (Figure 3), the toolbox produces a spatialized fish harvest potential by using as model inputs the daily water temperatures and fish growth parameters (Table 6). After producing the harvest potential map, the toolbox combines it with the feasibility scenario, according to Figure 2 and Table 5, by performing a simple overlay intersect: the output is the suitability scenario which shows the harvest potential of sites feasible for aquaculture.

## 5. Results

### 5.1. Maritime Space Potentially Available for Aquaculture

The space best suited for fish aquaculture is chiefly located at a certain distance from the coast. As expected, this nearshore portion of the basin is extensively occupied by a multitude of human activities (Figure 4) that ultimately render the area restricted to aquaculture use.

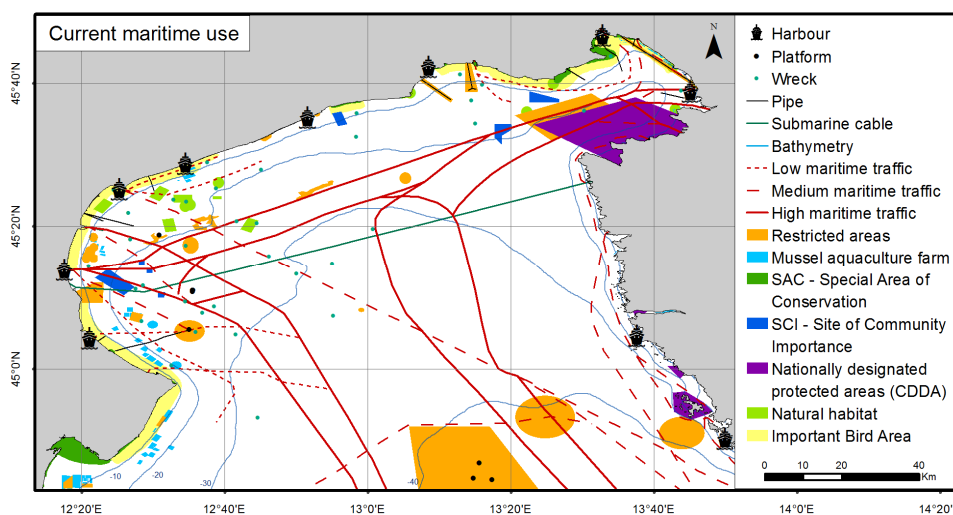


Figure 4. Current Maritime uses.

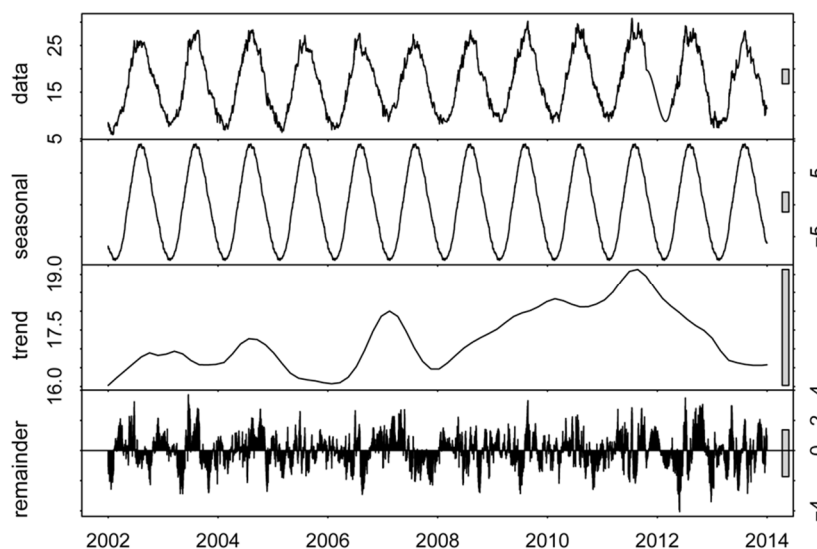
## 5.2. Feasibility Scenario

Toolbox step 1 (Figure 2), shows that seawater temperature values range from a minimum of 3.98 °C to a maximum of 33.62 °C in the considered periods and, as shown in Table 7, there are five exceeding values: four nearshore (*i.e.*, Goro buoy which is the closest to the southern Po delta as shown in Figure 1) at different depths and one at the offshore buoy.

**Table 7.** Exceeding values of temperature measured *in situ* (NS = Nearshore; OS = Off Shore).

Station	Location	Extreme Values Recorded	Limits	Exceeding
Boa Mambo	NS	6.25	<5 °C	NO
Boa Mambo	NS	28.78	>30 °C	NO
Boa Goro –1 m	NS	3.38	<5 °C	YES
Boa Goro –1 m	NS	33.62	>30 °C	YES
Boa Goro –3 m	NS	3.98	<5 °C	YES
Boa Goro –3 m	NS	30.50	>30 °C	YES
Boa Goro –6 m	NS	5.91	<5 °C	NO
Boa Goro –6 m	NS	28.46	>30 °C	NO
Acqua Alta Platform	OS	5.80	<5 °C	NO
Acqua Alta Platform	OS	32.00	>30 °C	YES

Considering the CNR Acqua Alta Platform (OS) records, there is a general trend of increasing temperature values with peaks recorded in the summers of 2009 and 2011, and an increased velocity of this trend between 2008 and 2012 (Figure 5).

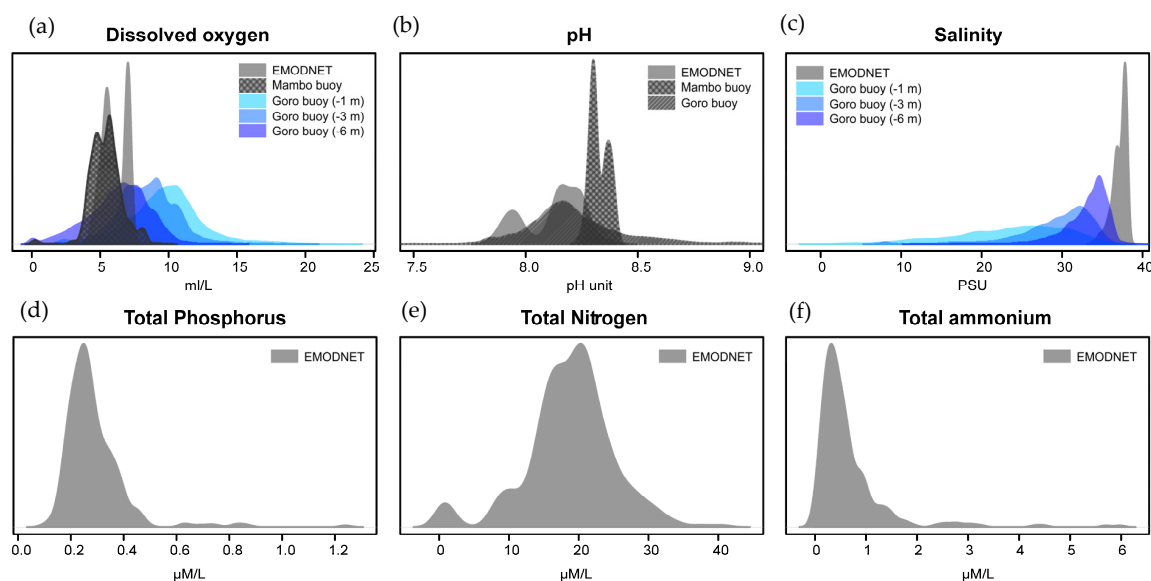


**Figure 5.** Signal analysis of sea surface temperature (°C) acquired at Acqua Alta Platform in the period 2002–2013. The figure summarizes the time series of temperature data, the seasonal and inter-annual trend and the residuals' ranges (remainder).

Temperature, despite the presence of exceeding values, is not a limiting factor to exclude *a priori* nearshore or offshore areas as infeasible.

As seawater is a saline solution, it is a buffered solution and pH variations occur gradually, thus not representing a limiting factor for sea bass and sea bream. The pH *in situ* measurements indeed do not have significant changes nearshore and offshore (Figure 6). Recorded pH values range between 7.8 and 8.5 and thus within the vitality range as described in Table 3.

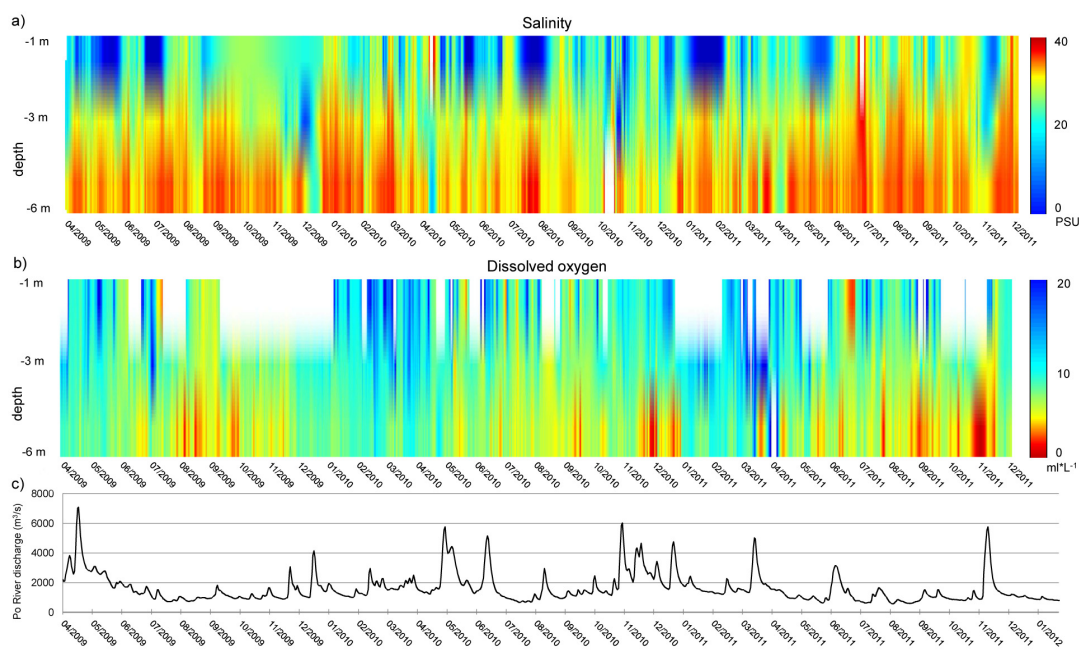
At the Goro buoy, pH and salinity concentration reduction show a higher variability moving from the deeper to surficial portion of the water column (Figure 6a,c).



**Figure 6.** Frequency distribution of *in situ* measurements of: (a) Dissolved oxygen; (b) pH; (c) Salinity; (d) Total phosphorous; (e) Total nitrogen; (f) Total ammonium.

On the basis of the concentration values recorded nearshore and offshore, the salinity fish vitality thresholds, as defined in Table 3, are not exceeded.

DO values lower than  $3 \text{ mL} \cdot \text{L}^{-1}$  are recorded by Goro buoy for short periods and are not recorded at all the three measurement depths (Figures 6a and 7b): DO measured at  $-1 \text{ m}$  is subject to fluctuation throughout the year and the presence of alert anoxia is evident only in some years, such as the summer of 2011.

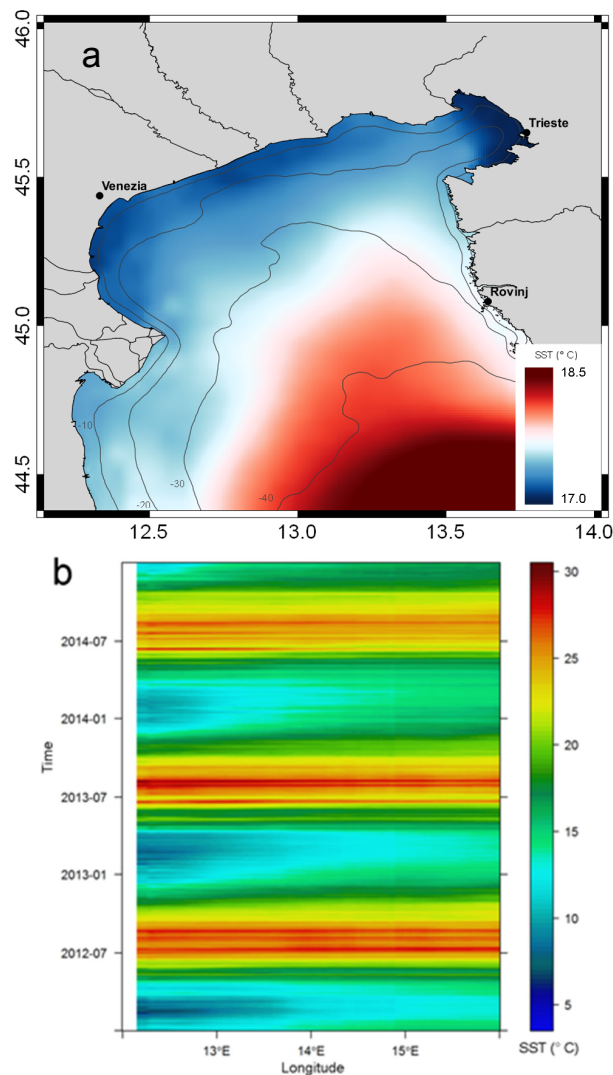


**Figure 7.** (a) Salinity acquired at Goro buoy at different depths during the period 2009–2012; (b) Dissolved oxygen acquired at Goro buoy at different depths during the period 2009–2012; (c) Po River discharge recorded at Pontelagoscuro station during the period 2009–2012.

Total phosphorus, total nitrogen and total ammonium values (see step 2 in Figure 2, Figure 6d,e,f) are lower than maximum threshold values which are, respectively,  $2.5 \mu\text{mol} \cdot \text{L}^{-1}$ ,  $100 \mu\text{mol} \cdot \text{L}^{-1}$ , and  $5 \mu\text{mol} \cdot \text{L}^{-1}$ .

These preliminary point screenings (step 1 and step 2 in Figure 2), despite in some cases highlighting exceeding values, cannot be considered as limiting factors that would halt the assessment process.

Result of SST analysis (step 3 in Figures 2 and 8) shows that no exceeding value is present over the entire basin (if locations with exceeding values had been found, then they would have been masked in order to be subtracted in the feasibility scenario).



**Figure 8.** (a) Example of mean annual SST, solid isolines are the bathymetric contour lines; (b) Hovmoller plot of SST (2012–2014) temporal profile in longitude dimension (averaged).

The result of the multitemporal analysis of EO Ocean Color products (step 4 in Figure 2) show that values related to high turbid conditions could be found for each considered parameter *i.e.*, Chl-*a*, CDOM and TSM. The area with higher Chl-*a* decadal average concentration corresponds to the shallower and nearshore portion, especially that close to the Po delta, thereby revealing Chl-*a* values exceeding  $5 \text{ mg} \cdot \text{m}^{-3}$  on average, *i.e.* more than double the threshold value, which is  $2.0 \text{ mg} \cdot \text{m}^{-3}$ . The monthly average of Chl-*a* concentrations for the period 2002–2012 confirms the dual character of the northern Adriatic Sea: a eutrophic nearshore and oligotrophic offshore (Figure 9).

Figure 10 illustrates the coastal turbid water limit, which defined the area to be considered as not viable for aquaculture. The high turbid area between the shoreline and this limit resulted in a higher level of nutrients and suspended matters, which affects primary production and consequentially does not provide favorable conditions for fish growth.



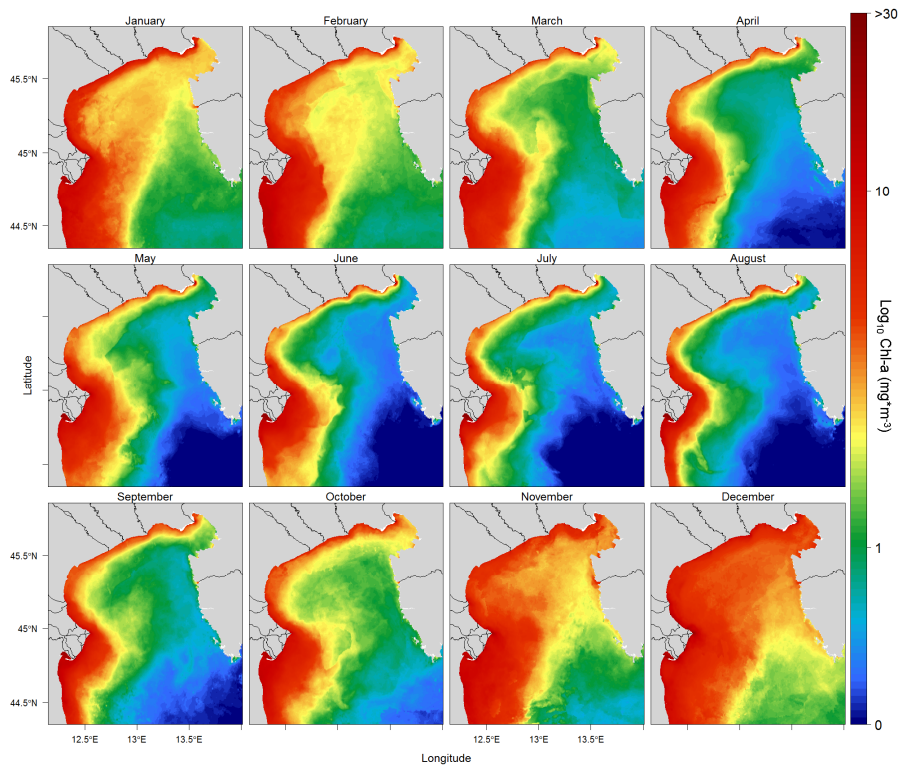


Figure 9. 2002–2012 monthly averages of log10 Chl-a concentration.

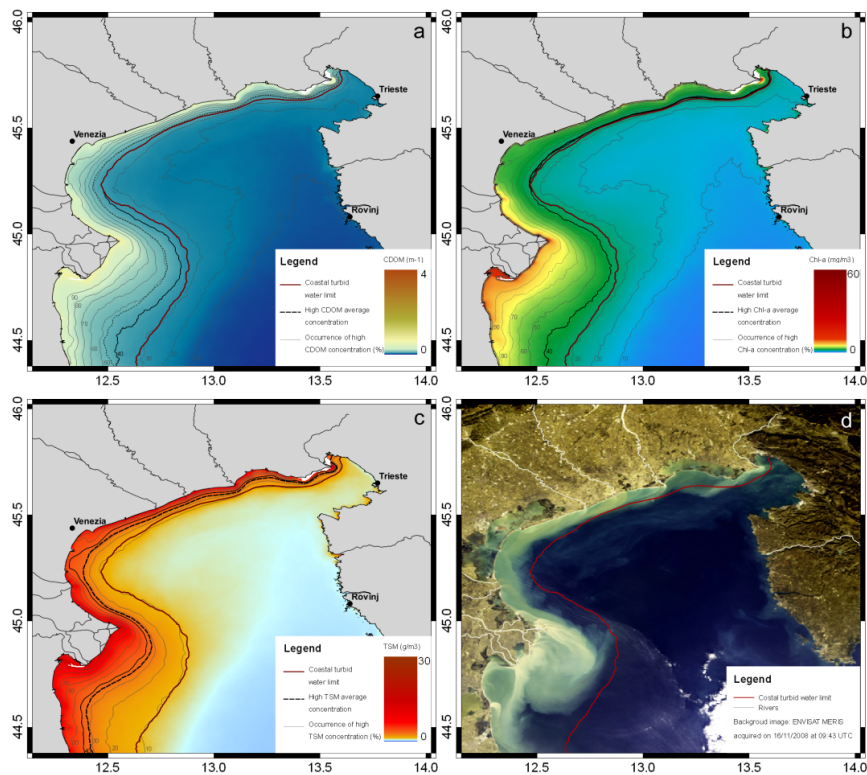
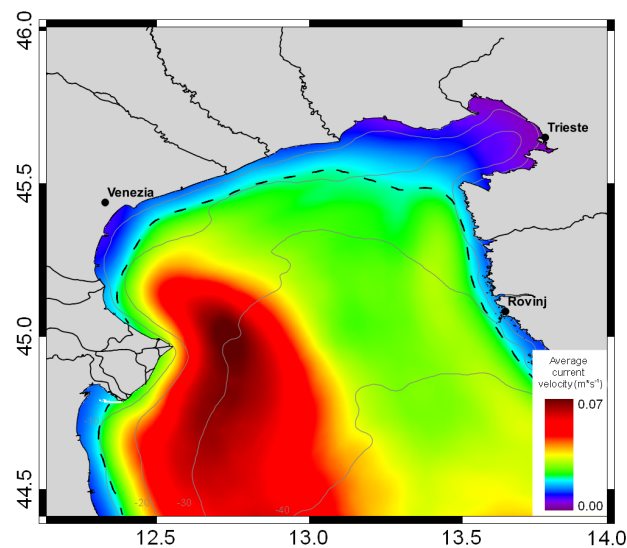


Figure 10. Maps derived from the multitemporal analysis of EO products for the definition of limits in the feasibility detection; (a) Decadal average CDOM map; (b) Decadal average Chl-a map; (c) Decadal average TSM map; (d) True color satellite image acquired by ENVIAT MERIS sensor on 16 November 2006 at 09:43 UTC.

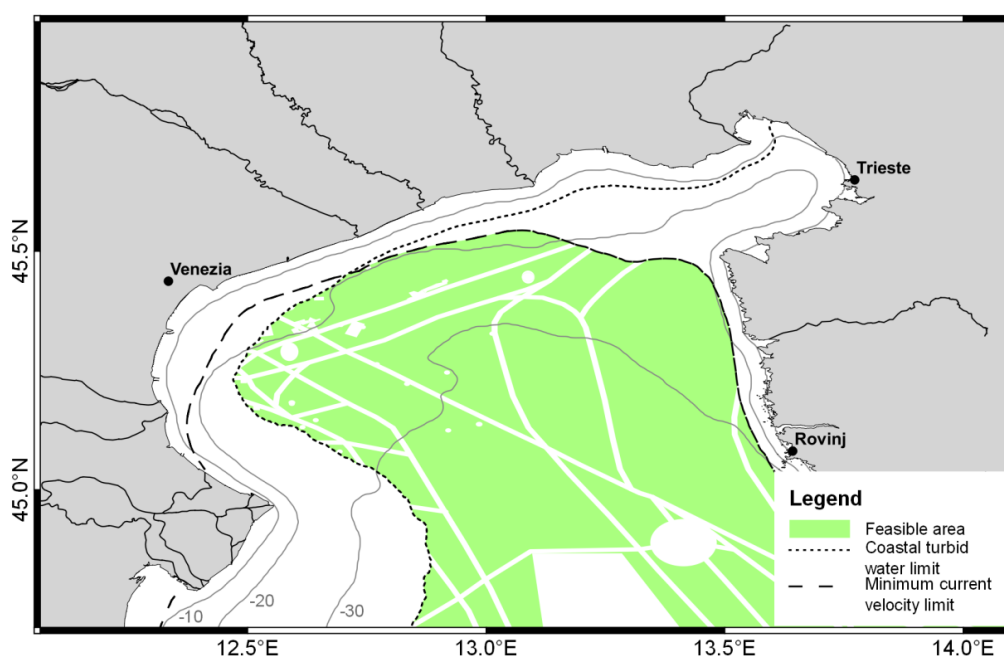
Decadal average concentrations of CDOM (Figure 10a) have spatial patterns similar to those of Chl-a (Figure 10b), while TSM shows higher concentrations mostly located in nearshore areas and in the offshore southeastern portion of the Po delta (Figure 10c).

Regarding current speed, average velocity ranges between 0 and  $0.07 \text{ m} \cdot \text{s}^{-1}$  (Figure 11); alongshore currents report velocities lower than  $0.02 \text{ m} \cdot \text{s}^{-1}$  while higher velocities are located offshore of the Po River delta in accordance with the Western Adriatic Coastal Current (WAC) driven by wind and thermohaline forcing.



**Figure 11.** Average current speed map for the period April 2010–March 2012, dashed line represents the  $0.02 \text{ m} \cdot \text{s}^{-1}$  contour line and solid isolines are the bathymetric contour lines.

As a final result of all these analyses, the toolbox output is a feasibility scenario delimiting the area of the northern Adriatic Sea basin in which—according to the considered parameters related to fish vitality and farm functioning—fish aquaculture is feasible or not feasible (green area and white area in Figure 12).



**Figure 12.** Feasibility scenario for fish aquaculture in northern Adriatic Sea.

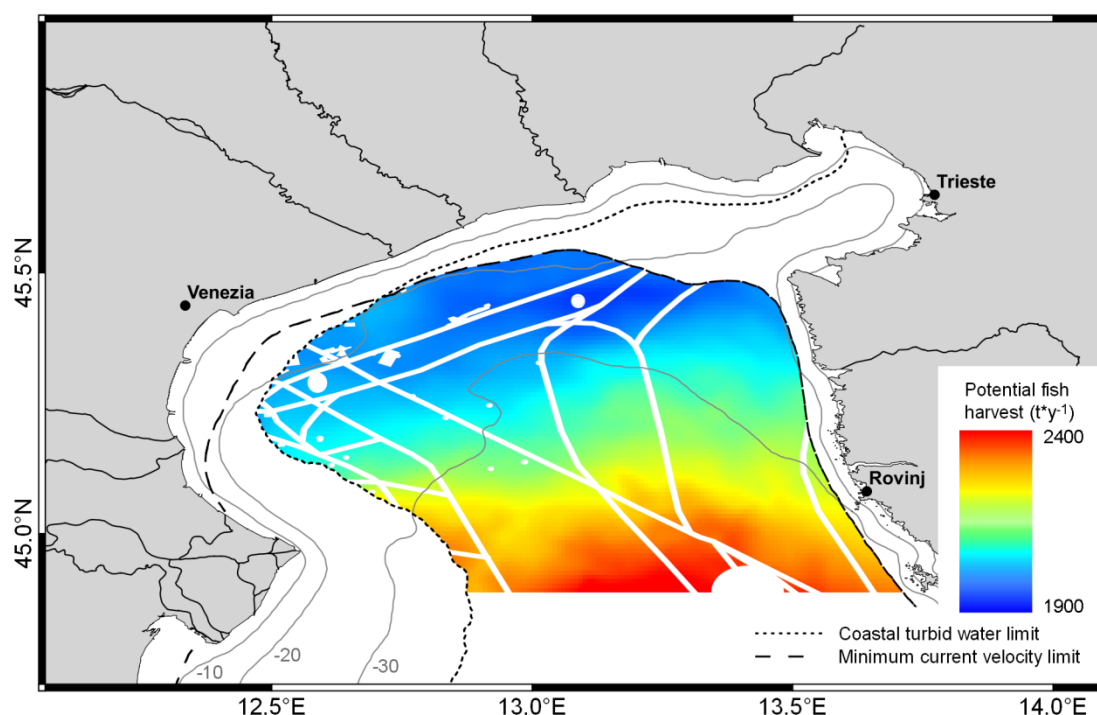
### 5.3. Suitability Scenario

Results from InVEST FinFish model consider that each pixel (grid cell) of the SST product represents a potential fish farm. The harvest simulation ran for a total of 6 years over all the pixels.

Analyzing the SST product—input of the harvest model—the most evident spatial pattern is the latitudinal gradient that increases moving from north to south (Figure 13).

In the harvest model, fish growth is mostly dependent on temperature, *i.e.*, warmer locations will enable fish to reach their target weight faster, while the total biomass of each farm depends on how many cycles of outplanting and harvesting are performed in the farm.

As a consequence, the suitability scenario spatial pattern (Figure 13) shows a decreasing harvest gradient moving from north to south.



**Figure 13.** Suitability scenario: potential fish harvest estimated within the areas identified as feasible for aquaculture (pixel spatial resolution 300 m).

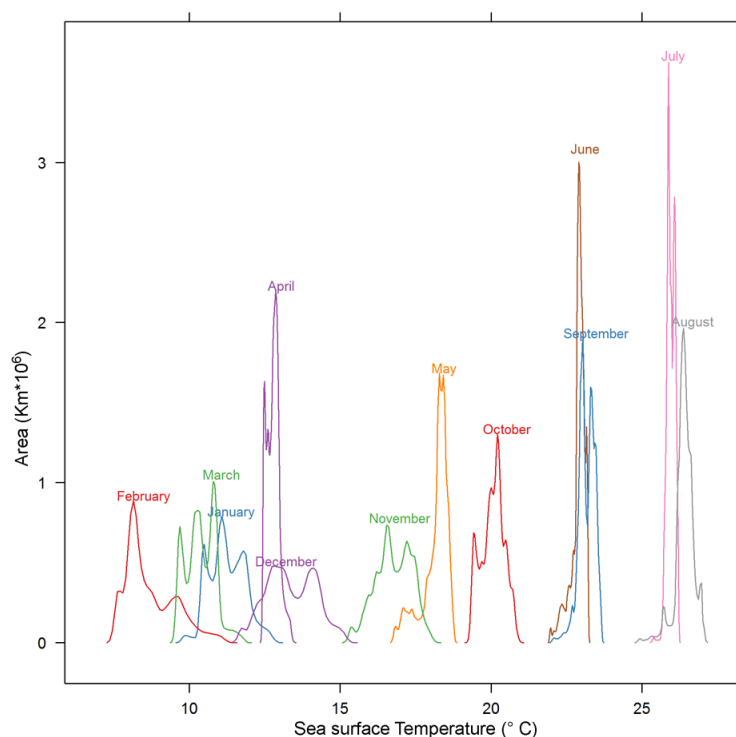
## 6. Discussion

Results suggest that offshore northern Adriatic Sea is a feasible site for fish aquaculture of sea bass and sea bream species, in terms of physical, chemical and biological parameters within the vitality ranges of the two selected fish species. On the other hand, nearshore coastal areas are not feasible for fish aquaculture because of low average current speed, frequent occurrence of high turbid water conditions, and periods of intense river discharge and seafloor sediment resuspension due to the shallower bathymetries. Bora and sirocco wind patterns revealed the intensity of extreme climate events that can significantly affect the variability of seawater temperature as well as the concentration of DO.

According to the toolbox rules (Table 5), as exceeding values were found (Table 7), further investigations were performed and we concluded that these exceeding conditions are related to episodic meteorological events and to riverine discharges.

By further investigations on sea surface temperature's exceeding values, a deeper understanding of critical situation was gained. The 2012 extreme winter conditions, for example, are likely related to

the occurrence of cold winds from northern Europe determining brief low temperature conditions and enhancing seawater heat loss (Figure 14).



**Figure 14.** 2012 monthly average of SST distribution over northern Adriatic Sea.

High variability of pH and salinity concentration moving from the deeper to surficial portion of the water column (Figure 6c) both recorded at Goro buoy can be attributed to the variable freshwater river discharge.

Despite typical DO concentrations in the northern Adriatic Sea being higher than  $3 \text{ mL} \cdot \text{L}^{-1}$ —*i.e.* the minimum threshold value for sea bass stress conditions—DO *in situ* measurements at Goro and Mambo buoys show evidence of critical hypoxic conditions exceeding this value. These phenomena, through temporal analysis on DO data, were recognized as short-lived and relevant only to a few years. For example, exceeding DO values recorded at Mambo buoy during the fall of 2012, according to further investigations, are due to singular extreme physical conditions of wind and waves that generate turbidity, thus not representing the rule but rather the exception.

Moreover, spatial patterns of TSM monthly average concentrations clearly exhibit the evidence of cyclonic gyre circulation, generated by steady Bora winds during winter periods (November to March), and spatial and temporal analysis revealed an increased turbidity nearshore due to sediment resuspension, and the evidence of an offshore suspended sediment transport driven by the altered circulation during intense wind forcing [60].

Considering that minimum current velocity for fish aquaculture is  $0.02 \text{ m} \cdot \text{s}^{-1}$ , average current velocities are feasible for fish farm installation in all the offshore part of the northern Adriatic Sea. The main water circulation (Adriatic basin circulation) of the area excludes the nearshore zones that in the end are also to be excluded considering the bathymetric constraints for cage installation.

In accordance with the results of the feasibility assessment, eligible areas are mostly located at a water depth over 20 m and this is in agreement with the general settings of aquaculture farm practice which usually places the plant at a depth of 25 m [61].

Nevertheless, it is noteworthy that through the analysis of images collected by an underwater webcam installed on the Acqua Alta Platform (2013–2014; 5 m of depth), the selected fish species

(*Dicentrarchus labrax* and *Sparus aurata*) never appear under the scientific platform, whereas other species of the same order do (e.g., *Oblada melanura* and *Diplodus sp.*). Scarce information regarding the vitality ranges of the latter species are available and were not taken into account within the scope of this study, though it is likely that their use in the harvest model would improve the selection of the areas under criteria of economic sustainability. For example, fish farmers could be interested in the aquaculture of these species that, even if in the frame of a global market would not have an important economic value, are nevertheless valuable at the local level.

As might be expected, because the harvest model depends mostly on temperature, harvest gradient is consistent with that showed by SST values. Nevertheless, it has to be mentioned that the Finfish InVEST model for potential fish harvest estimations was originally designed for salmon in the cold waters of the North Pacific [62]. In the northern Adriatic, warmer temperatures may occasionally be a limiting factor for fish growth (depending on species) and this could violate one of the assumptions of the growth model, which is that fish are experiencing temperatures that are on the ascending side of their thermal response curve (*i.e.*, that growth increases with temperature).

Considering the definition of aquaculture sustainability as a multidimensional concept that takes into account environmental, economic and social aspects [63], this study deals with environmental issues mostly related to fish growth.

Can we therefore consider our toolbox feasibility and suitability scenarios sustainable? From a fish point of view, the scenarios head in the right direction. However, when the sustainability definition includes environmental issues like pressures and impacts, or includes social and economic frameworks, our toolbox is lacking. For the environmental issues, it provides an initial state of seawater properties, against which the impacts can be eventually measured (not prevented) by monitoring activities. In this sense, satellite-derived information can support aquaculture farmers and policy makers by issuing warnings on potential water quality threats (e.g., pollution and harmful algal blooms) and monitoring the environmental impact of sea farms.

For the social and economic issues, we based the harvesting scenario on the commercial model for economic assessment (Section 3) and the final output from the model suggested a long-term economic outcome (20 years) based on the production of oversized (>600 g) fish. These settings do not affect the functioning of the toolbox nor the value of the potential aquaculture site suitability scenario. In fact, the result, if better integrated in the decision process of the toolbox, would cover sustainability in terms of economic interest of fish farmers, though it could not represent sustainability in terms of consumer interests or the point of view of the public authorities.

Therefore, the toolbox scenarios, accounting for fish vitality that depends on seawater properties, can be considered a pre-assessment towards the comprehensive evaluation of sustainable aquaculture planning, which requires additional analysis of social, economic and farm operational aspects.

Amongst other regions in the world, there has been a significant expansion of aquaculture in Mediterranean countries because of the encouraging EU policy measures and the socioeconomic benefits deriving from the growth of fish stocks and exploitation of the food provision ecosystem service [64]. Hence, a deeper knowledge on assessment useful for existing and to-be-planned aquaculture planting will be of key relevance. With regard to operation services based on EO data, namely Copernicus services, the toolbox could be considered as a prodrome of an additional CMEMS core service or a downstreaming one.

The ongoing development of the toolbox is oriented in the direction of supporting a coordinated spatial planning for overcoming the hindering effect of the lack of space.

## 7. Conclusions

The proposed toolbox develops an assessment of the northern Adriatic Sea basin for aquaculture in terms of species vitality range identification, physical, chemical and biological seawater properties, and in terms of potential fish harvest production.



The synergic use of fish vitality parameters and the satellite observations can assure the assessment and monitoring of conditions for fish vitality and aquaculture suitability.

In accordance with this assumption, the toolbox integrates different data sources as well as different products (from *in situ*, EO and numerical modeling) fostering the generation of added value products and consequently potential operational services for the aquaculture sector and contributing to the cross-border maritime spatial planning implementation.

The strength of the use of remote sensing is its cost effectiveness and synoptic capacity to provide information at a suitable spatial and temporal resolution for sustainable aquaculture planning even if the *in situ* measurements network is not ready to fully satisfy EO product validation and calibration.

The effective and sustainable management of an aquaculture site is a demanding activity that requires continuous monitoring of local conditions, allowing the early detection of potential hazards to the fish stocks and ensuring that production practices do not degrade the ecosystems or endanger public health. However, monitoring an extensive marine area is a logistical and economic challenge.

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**Conflicts of Interest:** The authors declare no conflict of interest.

## Acronyms

CDOM	Colored Dissolved Organic Matter
CFP	Common Fisheries Policy
Chl-a	Chlorophyll-a
CMEMS	Copernicus Marine Environment Monitoring Service
CNR	Consiglio Nazionale delle Ricerche (Italian National Research Council)
DO	Dissolved Oxygen
EMODnet	European Marine Observation and Data Network
ENVISAT	ENVironmentalSATellite
EO	Earth Observation
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
GVA	Gross Value Added
ISPRA	Istituto Superiore per la Protezione e la Ricerca Ambientale (Institute for Environmental Protection and Research)
ME	Mean Error
MERIS	MEDium Resolution Imaging Spectrometer
MODIS	Moderate Resolution Imaging Spectroradiometer
MSP	Maritime Spatial Planning
R <sup>2</sup>	Coefficient of determination
RMSE	Root Mean Square Error
RON	Rete Ondametrica Nazionale (Italian Data Buoy Network)
Rrs	Remote Sensing Reflectance
SST	Sea Surface Temperature
TSM	Total Suspended Matter
WAC	Western Adriatic Current

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