Diogo Filipe Prata Gomes

Licenciado em Ciências de Engenharia do Ambiente

GIS-based site selection and dynamic modelling of *Magallana* oyster in the Sado Estuary, Portugal

Dissertação para obtenção do Grau de Mestre em Engenharia do Ambiente

Orientador: João Pedro Salgueiro Gomes Ferreira, Professor Associado com Agregação, Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa

FACULDADE DE CIÊNCIAS E TECNOLOGIA
UNIVERSIDADE NOVA DE LISBOA

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Abstract

A case study was developed to assess the viability of Portuguese oyster (*Magallana angulata*) and Pacific oyster (*Magallana gigas*) aquaculture in the Sado Estuary, Portugal. It applies an integrative methodology for site selection of shellfish aquaculture, complemented with a farm-scale carrying capacity model to evaluate production, environmental effects and socio-economic outputs.

The site selection methodology uses a Multi Criteria-Evaluation (MCE) through Geographic Information Systems (GIS) software. When combined, both tools generate a holistic overview of aquaculture opportunities to support strategic planning decisions. The used MCE in this study, considers suitability factors based on water quality and food sources, as well as subsequent factors describing socio-economic and product quality suitability. Combining these to the regulatory and spatial constraints in the study area, a final site selection map was generated, screening out suitable areas for aquaculture. The dynamic model, FARM – Farm Aquaculture Resource Management, was later applied to the identified suitable areas for aquaculture practice, where the production and environmental effects of two different locations were estimated and compared at a farm-scale level.

This methodology illustrates how GIS-based models may be used in conjunction with farm-scale carrying capacity models to assist decision-makers in developing a sustainable approach to aquaculture.

Keywords: Aquaculture; Geographic Information Systems; Multi-Criteria Evaluation; Site selection; Pacific oyster; Portuguese oyster; Dynamic modelling

Resumo

Um caso de estudo foi desenvolvido para avaliar a viabilidade da aquacultura de Ostra Portuguesa (*Magallana angulata*) e Ostra do Pacífico (*Magallana gigas*) no Estuário do Sado, Portugal. Este aplica uma metodologia integrativa para a selecção dos melhores locais para a sua práctica, complementada com a aplicação de um software de modelação dinâmica, com o intuito de avaliar a produção, impactos ambientais e viabilidade económica.

A metodologia para a selecção de locais utiliza uma Análise Multi-Critério através de um software de Sistema de Informação Geográficos (SIG). Quando combinadas, ambas as ferramentas geram uma visão holística das oportunidades existentes face à aquacultura, que serve de auxílio aos decisores na formulação de estratégias de planeamento. A Análise Multi-Critério aplicada neste estudo considera factores de aptidão baseados na qualidade da água e fontes de alimento, bem como factores complementares que descrevem aptidão sócio-económica e qualidade do produto. Combinando estes factores com os limites espaciais existentes, um mapa final para a selecção de locais foi produzido, demonstrando quais as áreas mais adequadas para a aquacultura. O modelo dinâmico, FARM – Farm Aquaculture Resource Management, foi posteriormente aplicado às áreas identificadas como favoráveis, onde a produção e os efeitos ambientais de dois locais diferentes foram estimados e comparados à escala local.

Esta metodologia ilustra como modelos baseados em SIG podem ser integrados com modelos de capacidade de carga à escala local, para assistir os decisores a formularem uma abordagem sustentável para a aquacultura.

Palavras-chave: Aquacultura; Sistema de Informação Geográficos; Análise Multi-Critério; Selecção de locais; Ostra do Pacífico; Ostra Portuguesa; Modelação dinâmica

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Acronyms list

AHP	Analytical Hierarchy Process
APA	Agência Portuguesa do Ambiente
ArcGIS	ArcMap Geographic Information Systems
B2K	BarcaWin2000
CI	Consistency Index
CLC	Corine Land Cover
COS	Carta de Ocupação de Solos
DGRM	Direcção-Geral de Recursos Naturais, Segurança e Serviços Marítimos
DIN	Dissolved Inorganic Nitrogen
DO	Dissolved Oxygen
EAA	Environmental American Agency
EC	European Commission
EPA	Environmental Protection Agency
ERL	Effects Range Low
ERM	Effects Range Median
EU	European Union
FAO	Food and Agriculture Organization
FARM	Farm Aquaculture Resource Management model
GIS	Geographical Information System
ICNF	Instituto da Conservação da Natureza e Florestas
IDW	Inverse Distance Weighted
INE	Instituto Nacional de Estatística
MCE	Multi-Criteria Evaluation
NOAA	National Oceanic and Atmospheric Administration
PEL	Probable Effect Level
POC	Particulate Organic Carbon
POM	Particulate Organic Matter
PORNES	Plano de Ordenamento da Reserva Natural do Estuário do Sado
psu	Practical Salinity Units
TEL	Threshold Effect Level
TPA	Total Protected Areas
tPAH	Total Polycyclic Aromatic Hydrocarbon

TPM Total Particulate Matter

SNIRH Sistema Nacional de Informação sobre os Recursos Hídricos

SQG Sediment Quality Guidelines

t tonnes

WFD Water Framework Directive

WTP Waste Treatment Plant

WWTP Waste Water Treatment Plant

1. Introduction

During the 1960s, oyster aquaculture in the Sado Estuary (Portugal) played an important role in Setúbal's local communities and the national economy. However, in the first part of the 1970s, production decreased sharply due to species overexploitation and water pollution caused by industrial discharges on the estuary. Other factors like absence of fish nurseries, deficient management of the oysters' beds, use of antifouling paints in the shipyards and appearance of diseases, also contributed to the disappearance of the Portuguese oyster (*Magallana angulata*) populations. The effects of these factors almost led to the extinction of the native species in this region. On the other hand, Pacific oyster (*Magallana gigas*) populations thrived and, over the years, became the most exported oyster in Portugal. Portuguese oyster production fell to numbers without economic influence and the small number of surviving individuals presented clear signs of weakness and malformations in their shells. This demanded the producers to focus on the production of Pacific oyster, in order to maintain the sector profitable and sustainable.

Nowadays, the pollution situation in the estuary seems to be turning, as some studies (e.g. Portela, 2016) addressed the improvement of water quality and the re-population of the *M. angulata* species in the natural beds. A future goal could be resuming the past productivity numbers and the rehabilitation of *M. angulata* in the estuary oyster beds since pure populations are important to maintain the balance of the ecosystem and preserve biodiversity. Though, the Portuguese cupped oyster is very close related to the Pacific species and their taxonomic status has been subject of discussion over the last decades. At present, such in Ria Formosa (Ferreira et al., 2012), natural recruitment contains both Pacific and Portuguese oysters, as well as hybrids of the two species, which makes the certification of the Portuguese species unfeasible.

This way, in order to give an overview of possible implementation and management of aquaculture activities in the Sado estuary, was developed a site selection procedure to identify suitable areas for Pacific and Portuguese oyster aquaculture practice, followed by a dynamic model to study environmental and economic outputs of the identified farms.

1.1 Thesis key objectives and expected outcomes

The development of an aquaculture site selection methodology and application of dynamic farm-scale model relies on the following main objectives:

- Identification of key factors for the development of shellfish aquaculture in the Sado Estuary, as well as existing spatial and legal constraints;
- Evaluation of shellfish aquaculture suitability, according to the GIS-based site selection;
- Quantification of the potential environmental and economic impacts that oyster production may have in a small area (farm-scale);
- Provide management recommendations to assist the decision-making process and reduce socio-economic and environmental problems associated with aquaculture expansion;

By the end of this thesis, the following questions should be answered in order to assess the viability of the shellfish aquaculture implementation in the study area:

- What are the major spatial constraints to shellfish aquaculture in the Sado Estuary?
- Which areas gather the best conditions for shellfish growth?
- Which areas have better accessibility? On which areas shellfish production is most facilitated?
- Which are the most contaminated areas in the study area that can reduce product's quality?

1.2 Thesis layout

This thesis is divided into 5 main Chapters. The first one consists in the problem definition and tries to answer the question "Why should this thesis matter and why was it done?". It also describes the thesis main objectives and the layout.

Chapter 2 corresponds to the "State of the Art", which encompasses the theoretical rationale for aquaculture's importance in the World, Europe and Portugal, focusing on the main aspects of both oysters in study, as well as, seed gathering, culture practices and introduction of diseases and alien species. This chapter also reports the importance of an appropriate site selection regarding aquaculture feasibility, licensing and deployment, using a GIS-based Multi-Criteria Evaluation.

Chapter 3 describes the thesis methodology and is divided into four different steps: the first three refer to a Multi-Criteria Evaluation by means of a GIS tool and the last one to the application of FARM model to the most suitable areas identified for shellfish aquaculture;

Chapter 4 contains the GIS site selection procedure and dynamic model results and respective discussion, where the final suitability maps created by the Multi-Criteria Evaluation are presented and discussed. FARM's outputs are also analysed in order to simulate oyster aquaculture environmental and economic significance. Possible limitations are also identified and emphasized.

Lastly, conclusions are presented in Chapter 5, where the question "Is oyster aquaculture viable in the Sado Estuary?" will be answered, according to the final outcomes. Management recommendations to assist the decision-making process are also performed in this chapter.

2. State of the art

2.1 World

The world faces one of its greatest challenges – how to feed 9 billion people by 2050 – meaning that food sectors, such aquaculture, will need to increase production over the next few decades to ensure enough animal protein for human population (Béné et al., 2015; FAO, 2016; Godfray et al., 2010; Ross et al., 2013).

During the period of the 1960s to 2016, global consumption of aquatic animals increased from 9.9 kg per capita to an all-time high of 20.1 kg per capita, in times where production from capture fisheries has levelled off, as most of the fishing areas reached their maximum potential (FAO, 2018a; Lopes, 2016; Lopes et al., 2017). Fish supplies from capture fisheries will, therefore, not be able to meet the growing global demand for aquatic products, allowing aquaculture to bridge the supply and demand gap for these products in most regions of the world (Asche & Khatun, 2006; FAO, 2016, 2018a).

FAO's statistics (2018) (Table 1) show that there is a global upward trend in aquaculture production over the last 60 years. Since the beginning of the period, Asia, and particularly China, have been responsible for most of the worldwide production. In 2016, Asia represented 92.1% of the global aquaculture production, with China producing more than 63 million tonnes of aquatic products and, representing nearly 60% of the worlds' production. In contrast, developed countries, such as France and the USA, decreased their production over the last decade, representing only 0.2 and 0.4% of the total aquaculture production in 2016, respectively. Furthermore, over the past 40 years, the growth rate of exportation of aquaculture products from developing countries has been increasing significantly faster in comparison with developed countries (FAO, 2018a).

Table 1: Aquaculture production (tonnes) by continent and major producers over the period of 1956 – 2016 (FishStat FAO, 2018).

	Aquaculture production (thousands of t)							Contribution to aquaculture production in 2016 (%)
	1956	**1966**	**1976**	**1986**	**1996**	**2006**	**2016**	
Continents								
Africa	5.0*	9.4*	16.7*	55.9	182.1	843.2	2,121.2*	1.9
Americas	101.7*	117.8*	195.7*	480.8	1,124.6	2,406.8	3,363.3	3.1
Asia	916.3*	2,210.8	4,400.1	10,721.5	30,698.7	55,973.9	101,546.9	92.1
Europe	208.9	377.9	652.3	1,052.6	1,673.4	2,193.7	2,946.6	2.7
Oceania	6.5	9.1	13.1	36.6	111.8	174.6	230.2	0.2
Others	54.0	66.7	130.6	323.5	-	-	-	-
TOTAL	**1,292.4**	**2,791.7**	**5,408.5**	**12,670.9**	**33,790.7**	**61,592.2**	**110,208.2**	**100.0**
Countries								
China	406.6*	1,144.8*	1,841.4*	5,248.2	22,156.6	39,570.0	63,721.8	57.8
France	104.0	102.7	148.6	243.7	285.5	237.4	166.6*	0.2
Indonesia	70.2	104.3	156.7	411.6	881.1	2,2479.2*	16,616.0*	15.1
Japan	203.3	442.2	926.7	1,292.0	1,349.5	1,224,189.5	1,068.0	1.0
USA	98.8*	114.2*	183.9*	372.2	393.3	520.0	444.4	0.4
Others	409	883.5	2,151.2	5,103.4	8,724.6	17,561.4	28,191.4	25.6
TOTAL	**1,292.4**	**2,791.7**	**5,408.5**	**12,670.9**	**33,790.7**	**1,284,557.4**	**110,208.2**	**100.0**

**Estimated numbers by FAO (2018).*

This discrepancy in production values (tonnes) among developed and developing countries is mostly explained by the stringent regulation and management interventions that developed countries are required to exert (Asche & Khatun, 2006; FAO, 2018a; Ferreira et al., 2012). Over the years, the rapid expansion of aquaculture has led to several impacts on the environment (e.g. sediment organic enrichment, eutrophication, chemical pollution and loss of endemic populations), leading the governments and stakeholders to become increasingly concerned about its protection, developing regulations to safeguard natural resources and product quality, as well as manage aquaculture activities in accordance with the other uses of the territory (Asche & Khatun, 2006; Costa-pierce, 2003; Godfray et al., 2010; Ross et al., 2013; Silva et al., 2011; Stevens et al., 2018). Additionally, the bulk of fish production in developed countries is generally destined to human consumption, and demand far outweighs domestic production (FAO, 2016, 2018a). This way, consumption levels can only be achieved through heavy dependence on imports, frequently from developing countries (FAO, 2016, 2018a; Ross et al., 2013).

In developing countries, aquaculture development is needed to help alleviate poverty and increase protein food supply, however, poverty and environmental conservation cannot coexist (FAO, 2006; Pullin et al., 1993; Rivera-Ferre, 2009). As stated by Little et al. (2013), in Ross et al. (2013): "*external interventions to stimulate aquaculture in developing countries, have often been driven by short-term objectives and geo-political boundaries, without paying attention to other key criteria for successful aquaculture, often resulting in limited development and sustainability*"; since aquaculture represent an important source of income for local communities and employment benefits along the value chain (not directly involved in farming), healthy food provision has not been a major concern (Asche & Khatun, 2006; Ross et al., 2013). In recent years, this imposed serious obstacles for developing countries to expand their participation in the international trade market, since aquaculture products are stringent to food safety requirements that many developing countries find difficult to meet (Asche & Khatun, 2006; STECF, 2016).

Moreover, developing countries are becoming not only sellers but also consumers (FAO, 2018a): 53% of fish was destined to human consumption in 2016 and 58% for developed countries, in 2016; According to FAO (2016), in developing countries, annual per capita fish consumption will rise to 21.5 kg in 2025, while in developed countries it is estimated to reach 23.4 kg, by the same year. Meaning that the consumption gap between developed and developing countries is narrowing.

At present, the Member States of the United Nations implemented the 2030 Agenda for Sustainable Development (2017). Its purpose is to set aims for aquaculture towards of food security and nutrition, as well as safeguard the sustainable development of the sector in environmental, economic and social terms (FAO, 2016, 2017). One of the main challenges of the Agenda implementation is the sustainability divide between developed and developing countries, that resulted from limited governance and management capacity, as well as economic interdependencies (FAO, 2018a). Since the world is expected to contain over 9 billion people, by 2050, aquatic products will most certainly be cultivated in these developing countries, so, the Agenda states that global community needs to support these countries, in order to achieve the full potential of aquaculture and maintain the sustainability of the sector (FAO, 2018a; Ferreira et al., 2012).

2.2 Europe

In Europe, aquaculture is an important economic activity in many coastal and continental regions, mainly composed of SMEs or micro-enterprises, employing directly 85 000 people (OECD, 2017; STECFA, 2014). Europe is among the world's highest consumers of fish, consuming twice as much seafood as they produce, with imports filling the gap (EUMOFA, 2016, 2017; WWF, 2017).

In recent years, aquaculture production in the EU almost levelled off, mostly due to stringent regulation to safeguard the environment and the sustainability of the sector (as mentioned before for developed countries), but partially due to market factors (Ferreira et al., 2012; Hedley & Huntington, 2009; Telfer et al., 2009). Such the rest of the world, urban coastal areas are expanding in Europe, leading to competitive uses of the coastal natural resources (Bricker et al., 2018; EEA, 2006; Fernandes et al., 2001). This has highlighted a need to implement control measures that ensure the development of the sector in cooperation with the sustainable use of the natural resources and the surrounding environment (EEA, 2006; Fernandes et al., 2001).

Long (2016) claimed that the EU legislation touches all the aspects of the aquaculture sector, including: i) licensing; ii) planning; iii) consumer safety; and iv) environmental protection; It also provides spatial planning measures to resolve conflicts with other uses of the marine environment (Long, 2016). In terms of environmental protection, the EU holds an extensive body of legislation, which includes the Water Framework Directive (WFD 2000/60/EC) and the Marine Strategy Framework Directive (MSFD 2008/56/EC) (Borja et al., 2013; European Commission, 2016). Several authors (i.e. Borja et al., 2013; Long, 2016) concluded that both Directives will have a crucial part on the long sustainable and dynamic development of the sector. The table below (Table 2) describes the most relevant environmental regulatory legislation to aquaculture activities in Europe.

Table 2: Relevant regulatory legislation for aquaculture in the Europe.

Regulatory legislation	Description
Water Framework Directive (WFD)	The WFD is a set of environmental objectives to protect and restore aquatic ecosystems and ensure the sustainable use of water for people, business and nature, in the longer term (European Commission, 2014). It aims to improve and protect the chemical and ecological status of surface waters and groundwater bodies throughout a river basin catchment, including: rivers, lakes, groundwater, coastal waters and estuaries (European Commission, 2014, 2016). To achieve this, Member States are required to establish River Basin Districts (RBDs) and, for each, develop a River Basin Management Plan (RBMP) (European Commission, 2016). The WFD cancelled the Council Directive 79/923/EEC of 30 October 1979 on the quality required for shellfish waters. This brought some concerns to shellfish producers since the Directive aimed to restore and protect water bodies in order to support shellfish life and growth (European Commission, 2016). Nevertheless, each Member State is required to perform a proper implementation of the WFD, securing the same level of protection defined in Shellfish Waters Directive (79/923/EEC) (European Commission, 2016).
Marine Strategy Framework Directive (MSFD)	The MSFD is an environmental pillar of the EU's policy in terms of protection of the marine environment (European Commission, 2016). Its main purpose is to achieve Good Environmental Status (GES) of the EU's marine waters by 2020, throughout an ecosystem-based approach to the management of human activities (Berg et al., 2015; European Commission, 2016). This way, each Member State is required to develop and implement strategies (i.e. Marine Strategy) for their marine waters, based on the ecosystem approach (Borja et al., 2013; European Commission, 2016).
Natura Network 2000	The Natura 2000 network has a crucial role in the EU biodiversity policy; with the main purpose of ensuring long-term survival and maintenance of the most vulnerable species and habitats, across the European territory (European comission, 2012; Policy, 2015). The network was established under the Birds Directive (2009/147/EC) and the Habitats Directive (92/43/ECC), spreading to all 28 EU countries, both on land and sea (European Commission, 2012). The inclusion of sites on the Natura 2000 network is a shared responsibility of the EC and the new EU's Member States. Under the Birds Directive, Member States are required to designate special areas of conservation, which will be evaluated and approved by the EC, and directly included in the Natura 2000 network. Under the Habitat Directive, the site selection procedure is slightly different: Member States identify and propose the most important locations for habitat and species protection, then the EC, with the Member States help. selects the sites of community importance (SCI), whose status will furtherly change to Special Areas of Conservation (SAC) (European comission, 2012; Mcleod et al., 2009).

As for today, the EU intends to boost the aquaculture sector through the Common Fisheries Policy (CFP) reform and, in 2013, published Strategic Guidelines to assist Member States managing aquaculture activities through an open method of coordination; presenting general objectives and common priorities at the EU level (Alexander et al., 2015; European Commission, 2013; STECF, 2016). Its main purpose is to develop the full potential of EU aquaculture in line with the Europe 2020 objectives: i) sustainability; ii) food security; iii) growth and employment; and iv) stake-holder engagement in policy matters, to improve management of aquaculture activities (Long, 2016; Maritime Affairs and Fisheries, 2013);

Data from FAO (2018) (Table 3) illustrates that Europe produced nearly 3 million tonnes, regarding both inland and marine and coastal aquaculture, in 2016 (FAO, 2018). By that year, Norway represented the major aquaculture producer with 45% of Europe total production, mainly with export of salmon and rainbow trout (Moe, 2016). France has historically been one of the most important aquaculture producers in Europe, however, over the last 20 years, production has been following a downward trend and the Member State is losing representativeness not only in Europe, but worldwide. Despite the good conditions for aquaculture (i.e. extensive rivers, thousands of hectares of ponds and 5 500 km of coast line), the major issues currently in France aquaculture concern competition for and access to sites and authorization to new facilities (Hedley & Huntington, 2009). One the other hand, the United Kingdom and the Russian Federation have been increasing their aquaculture production over these last 20 years.

Table 3: Five major aquaculture producers in Europe over the period of 1956 - 2016 (FishStat FAO, 2018).

	Aquaculture production (thousands of t)							**Contribution to aquaculture production by 2016 (%)**
	1956	**1966**	**1976**	**1986**	**1996**	**2006**	**2016**	
Country								
Norway	-	0.20	3.48	49.39	321.52	712.37	1,326.22	45.01
Spain	5.70	65.30	186.90	268.45	231.63	292.83	283.83	9.63
United Kingdom	0.04	0.20	0.69	24.01	109.90	171.85	194.49	6.60
Russian Federation	-	-	-	-	53.31	106.34	173.84	5.90
France	104.00	102.70	148.59	243.67	285.53	237.38	166.64	5.66
Others	99.12	209.53	312.67	467.06	671.55	672.98	801.61	27.20
TOTAL	**208.85**	**377.93**	**652.32**	**1,052.59**	**1,673.44**	**2,193.75**	**2,946.63**	**100**

2.3 Portugal

Portugal, such the rest of the world, is increasing aquaculture production in response to the decreasing of fish stock in the oceans (Lopes, 2016; Tomé, 2008). As shown in Table 4, the production of aquatic products in Portugal began in the 1960s and rose above 10 000 tonnes in the 1980s decade. Despite this promising start, in 2009 Portuguese aquaculture only accounted for 1% of all available seafood and 3.3% of official production (FAO, 2015; Lopes, 2016). In 2016 production was 9 787 tonnes, primarily consisting of marine bivalves and marine fin fish grown mostly from mariculture and land-based aquacultures farms (FAO, 2005; INE, 2018). In spite the highest production numbers in 1986, there was more profit value (k €) from aquaculture products in 2016; mostly due to an increase of market value of aquaculture products (EUMOFA, 2016, 2017).

Table 4: Aquaculture production in Portugal over the period of 1956 to 2016 (FishStat FAO, 2018).

	Portugal						
	1956	**1966**	**1976**	**1986**	**1996**	**2006**	**2016**
Production (t)	0	3*	265*	10,331.00	5,364.00	7,894.00	9,787.22
Value (k €)	**-**	-	-	54,288.57	31,332.80	54,309.34	66,932.23

**Estimated numbers by FAO (2018).*

Notwithstanding favourable consumer-based market conditions, aquaculture development in Portugal still has several constraints (Lopes, 2016). These derive from its geographic location and natural conditions, corporate difficulties related to production associations and access to hatcheries and nurseries for different species (Lopes, 2016). Institutional and legal complications, mainly due to slow complex licensing procedures and the large number of governmental institutions involved, have also been identified by responsible entities and efforts are being made to simplify the licensing process (DGRM, 2014; Lopes, 2016). As a member of the EU, fisheries management in Portugal, under the responsibility of the Directorate-General of Natural Resources, Safety and Marine Services (DGRM), is governed mainly by the EU Common Fisheries Policy (CFP) (FAO, 2018b).

According to Lopes (2016), the potential for the development of innovative commercial endeavours remains: an example of success given by the author was the offshore IMTA park south of the Ria Formosa in the Algarve, which is one of the first for commercial use in Europe (see Ferreira et al., 2012, 2014); However, despite coastal and offshore solutions being promising alternatives to a growing demand for seafood, the characteristics of the national coast are not very attractive for installation of offshore aquaculture, demanding more advanced technological solutions in order to overcome the hydrological conditions (Kapetsky et al., 2013; Lopes, 2016).

This way, most of aquaculture activities occur in estuaries, and the Sado Estuary plays an important contribution for national aquaculture production (Portela, 2016; Tomé, 2008). Within the estuary, the bulk of these activities are concentrated in the Nature Reserve area, due to the transformation of deactivated salt works (Coutinho, 2003; Tomé, 2008). Gilthead Bream (*Sparus aurata*), European Seabass (*Dicentrarchus labrax*) and Common Sole (*Solea Solea*) are currently the main produced species in the estuary, however, until the 1970s, Portuguese oyster (*Magallana angulata*) was abundant, and its production was important to the country economy (Portela, 2016). According to Vilela (1975), more than 50 000 tons of Portuguese oyster from the Sado were exported to France between the period of 1964 and 1972, which made this resource very important between the commercial exchanges among both countries (Dias, 1994).

Data from the latest report from INE (2018) reveals that, in 2017, oyster production accounted 1 014 tons, representing a decrease of 2% in production, compared to the previous year. As for that year, there were produced 633 tons of Pacific Oyster and 241 tons of Portuguese oyster, representing total values of 1 668 thousand euros and 716 thousand euros, respectively (INE, 2018).

2.4 *Magallana angulata* and *Magallana gigas* oysters

Currently, the World Register of Marine Species (WoRMS) registers all cupped oysters that formerly members of the genus ***Crassostrea*** into a new genus – ***Magallana*** (Bayne et al., 2017; Salvi and Marionitti, 2016). The proposal was made in two publications by Salvi et al. (2014) and Salvi & Mariottini (2016), which addressed the need for a taxonomic revision of the genera *Ostrea*, due to phylogenetic and biogeographical evidence that the Asian species of *Crassostrea* from the Pacific Ocean are assigned to the *Magallana* genus (Salvi & Mariottini, 2016; Salvi, 2014).

However, according to several scientists (i.e. Bayne et al., 2017), this change has caused dismay among biologists, farmers and other stakeholders with an interest in cupped oysters. These affirmed that the reports from Salvi and his colleagues were not robust enough to support the proposed taxonomic change because: i) a limited number of genes sequenced; ii) incomplete sampling of other species of the *Crassostreinae*; and iii) the absence of phenotype diagnosis that includes traits other than DNA sequence data; concluding that this change counters the demands for an integrative taxonomy, which requires multiple lines of evidence when proposing a taxonomic change, including multigene and multitaxa analysis (Bayne et al., 2017). Despite this controversy, the cupped oysters in this document are referred as the genus credited by WoRMS, *Magallana.*

The two cupped oysters *Magallana gigas* and *Magallana angulata* were first described respectively by Thunberg in Japan in 1793 and Lamarck in Portugal in 1819, respectively (Batista et al., 2008a, 2008b, 2009; Fabioux et al., 2002; Huvet et al., 2002; Portela, 2016). These, as the rest of the *Magallana* genus, are among the most important commercial aquatic species in the world and have been harvested from the wild and cultivated since centuries (Batista et al., 2008). *M. gigas* and *M. angulata* were long assumed to be native from Asia and the northeast Atlantic, respectively (Batista et al., 2009a), nevertheless, several studies (e.g. Batista et al., 2008; Foighil et al., 1998) have addressed that the Portuguese oyster has an Asian origin.

The Portuguese oyster (*Magallana angulata*) was a species of economic importance in Europe until the early 1970s (Batista et al, 2008; Vilela, 1975). According to several authors (i.e. Batista, 2007; Batista et al., 2008; Comps, 1988; Grade et al., 2016), between the period of 1967 and 1973, mass mortality events almost led to its disappearance from Europe. In Portugal, it is estimated that natural populations of Portuguese oyster started to decline (in the Tagus and Sado estuaries) around 1966, mostly due to (Batista, 2007; Vilela, 1975): i) spoiling of water quality with origin in industrial discharges around the estuaries margins (Caeiro et al., 2002; Vasconcelos et al., 2007); ii) introduction of an anti-fouling agent, tributyltin (TBT) in dockyards within the estuary (Phelps & Page, 1997; Vasconcelos et al., 2007); iii) diseases, namely gill injuries (known as “gill disease”) that reduced its filtering capacity (Bento, 2008), and an excessive thickening of the shells (Phelps & Page, 1997); and, lastly, iv) overfishing and bad resource management, (Batista, 2007; Vasconcelos et al., 2007). One the other hand, Pacific oyster (*Magallana gigas*) populations thrived in the Sado Estuary and became main exported oyster in Portugal, as previously mentioned (Batista, 2007; DGRM, 2014; INE, 2018).

The Pacific oyster (*Magallana gigas*) was introduced in different regions of the world, being currently farmed throughout the Americas, Africa, Australia, Europe and Asia (FAO, 2016; Miossec et al., 2009). In Europe, was introduced in France and Portugal to fill the gap of Portuguese oysters disappearance and sustain the oyster production sector (Boudry et al., 1998; Magro, 2016). Production expanded from 156 000 tonnes in 1950 to 437 000 tonnes by 1970, and 1.2 million tonnes by 1990 (FAO, 2004). Expansion was very rapid in the 1990's, rising to 3.9 million tonnes by 2000. It continued over the years, reaching nearly 4.4 million tonnes by 2003 (FAO, 2004). Yet, according to the latest report from FAO (2018a), in 2016, the Pacific cupped oyster represented 3% of the world production of molluscs, and its production has been decreasing steadily since 2010. Which might be related to the continuous coastal urbanization and the increase need to share the common coastal resource with other users (e.g. Bricker et al., 2018; Clark, 1992).

As for today, the taxonomy of *M. gigas* and *M. angulata* is still under question, as they are very similar to each other and possibly conspecific (Batista et al., 2009; Burayu & Chinaowong, 2006; Gagnaire, 2018). They have been declared as a single species by Huvet et al. (2002) because: i) when bred together, produce fertile descendants; ii) are morphologically very similar; and iii) differ very little at the genetic level; However, the high degree of morphological similarity and the reduced knowledge of reproductive barriers, has supported the controversy between their genetic and taxonomical differentiation (Gagnaire, 2018). In recent years, studies on mitochondrial DNA and microsatellite data (Batista et al., 2005) have revealed evidence that the two taxa are genetically distinct although closely related (Gagnaire, 2018).

2.4.1 Seed and culture practice

In bivalve culture, a steady supply of seed is of paramount importance (Batista, 2007). Seed can be collected from the wild or produced in the hatchery, yet, the majority of seed used worldwide for bivalve culture is gathered from natural collection (FAO, 2018a).

Collection of seed from the natural environment can vary considerable from year to year because of fluctuations in environmental conditions (e.g. temperature, salinity, food) (Batista, 2007; Lubet et al., 1994; Portela, 2016). Meanwhile, anthropogenic pollution of the natural environment (e.g. anti-fouling paints containing TBT) can drastically reduce natural populations (Quayle, 1988). As stated by Batista (2007), the successful collection of seed from the wild greatly depends on the knowledge about life cycle, spawning period, larval development and settlement process of the target species, which are important factors to forecast when and where to collect the juveniles.

In the Sado Estuary, most oyster seed are supplied from hatcheries in France, which makes producers independent from catching it from the existent natural beds, where the number of individuals is very fluctuant (Magro, 2016). *M. angulata* seed is not available neither from natural collection nor from commercial hatcheries, which impels farmers to introduce cultures of *M. gigas*, whose seed is more abundant and easily obtained (Baptista, 2007). However, despite Batista (2007) statements, some contacted oyster producers claim to acquire *M. angulata* seed from the Mira Estuary, which still holds healthy oyster beds.

At present, there are 40 licensed installations producing oyster in the Sado Estuary, of whom 20 are dedicated to oyster production only (Portela, 2016). According to the producers in the area and literature review (i.e. Birmingham, 2010; Forrest et al., 2009; STECFA, 2014): oyster extensive rearing is mostly located in areas between tides, called intertidal areas, and performed in baskets or net bags, which allow high density production. Oysters initially grow on trestles and then transferred to the bottom. This type of cultivation requires daily management and routine operations, for example, net cleaning to prevent the clogging of the holes due to the excess of algal growth, since it is crucial to maintain water circulation inside the bags or baskets.

Due to the statements above, the work will singularly focus on intertidal cultures in an extensive culture system for oyster production. This way, only intertidal areas will be studied to assess aquaculture suitability.

2.5 Diseases and introduction of alien species

Over the years, concerns about intentional introductions of species was for production purposes only, without considerations about the ecosystem receipt of exotic species (Miossec et al., 2009). Little care was taken to ensure that only the intended species were introduced (Barber, 1997). As result, several alien species were introduced along with the intended species, and the impact of these additional exotic species on native ecosystems was not generally realized until sometime after the original introduction (Miossec et al., 2009). As stated by Ferreira et al. (2012), the problems associated with the introduction of non-indigenous species include: i) competition with native species; ii) hybridization between the introduced species and native ones; iii) the transport of pathogens and diseases through transportation/relocation of seeds and clam; iv) cross-contamination between different types of shellfish;

According to Comps (1988), in Europe, mass mortalities of *M. angulata* were associated with two irido-like viruses between late 1960s and 1980s – gill necrosis virus disease (GNVD) and hemocytic infection virus disease (HIVD). The same author stated that gill necrosis virus causes, principally in Portuguese oysters, an evolutive ulceration of the gills, including cellular hypertrophy and severe inflammation. Additionally, hemocytic diseases were the most responsible for the Portuguese oyster mass mortalities in Europe. It induces cytoplasmic lesions in the hemocytes and causes severe injuries to interstitial tissues (Comps, 1988, 1970). After this mass mortality event, the distribution of the Portuguese species populations was poorly known in Europe, and only a few populations were known in centre and southern Portugal (e.g. Sado Estuary and Ria Formosa), which presented clear signs of these viral diseases (Fabioux et al., 2002; Huvet et al., 2000).

As for the *M. gigas* oyster, part of the success as an aquaculture species, is due to its high resistance to diseases (Batista, 2007; Forrest et al., 2009). Nevertheless, high mortalities of know and unknow sources have been reported in larvae, juveniles and adults of the Pacific species (Batista, 2007; Gagnaire, 2018). There is evidence that the species was also affected by the diseases described above, however, other diseases (ostreid herpes virus – OsHV-1) and parasites (planocerid flatworm and mud-worm) poses a threat to its production, mainly in hatcheries (Forrest et al., 2009). As stated before, the Pacific oyster was introduced in several regions of the world to replenish areas with declining populations of native oysters and Ruesink et al. (2005) concluded that this species has been identified as an invasive alien species in 17 of the 66 reviewed countries.

Despite the fact that Pacific oysters can be a major cause for the economic development in the regions where it is cultivated, it may also arise negative impacts on the environment (Harris, 2008); as an ecosystem engineer, the Pacific oyster has the capacity to modify natural habitats to suit its biological needs, thus changing both the physical and chemical properties of the environment (Padilla, 2010). This, adding to its high filtration rate, might cause food depletion in the water column and further impact autochthonous filter-feeding species and its resistance to stress conditions; making it a troublesome invasive species to deal with and enhancing the need for sustainable management practices (Harris, 2008; Padilla, 2010).

2.6 Use of Geographic Information Systems and Site Selection procedures in aquaculture studies

The use of Geographic Information Systems (GIS) in aquaculture started in the beginning of the 1980s decade and became an important tool for research, in the following decade, due to cost reduction and technological development of computers (Wright & Barlett, 2000). According to Viann & Bonetti (2016), GIS software's are used in aquaculture to: i) characterize aquaculture environments; ii) evaluate aquaculture potential; and iii) develop site selection procedures for aquaculture practice;

As for the application of GIS tools in site selection studies for aquaculture, it has been increasing over the years and performed over a wide variety of scales, regarding (Viann & Bonetti, 2016): inland pond-based aquaculture (e.g. Kapetsky, 1994; Kapetsky & Nath, 1997) and near-shore coastal culture of shellfish, shrimp and fish (e.g. Kapetsky et al., 1988; Pérez, et al., 2003; Ross et al., 1993; Silva et al., 2011); Site studies have been developed for both developing and develop countries and, today, specific tools and methodologies are still under development (Pérez et al., 2003, 2005).

Coastal waters, due to their proximity to urban areas, gather considerable attractivity for aquaculture siting (e.g. sources with urban aquaculture), however, the multitude of activities, and the continuous urban expansion, might arise some problems due to the incompatible uses of the territory (Bricker et al., 2018; Clark, 1992). This way, if aquaculture is not properly sited, can result in stressed ecosystems, stressed culture species, decrease production, inferior economic performance, displeased neighbours and a disgruntled public (Longdill, et al., 2008; Ross et al., 2013). Hence, there is a need to pinpoint the best locations for aquaculture, that ensure its success and minimizes the social and environmental negative effects, which are addressed by site selection studies.

Henceforth, site selection is a complex spatial decision problem that has many alternatives (i.e. different initial choices implicate the definition of different solutions) and that involves decision makers carrying different stakes and preferences. Consequently, this choice is not easily and univocally identifiable (Dapueto et al., 2015).

2.6.1 Multi-Criteria Evaluation technique

The Multi-Criteria Evaluation (MCE) technique is one of the most commons methods for aquaculture site selection (e.g. Dapueto et al., 2015; Falconer et al., 2016; Hossain et al., 2009; Silva et al., 2011). It focus on specifying, creating, and aggregating comprehensive sets of evaluation criteria which reflects concerns relevant to the decision problem (Nath, et al., 2000; Pérez et al., 2003, 2005). Criteria in evaluation can be either represent contributing factors (a parameter which enhances suitability) or constraints (parameters limiting the use of locations) (Nath et al., 2000). Integration of this criteria into the GIS software, builds the spatial database on which evaluation is performed (Longdill et al., 2008). Then, criteria images representing suitability may be combined to form a single suitability map from which the final choice/decision will be made.

In order to compare results, all variables must be reclassified into a common scale (e.g. 0 – 1, 0 – 100, 0 – 255) (Eastman, 1999). The process of converting data to such numeric scales is most commonly called standardisation (Voogd, 1982). Afterwards, to define overall suitability, criteria are combined using either additive or multiplicative models, with or without individual weightings (Longdill et al, 2008). These weights can be obtained based on expert knowledge, literature in similar works or comparison between relative weights (i.e. Analytical Hierarchy Process) (Falconer et al., 2016; Hossain et al., 2007; Lin, 2010; Nath et al., 2000; Saaty, 1980).

According to Eastman (1999), in GIS, MCE has most typically been approached in one of two ways:

1) All criteria are converted to Boolean statements (i.e. logical true/false) of suitability for the decision under deliberation: in site selection studies, this method is mostly applied to constraints, since these illustrate areas that are not suitable for the objective in study. These variables can be further combined by different degrees of intersection (i.e. logical AND) or union (i.e. logical OR);

2) Quantitative criteria, expressing different degrees of suitability, are evaluated as continuous variables and converted into a common scale (Voogd, 1982). Afterwards, factors are combined by means of Weighted Linear Combination (WLC), where each factor is multiplied by a specific weight, with results being summed to reach a multi-criteria solution. This procedure is most common among aquaculture site selection studies (e.g. Falconer et al., 2016; Hossain et al., 2007), when compared to the one stated above. Additionally, the result may be multiplied (i.e. intersected) by the product of the Boolean constraints that may apply, as stated in Eq. (1):

$$\text{Suitability} = \sum w_i X_i * \prod C_j \qquad (1)$$

Where:
w_i = weight assigned to factor i;
X_i = criterion score of factor i;
C_j = constraint j;

Complications arise as result of the variety of scales and units on which criteria is measured (Pérez et al., 2005). Some authors (e.g. Nath et al., 2000; Dapueto et al., 2015) have addressed, in their studies, some limitations inherent to the use of GIS that might limit the final outputs: i) the accuracy of the collected data; ii) high spatial resolution data can be limited by hardware and budget; iii) inputs are subjective and are opened to interpretation; and iv) disregard of the real studied area, by focusing only on the GIS maps.

As stated in Silva et al. (2011), the bulk of aquaculture site selection studies using MCE methodologies (e.g. Dapueto et al., 2015; Falconer et al., 2016; Hossain et al., 2009; Lin, 2010) do not include dynamic models for estimation of carrying capacity and temporal variability of environmental effects, which might be considered disadvantageous to differentiate successful and unsuccessful aquaculture practices.

2.7 Dynamic modelling

The Farm Aquaculture Resource Management (FARM^{TM}) model is targeted at both farmers and managers, with the purpose of determining the appropriate shellfish density for optimal carrying capacity of coastal and offshore shellfish cultures (Ferreira et al., 2007a; Ferreira et al., 2009). It simulates processes at the farm-scale by integrating a combination of: i) physical and biogeochemical models; ii) shellfish individual growth models; and iii) screening models for determining production and eutrophication assessment (Ferreira et al., 2007a; Ferreira et al., 2009; Silva et al., 2011). These components are illustrated in Fig. 1.

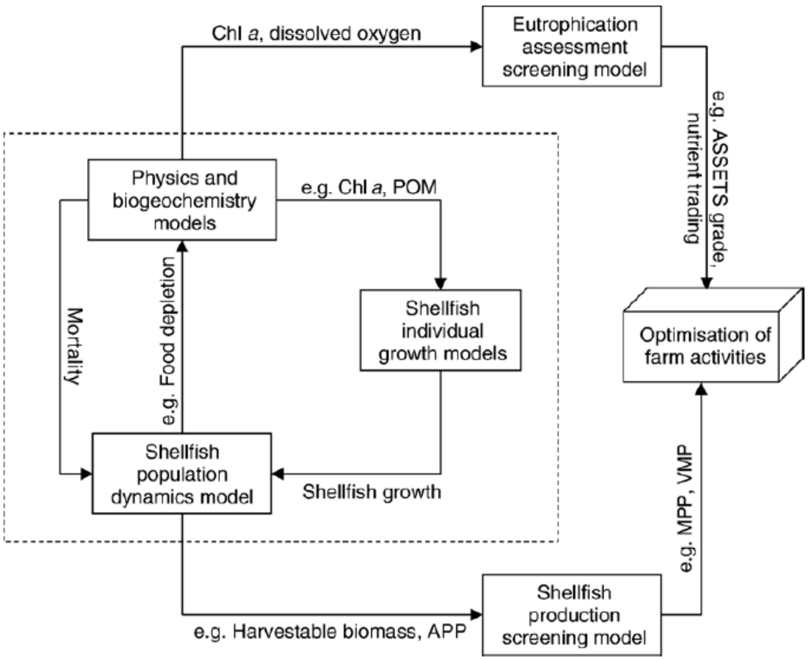


Figure 1: Conceptual scheme of the various components of the FARM model. The model core is within the dotted rectangle, the screening models are external (Ferreira et al., 2007a).

FARM inputs may be grouped into data on: i) farm layout, dimensions, species composition and stocking densities; ii) suspended food entering the farm; and iii) environmental parameters (Ferreira et al., 2007a; Silva et al., 2011); The general layout input is illustrated in Fig. 2 and can be applied to bottom culture, as well suspended rafts or longlines (Ferreira et al., 2007a).

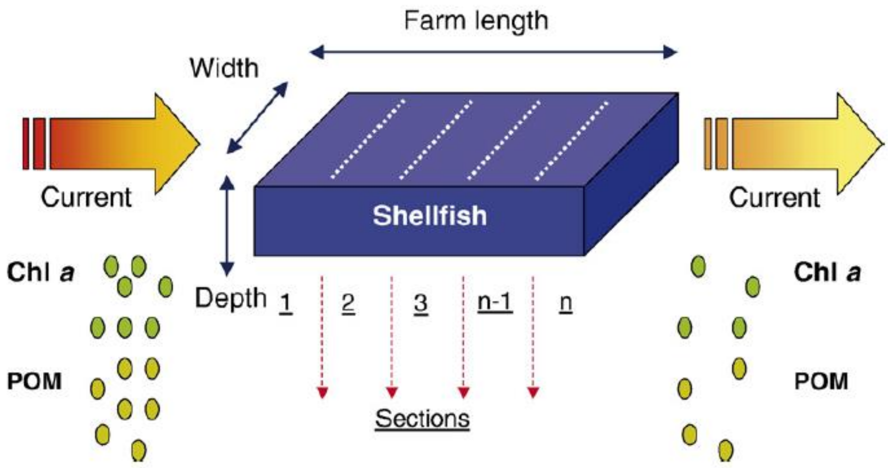


Figure 2: Farm layout (rope and bottom culture) (Ferreira et al., 2007a).

Model outputs allow a detailed analysis of the production market-sized animals for each cultivated species (Ferreira et al., 2007a; Ferreira et al., 2009). In this work was performed a simplified version of FARM and outputs focus mostly on production, defined as the original paper (Ferreira et al., 2007a); aquaculture production is based on Cobb-Douglas production function (e.g. McCausland et al., 2006), which establishes a relation between total physical product (TPP) and total fresh weight (TFW), as stated in Eq. 2:

$$Y = f(x_1 | x_2, x_3, \dots x_n) \tag{2}$$

Where:
Y = output of harvestable shellfish;
x_1 = initial stocking density of seed, considered the only variable input;
$x_2 - x_n$ = other inputs considered to be held constant;

The FARM model also calculates the Average Physical Production (APP) after each run (Eq. 3), providing an indicator of capacity of the capacity of the farm to produce harvestable animals (Ferreira et al., 2007a; Ferreira et al., 2009):

$$APPx_1 = \frac{TPP}{x_1} \tag{3}$$

Where:
$APPx_1$ = average physical production;
x_1 = initial stocking density of seed;
TPP = total physical product;

Lastly, in order to optimize culture densities and maximize profit, was applied Eq. 4, where the first order derivate of the production function provides the marginal physical product (MPP). According to Ferreira et al. (2007a), farmer's profit will be maximised when the value of the marginal product (VMP) equals the input unit cost (P_x). Used input and output (P_y) seed cost represent constant values:

$$VMP = MPP * P_x = P_y \tag{4}$$

Where:
VMP = value of the marginal product;
P_x = output unit cost, sale price of market-sized of cultured oyster;
P_y = input unit cost, seed cost;

In conclusion, tools such as FARM, together with a broad range of other models and complementary approaches for carrying capacity and site selection, are essential to ensure that the provision of aquacultured food for the next generations is not accompanied by systematic environmental damage, often fostered by the legislative and governance between the developing and developed countries (Ferreira et al., 2012).

For this work, the FARM was selected for dynamic modelling because it provides the necessary outputs for the study and has been extensively tested over the world (i.e. USA, China, Portugal, Chile) (Silva et al., 2011).

3. Methodology

3.1 General methodology

The present work identifies and quantifies favourable sites for shellfish aquaculture by means of GIS tools, complemented with the application of a dynamic model (FARM model). Thus, the general approach used in this thesis combines the results of a four-stage analysis (adapted from Silva et al., 2011) to identify optimal sites and evaluate carrying capacity of the identified farms, as illustrated in Fig. 3.

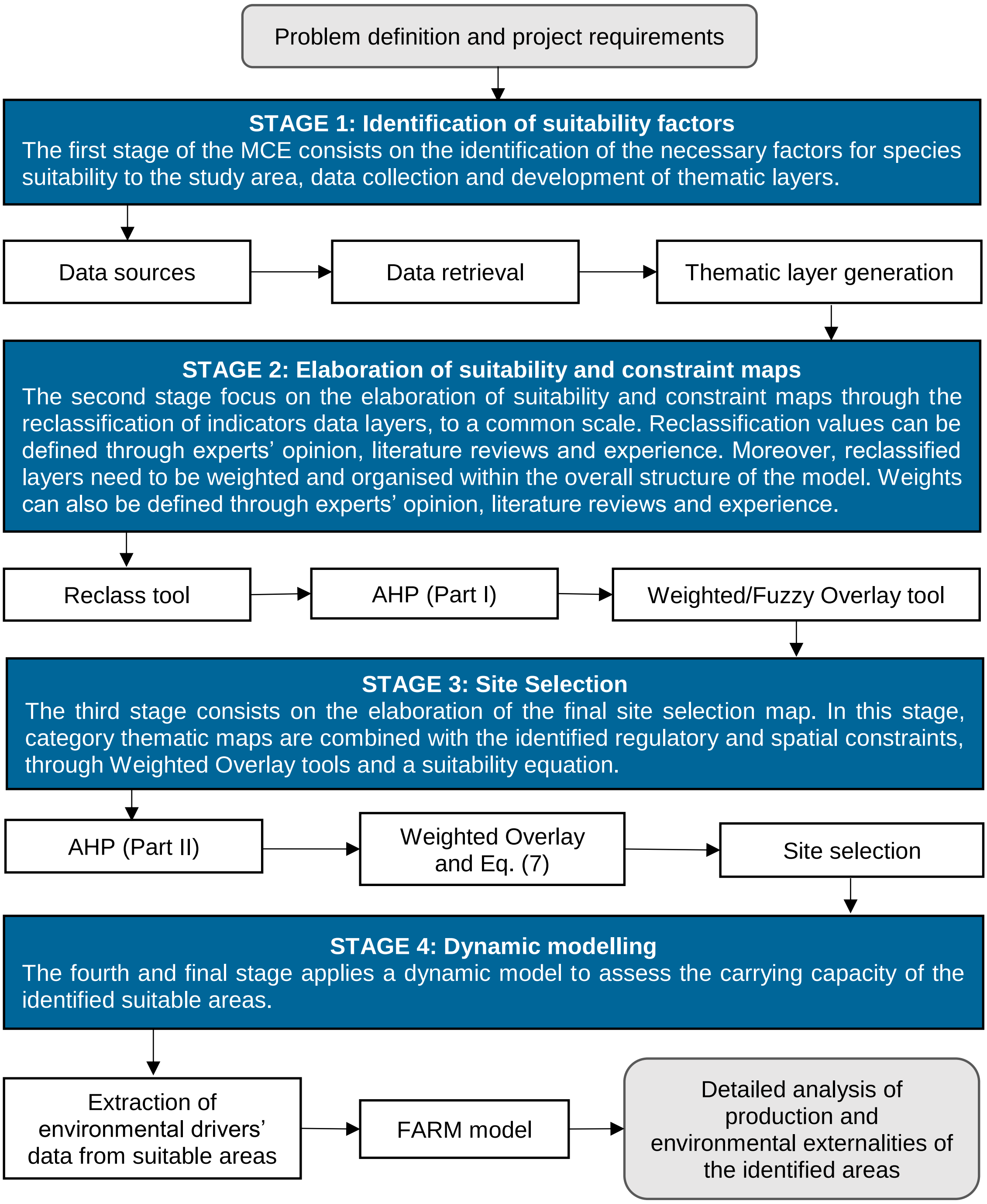


Figure 3: Flowchart of the applied methodology (adapted from Silva et al., 2011).

As shown above (Fig. 3), the first three stages apply a Multi-Criteria Evaluation (MCE) through GIS tools. Here, several factors for oyster suitability to the study area, as well as spatial constraints to farm implementation are weighted and combined to generate a final suitability map. Lastly, environmental data of the identified areas is extracted in order to apply the FARM model and study economic and environmental impacts associated with the selected farms.

This site selection methodology was tested for both Pacific and Portuguese oyster (*Magallana gigas* and *Magallana angulata*, respectively) in the Sado Estuary (38º28'N, 8º45'W), located in Portugal southern region. In this work, both species were addressed as a single model (i.e. same suitability factors and survival thresholds) due to their similarities and being possibly conspecific, as seen before in this work (see Chapter 2.4, as well as the following studies: Batista, 2007; Batista et al., 2008; Batista et al., 2009; Burayu & Chinaowong, 2006; Gagnaire, 2018).

3.2 Study area

The Sado Estuary (38º28'N, 8º45'W) (Fig. 4) is the second largest estuary in Portugal and one of the most important estuaries in Europe, due to the multitude of activities it comprises (Coutinho, 2003; Freitas et al., 2008). It is located in the western coast of Portugal, on the Setúbal Peninsula (50 km south from Lisbon), being classified as a bar estuary due to its physical structure and topography (Carvalho et al., 2001; Pritchard, 1955). In the northern margin is comprised the city of Setúbal, with approximately 100 000 inhabitants, while, in the southern margin, is located the Tróia touristic complex with a fluctuant population of 170 000 people (Caeiro et al., 2005; Coutinho, 2003; Freitas et al., 2008). Most of the estuary, except for the city of Setúbal, its port and, a considerable part of its surroundings area, is classified as a Nature Reserve (Order nº 430/1980): it is intentionally protected by the Ramsar Convention due to high biodiversity values, with a great variety of animal and plant species (Caeiro et al., 2002);

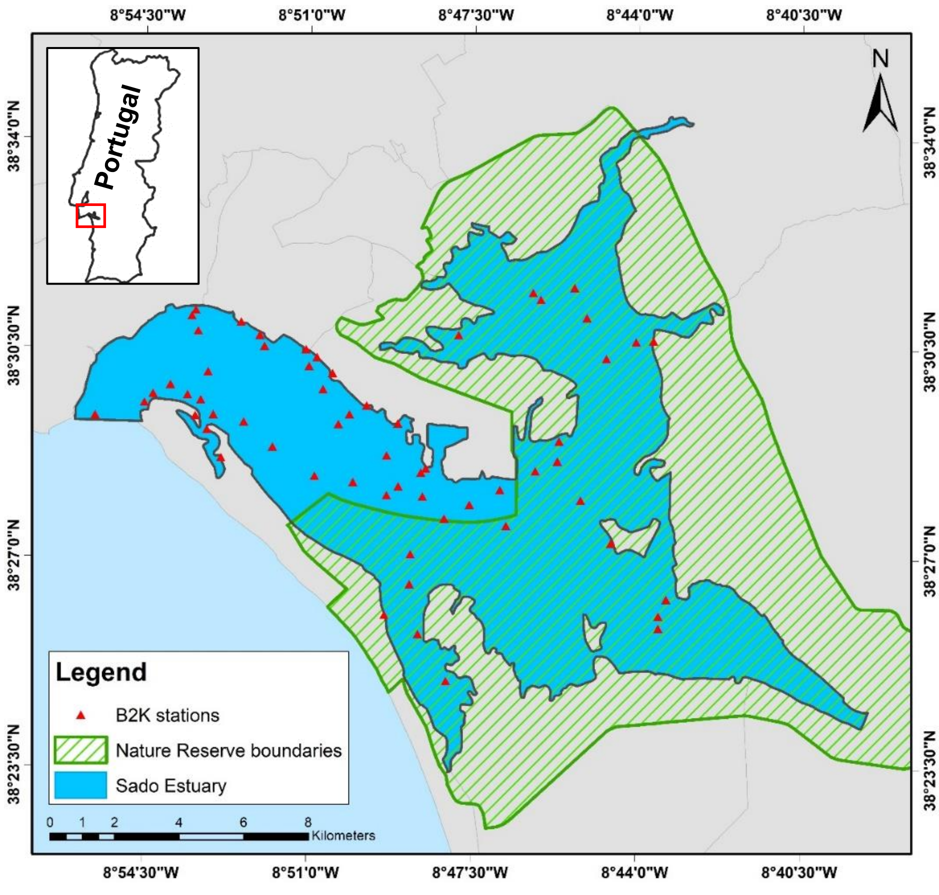


Figure 4: Study area and respective location.

The estuary holds a shallow basin, with a complex morphology and irregular bathymetry (Ferreira et al., 2003; Freitas et al., 2008). It has a volume of $500x10^6$ m^3 and an average depth of 8 m. The tides are semidiurnal with amplitudes ranging from 1 m at neap tide to 3.5 m at spring tide (Rosa, 2010). The salt water inflow wavers between 250 and $300x10^6$ m^3, not being strong enough to guarantee an ebbing current capable to disperse dissolved, or suspended, pollutants in the months where the inflow is below the regular levels (Ruano & Dias, 1994; Vilela, 1975). Due to this, the Sado Estuary is particularly sensitive to pollution events (Caeiro et al., 2005; Portela, 2016).

The Sado River starts at 230 m of altitude, in Vigia mountain, and drains an area of 6 700 km^2, ending in Sado Estuary (Ferreira et al., 2003; Portela, 2016). It is the major source of freshwater on the estuary (80-90%) and the river flow is very irregular, varying from 1 m^3s^{-1} in summer to 60 m^3s^{-1} in winter, and exhibiting large interannually fluctuations (Brogueira et al., 1994). Additionally, the Marateca Channel, on the north side of the estuary, represents about 10% of total freshwater inflow. The estuary is well mixed for normal river flow conditions, although high discharge in some winter months may cause moderate stratification in some parts of the estuary (Ferreira et al., 2003).

The flooded area at high water is of about 150 km^2 and extends NW-SE upstream for 37.5 km to Alcácer do Sal and in NNE-SSW direction for 25 km to Águas de Moura and Comporta (Freitas et al., 2008). The central area of the estuary, named Central Bay, is divided into two channels: the northern one (Canal do Norte), where predominates a superficial flood current which may vary with the tide cycles, and the southern one (Canal do Sul), where predominates a stronger ebbing current. Both channels are divided through intertidal sand shoals (Santos, 1991; Coutinho, 2003; Freitas et al., 2008). Most of the water exchange is made through the southern channel, which reaches a depth of 25 m, whereas the northern channel's maximum depth is 10 m. The estuary is linked to the ocean by a narrow and deep channel (maximal depth of 50 m), 2 km wide, that prevents propagation of oceanic waves and makes the major contribution to the general pattern of estuarine circulation (Neves, 1986). This tidal inlet is constrained by the northern extreme of Tróia sand bar and the Arrábida mountain.

The estuary is subject to intensive land use practices and plays an important role in the local and national economy (Coutinho, 2003; Freitas et al., 2008). There are many industries of different types, as well as hazardous waste landfills, mainly located on the northern margin of the estuary (Catarino et al., 1987; Ferreira, 1998). Furthermore, the harbour associated activities and the city of Setúbal, along with the mines on the Sado watershed, use the estuary for waste disposal purpose without suitable treatment (Catarino et al., 1987; Ferreira, 1998). In other areas around the estuary, intensive farming (mostly rice fields) is the main land use (about 4000 ha) together with an increasingly intensive fish farm (about 1000 ha) (Coutinho, 2003; Portela, 2016). Some of these activities have negative effects on water, sediment and biotic communities; specifically, because they discharge in the estuary contaminants like heavy metals, hydrocarbons, pesticides and fertilizers (Caeiro, 1996, Ferreira, 1998; Cerejeira et al., 1999).

According to Vasconcelos et al. (1999) the establishment of the Natural Reserve seemed to have kept industrial uses away from the protected area, though the expansion of urban land inside the Protected Area might constitute a threat if not properly controlled. As stated by Portela (2016), soon, the northern part of the Reserve will probably be under demographic pressure and will require urgent management measures. Difficulties of Reserve authorities in managing urban growth are reflected in the higher urban growth rate areas inside the protected area boundary, when compared with its surroundings. This is probably due to the numerous official bodies that are responsible for land use planning in the Reserve area, causing, at times, management bottlenecks.

3.3 GIS-based Multi-Criteria Evaluation for shellfish aquaculture site selection

As stated before, this study applied a Multi-criteria Evaluation (MCE) over the first three stages of the general methodology: first, factors on species suitability to the study area were gathered, as well as spatial and regulatory constraints to farm locations; then, suitability factors were organised into categories, which can be referred as "Suitability Categories", since each affect the overall suitability score for shellfish aquaculture;

Later, suitability factors were mapped through GIS tools and thematic maps were generated; thematic maps were then grouped according to each respective category in order to produce a final category suitability map. In the end, by grouping each studied category, a final site selection map was generated and available areas for shellfish aquaculture practice were screened out.

This approach follows what has been performed, over the years, in site selection studies such as: e.g. Dapueto et al., 2015; Falconer et al., 2016; Hossain et al., 2007, 2009; Nath et al., 2000; Bolte, Ross & Aguilar-Manjarrez, 2000; Silva et al., 2011;

3.3.1 Stage 1: Identification of suitability categories

The identification of relevant data sets is an integral step in any MCE technique (Longdill et al., 2008). Therefore, the first stage of the MCE methodology focused on the identification and data collection on species suitability to the study area (i.e. suitability categories). These categories are the result of the group of several indicators, which were chosen according to literature review and later adapted to the conditions in the Sado Estuary. Suitability criteria were organized into four main categories, from an adaption of the methodology proposed by Silva et al., (2011): Environmental, Socio-economic, Product quality and Spatial Constraints;

As stated before, this thesis approaches suitability for two *Magallana* spp. (*M. gigas* and *M. angulata*), consequently, factors were chosen according to site suitability of both species (Fig. 5).

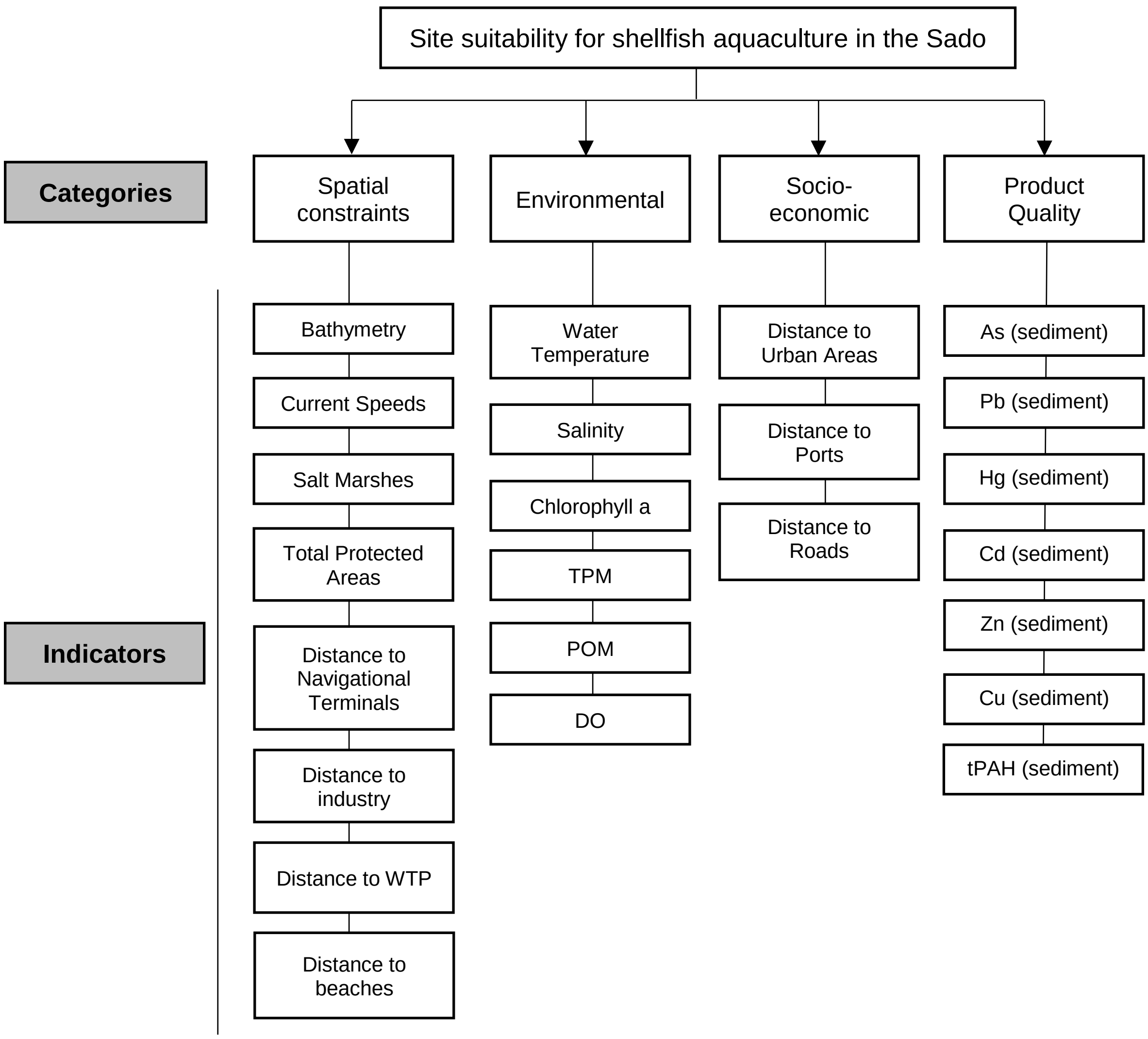


Figure 5: Suitability Categories and respective indicators for shellfish aquaculture site selection in the Sado Estuary,

The last step of this stage was the generation of thematic criteria maps. Maps were created under the same coordinate system (WGS 1984) and assigned a Sado Estuary Analysis Mask so that processing only occurs on locations that fall within the mask, with locations outside of it assigned to Nodata in the output (e.g. Silva et al., 2011).

3.3.1.1 Spatial Constraints

Spatial constraints are here described as all legal obstacles and anthropogenic activities that screen out unsuitable areas for aquaculture activities in the estuary. In terms of assisting the decision-making process, studying these constraints allow the identification and mapping of the maximum suitable areas for shellfish aquaculture; by studying safety distances to human activities which release undesired concentrations of pollutants (i.e. industries and WTP) or should not be compromised (i.e. beaches and navigational terminals), as well as, culture practices (i.e. bathymetry and current speeds) or legal constraints (i.e. Salt marshes and TPA). The table below (Table 5) provides a more detailed explanation of each constraint in study.

Table 5: Identified legal and spatial constraints to farm siting in the Sado Estuary.

Indicator	Description
Natura network 2000	Natura Network 2000 was briefly described in Table 3. The directive aims to protect rare threatened species and some rare natural habitat types, within the EU territory. The Nature Reserve of the Sado Estuary (Order nº 430/1980) (23 160 ha) aims to secure the natural balance of the estuary, by managing the human activities within the area and promote the correct use of its natural resources, as well as other recreational activities. Due to its high biodiversity, the area was classified as Special Protection Area (SPA) (PTCON0011 Sado Estuary) in the Birds Directive 92/43/EC, being as well included in the Ramsar Convention, since 1996 (Caeiro et al., 2002; ICNF, 2007; Portela, 2016).
Total Protect Area	Total Protected Areas are defined as natural habitats with high ecological sensitivity. This way, these areas are regulated to safeguard its natural functions and ecological value (ICNF, 2007), being considered, in this study, as unsuitable for aquaculture siting. In the estuary, the main identified TPA are the Ilha do Cavalo (Horse Island) and the salt marsh of the Mitrena Peninsula. According to ICNF (2007), some other areas in the southern area of the estuary are as well classified as being totally protected.
Salt marshes – Partial Protect Area (type I)	Salt marshes are one of the most productive systems in the biosphere (Adam, 1990). The state and evolution of a salt marsh are crucially dependent on the interplay between sediment input and transport, eustatism, hydrodynamic regimes and biotic factors (e.g. vegetation colonization) (Silvestri & Marani, 2004). These are fragile ecosystems and one of the most endangered ones, due to anthropogenic interference in the natural sediment and nutrient regime (Lousã, 1986). Within the estuary, salt marshes are characterized as Partial Protection Areas (type I), due to their moderated ecological sensitivity. According to Cloern (1982) salt marshes are ideal place for shellfish aquaculture practice, still, in the terms of this study, salt marshes included in the Ramsar Convention were considered unsuitable for siting.
Bathymetry	Bathymetry of a site determines the type of culture system and potential cultured organisms (Silva et al., 2011). Depth, in conjunction with water turbidity and light, may affect chlorophyll concentrations, and consequently, the amount of food available for shellfish at any given depth. Boudry et al (1998) stated that *Magallana* species can be found till 40 m of depth, however, according to Longdill et al. (2008), shellfish may be cultured at depths between 4 and 25 m.
Current speeds	Water is essential for all forms of aquaculture and is a key factor in determining where aquaculture may develop (Aguilar-Manjarrez & Nath, 1998). Water circulation is known to be beneficial to shellfish culture in the supply of dissolved oxygen, food particle and dissipation of waste products, however, slack water and strong currents have detrimental effects (Vincenzi et al., 2006): in farm context, excessive currents increase drags on ropes, lines, trays, or other structures of aquaculture systems (Silva et al., 2011).
Distance to industry	Currently, there are many industries located in the northern margin of the estuary, between Setúbal city and Mitrena peninsula, whose effluents tend to discharge directly in the estuary waters (Coutinho, 2003). This area includes a large heavy-industry belt characterised by many potential polluting activities, being one of

	Portugal's highest concentration of heavy industries (Caeiro et al., 2005; Carreira et al., 2013). This way, an appropriate safety distance to industries is important to screen out.
Distance to beaches	In aquaculture studies, assessing a distance to beaches could provide protection from potential farm pollution (Dapueto et al., 2015); the study area includes estuarine and maritime beaches with high ecological and touristic values (e.g. Tróia bar beaches and Arrábida) (ICNF, 2007); In these terms, a safety distance was applied to these areas in order to preserve them.
Distance to navigational terminals	The maritime traffic in the estuary is mainly associated with the activities in the Setúbal port, situated in the downstream part. It includes 14 navigational/industrial terminals, with two docks, one recreational marina, summer anchorages and ferry boats that daily transport people and vehicles between Tróia and Setúbal, (IMAR, 2012).
Distance to WTP	In the Sado Estuary the water has numerous uses, being one of the most significant the reception of residual and industrial effluents (Ferreira, 2007b). Pollution from urban origins consists in discharges from the sewage network and from the WWTP in Setúbal city (Coutinho, 2003). As of 2019, only Setúbal and Alcácer do Sal have a WWTP, while Tróia discharge directly into the estuary. These areas release excessive loads of nutrients into the water, becoming potential sources of pollution for the farms. This way, a safety distance to these areas is important to screen out.

Thematic maps created from point files (vector and table list) were either interpolated with the Inverse Distance Weighted tool (IDW) within the used estuary mask (i.e. current speeds) or processed through safety buffers created around each point (i.e. Distance to WTP); thematic maps based on polygon files were created by selecting the necessary features (e.g. selecting "industry" from CLC12) (Table 6). The only exception was the estuary bathymetry which represents a raster file. Since the file did not match the estuary mask, even being in the same coordinate system (WGS 1984), it had to be synchronized using R programming software (R Studio), in order to be studied in conjunction with the other layers.

Table 6: Data sources and GIS map types used to assess spatial constraints in the area.

Indicator	Data sources	GIS Map type
Salt marshes	Copernicus (2012)	Polygon
TPA	Defined according to ICNF (2007)	Polygon
Natura Network 2000	EEA (2018)	Polygon
Current speeds	Interpolated data from B2K database	Point
Bathymetry	Provided by Ferreira, J. G. (2018)	Raster
Distance to beaches	Copernicus (2012)	Polygon
Distance to industry	Copernicus (2012)	Polygon
Distance to WTP	Coordinates obtained through APA (2018)	Point
Distance to navigational terminals	DGT (2015)	Polygon

3.3.1.2 Environmental

Estuaries can be distinguished by the instability of environmental conditions, variations in great amplitudes of different parameters such as tides, temperature, salinity, dissolved oxygen, organic substances, nutritive salts, turbidity and multiplication of the various allowing important energetic transfers (Bento, 2008; Lubet et al., 1984). The *Magallana* species are especially well adapted to those fluctuant conditions and their nutritional needs well covered in these estuarine environments (Batista, 2007; Lubet et al., 1984).

As other shellfish, oysters are filter feeders with a key role in estuarine environments (e.g. the improvement of water quality), therefore, high densities of these species might be beneficial to the ecosystem in terms of removal of undesired pollutants from the water column (Forrest et al., 2009; Kjelland et al., 2015). This way, optimal sites for shellfish cultures should be characterised by the conditions leading to relatively enhanced growth rates, since rapid growth and high-quality shellfish are essential for the economic sustainability of the industry (Longdill et al., 2008).

This way, the Environmental category is a result of the group of specific factors on growth and survival of the studied species. Many studies addressed the environmental elements that should be taken into consideration in shellfish aquaculture (e.g. Bacher et al., 2003; Ellis et al., 2002; Inglis et al., 2000; Hatcher et al., 1994; Lin, 2010; MacDonald & Thompson, 1985; Radiarta et al.,2008; Silva et al., 2011), being the ones illustrated in Table 7, the most common among the previous studies.

Table 7: Set of Environmental indicators and respective description.

Indicator	Description
Water temperature	Pacific oysters are poikilothermic organisms, therefore, their metabolism is influenced by water temperature (Batista, 2007). An increase in temperature enhances growth rates, yet, high temperatures can negatively affect during periods of low food availability and positively affect growth when combined with elevated levels of food supply (Kobayashi et al., 1997). Growth of *M. gigas* can occur at temperatures of 5-35ºC, being the optimum temperature between 11-34ºC (Mann et al., 1991). According to Kobayashi et al. (1997), *M. gigas* growth rates reduces significantly at temperatures lower than 8ºC. As for *M. angulata* water temperature for optimal growth ranges between 18ºC-20ºC, according to the results from Portela (2016) for the natural populations in the Sado Estuary, being growth null at temperatures below 10ºC.
Salinity	Water salinity is an important factor for oysters, since it influences respiration and filtration rates and, consequently, its growth (Silva et al., 2011). In the Sado Estuary, salinity values slightly fluctuate in the downstream area due to oceanic currents. On the other hand, in the upper part of the estuary, there is a higher oscillation of salinity values due to river currents (Oliveira & Coutinho, 1992; Portela, 2016). Kobayashi et al. (1997) concluded that *M. gigas* growth and survival is negatively affected at salinity values below 10 ppm and superior to 35 ppm. Some studies (i.e. Bento, 2008; Magro, 2016) addressed the *M. angulata* resistance to salinity values in the same range as the pacific species, being the optimal levels between 20 and 25 ppm.
TPM	Total particulate matter includes both organic and inorganic suspended particles in the water column, controlling the turbidity and transparency of the water; turbidity is as higher as the concentration of suspended particles in the water (Hancock & Hewitt, 2012).
DO	Dissolved oxygen is crucial for shellfish respiration (Kobayashi et al,. 1997). The concentration of oxygen that can be dissolved in the water depends on the temperature of the water, as well as the presence of other substances (Weber et al., 2011). By this fact, water in estuaries holds less oxygen than freshwater environments. Water flow should be considerable when selecting a site. Low DO levels will be of great concern in areas that are stagnant or that receive very little water exchange (Weber et al., 2011). If the oxygen concentration in the water becomes too low, bivalves' circulatory system will cease the oxygen transfer, and begin to use anaerobic metabolism (Weber et al., 2011;Vincenzi et al., 2006). According to Weber et al., (2011) and Vincenzi et al,. (2006) hard clams can maintain respiration levels down to 5 mg L^{-1}.
Chl a	Oysters are filter feeders, feeding on planktonic algae and organic particles on the water column, which are in good conditions for nutrition and growth in estuarine environment (Lubet et al., 1984). Phytoplankton has a photosynthetic pigment, named chlorophyll a (Chl a), that mediates photosynthesis and, consequently primary production (Komorita et al., 2014). Thus, the chlorophyll a indicator is used as a proxy to describe phytoplankton biomass i.e. the food availability for oysters. According to Coutinho (2003), the Sado Estuary has a "low to moderate" primary production. Chl a concentration can oscillate between 2 to 3 mg/m^3 in the downstream area, 5 to 10 mg/ m^3 in the upper area (Marateca Channel) and 20 to 40 mg/ m^3 in the Alcácer Channel (Cabeçadas et., 1994; Coutinho, 1994).
POM	As Chl a, POM is used to assess food availability for oysters, since food sources for bivalves are also represented by organic matter of different origins, nutritive values, sizes and biomass (Müller-Solger et al., 2002). In estuarine environments, POM distribution is highly influenced by hydrodynamics (Secrist, 2013).

According to Inglis et al. (2000), information on environmental conditions to be incorporated into a GIS database is a fundamental step to access the suitability of the study area. Thus, the mentioned survival and growth factors were based on data gathered from BarcaWin2000 database (i.e. a relational database which holds water quality data collected by IPIMAR, as well as historical data obtained in other research projects performed over the years in the Sado Estuary) and, later, interpolated in ArcGIS (IDW tool), to generate the specific thematic map for each indicator. Table 8 illustrates the data source and the GIS map type for each environmental indicator previously mentioned.

Table 8: Environmental indicators data sources and map type.

Indicator	Data sources	GIS Map type
T (ºC)	Interpolated data from B2K database	Point
S (psu)	Interpolated data from B2K database	Point
TPM (mg L^{-1})	Interpolated data from B2K database	Point
DO (mg L^{-1})	Interpolated data from B2K database	Point
Chl a (µg L^{-1})	Interpolated data from B2K database	Point
POM (mg L^{-1})	POC to POM conversion: POC = 0.38POM (Grant & Bacher, 1998).	Point

3.3.1.3 Socio-economic

Socio-economic factors are here described as activities of human involvement which have a direct relation with operations for aquaculture activities (e.g. Nath et al., 2000; Lin, 2010; Radiarta et al., 2008). The Socio-economic category assesses distance between facilities (i.e. farms) to urban areas, piers and roads. These are important to evaluate when selecting a site for aquaculture, because all increase efficiency of farm operations: farms should be located at reasonable distances of labour sources and market infrastructures, not only to retail or acquire the product but, as well, to guarantee that enough people are involved in the operations; additionally, roads should be as close as possible to facilities in order to connect them to these infrastructures;

The selected category was named "Socio-economic" due to the interaction of social and economic factors. Moreover, literature review also played part in the name selection (i.e. Bay, 2010; Hossain et al., 2007). The table below (Table 9) provides a more detailed description of each indicator used in the study.

Table 9: Set of Socio-economic indicators and respective description.

Indicator	Description
Distance to urban areas	Distance to urban areas is important as they are a source of supplies, labour and could be also valuable markets for trade (Falconer et al., 2016). Aguilar-Manjárrez & Nath (1998) stated that, the larger the population the greater potential market for farmed fish. This way, urban market centres are potential locations for marketing of cultivated species (Kapetsky & Nath, 1997).
Distance to roads	Farm locations could be influenced by distance to roads in terms of access and transport networks (Falconer et al., 2016). According to contacted oyster producers, accessibility is important for aquaculture practices as it is important for seed production and transportation of broodstock and juveniles.
Distance to ports	In this study, ports have the same meaning as piers. Some authors (e.g. Serra, 2017) addressed the importance of this indicator in the way of accessibility to unload products, since transportation in estuaries is also made by boat. The city of Setúbal includes a port, very important on a national level, which contributes to the development of the industrial development of the area and the logistics of market products (Moreira, 2015).

Table 10 describes the data sources of each socio-economic indicator to be used in the GIS: Urban areas and piers were achieved by polygon files from DGT's Soil Occupation Chart (COS2015); and Roads were collected in a line format from OpenStreetMap database (2018) based off Infraestruturas de Portugal (IP, S.A.) thematic map;

Table 10: Socio-economic indicator data sources and map type.

Indicator	Data sources	GIS Map type
Distance to urban areas	DGT (2015)	Polygon
Distance to roads	OpenStreetMap (2018)	Line
Distance to ports	DGT (2015)	Polygon

3.3.1.4 Product Quality

Heavy metals are widespread and persistent in aquatic ecosystems, potentially toxic, since they can be adsorbed by suspended solids, then strongly accumulated in sediments and biomagnified along aquatic food chains (Suresh et al., 2012; Tang et al., 2014). Cupped oysters, like other shellfish, can remove heavy metals (e.g. Hg and Cd), as well as biotoxins (microscopic toxic phytoplankton) from surrounding water (Quayle, 1969); thus, due to their filtrating nature, the amount of heavy metals accumulated in their soft tissues might arise a problem to public health (Magro, 2016).

Most estuaries receive a high heavy metal input from industries and the Sado estuary is an example of that situation (Caeiro et al., 2005; Coutinho 2003; Dias, 1994). As stated before, the northern channel represents a highly industrialized area, where discharges are made into the estuary (Caramelo et al., 2011; Coutinho, 2003). Adding to that fact, the estuary has history of mining activities and pyrite outcrop erosion that have contributed to the input of metals, such as Cd, Zn, Cu and locally Hg and Pb (Lillebø et al., 2011);

This way, the Product Quality category addresses metal pollution as a variable that influences the product quality of shellfish aquaculture (e.g. Silva et al., 2011; Silva & Batista, 2008). Indicators were chosen according to the most representative metals in study area which can be assimilated by shellfish and, consequently, represent a risk to human health (Table 11). Additionally, organic compounds such PAH's are identified as an environmental factor that influence product quality of shellfish aquaculture (Silva et al., 2011), therefore, included in this category.

Table 11: Most representative pollutants in the Sado Estuary by sources, bio-processes and effects.

Pollutants	Sources in the estuary	Bioaccumulation	Biomagnification	Effects
As	Industrial discharges and agriculture (e.g. pesticides and herbicides) [1,2,3]	No [2]	No [2]	Not defined [2]
Cd	Industrial discharges and mining activities [3,4]	Yes [2,8,11]	Yes [2,8,11]	Liver and kidneys [2.8]
Cu	Industrial discharges, mining activities and Antifouling paints and coatings for ship [3,4]	No [9]	No [9]	Kidneys [9]
Hg	Industrial discharges [5,6]	Yes [4]	Yes [4]	Neurotoxic, carcinogenic and mutagenic [4,10,11]
Pb	Industrial discharges, wastewater and mining activities [1,4]	Yes [4]	No [4]	Kidneys, bone narrow and nervous system [4,10,11]
Zn	Industrial discharges and mining activities [3,6]	No [2]	No [2]	Abdominal pain, nauseas and pancreas damage [12]
PAH's	Wastewater and ship traffic [7]	Yes [13]	Yes [13]	Kidney and liver [14]

[1] Caeiro et al., (2005)
[2] Magro (2016)
[3] Hidroprojecto (2000)
[4] Oliveira (2012)
[5] Ferreira et al (2007b)
[6] Sousa et al. (2006)
[7] Martins et al. (2008)
[8] Silva & Batista, (2008)
[9] Kramárová et al. (2005)
[10] Goyer et al. (2004)
[11] Goyer & Clarkson (2001)
[12] ATSDR (2005)
[13] Bouloubassi et al. (2006)
[14] Rengarajan et al. (2015)

Caeiro et al. (2005) collected samples at the sediment level in order to assess its quality, in terms of metal contamination. Henceforth, metal concentrations studied in the present work were based off the mentioned paper. Since no coordinates regarding the sampling sites were found, as they were only mapped in the work, the stations were pinpointed using Google Earth Pro. Despite this not being the most efficient mapping procedure, it has been used in other site selection studies (e.g. Serra, 2017). PAH's values were gathered from 5 sampling sites from Carreira et al. (2013), in contrast with the 71 sites from Caeiro et al. (2005) (see Product Quality thematic maps in Annex B).

Afterwards, all gathered values were mapped in the GIS, and each point file (Table 12) interpolated with the IDW tool, achieving the distribution of the specified pollutants over the whole estuary mask. This follows the same procedure used in the Environmental and Spatial Constraints (i.e. Current Speeds) categories.

Table 12: Product Quality indicator data sources and map type.

Indicator	Data sources	GIS Map type
As in the sediment	Caeiro et al. (2005)	Point
Cd in the sediment	Caeiro et al. (2005)	Point
Cu in the sediment	Caeiro et al. (2005)	Point
Hg in the sediment	Caeiro et al. (2005)	Point
Pb in the sediment	Caeiro et al. (2005)	Point
Zn in the sediment	Caeiro et al. (2005)	Point
PAH’s in the sediment	Carreira et al. (2013)	Point

3.3.2 Stage 2: Suitability and constraint maps generation

The second stage of the MCE methodology focused on the generation of the final suitability and constraint maps, based off the thematic maps previously created. Figure 6 illustrates the schematic GIS process of Stage 2.

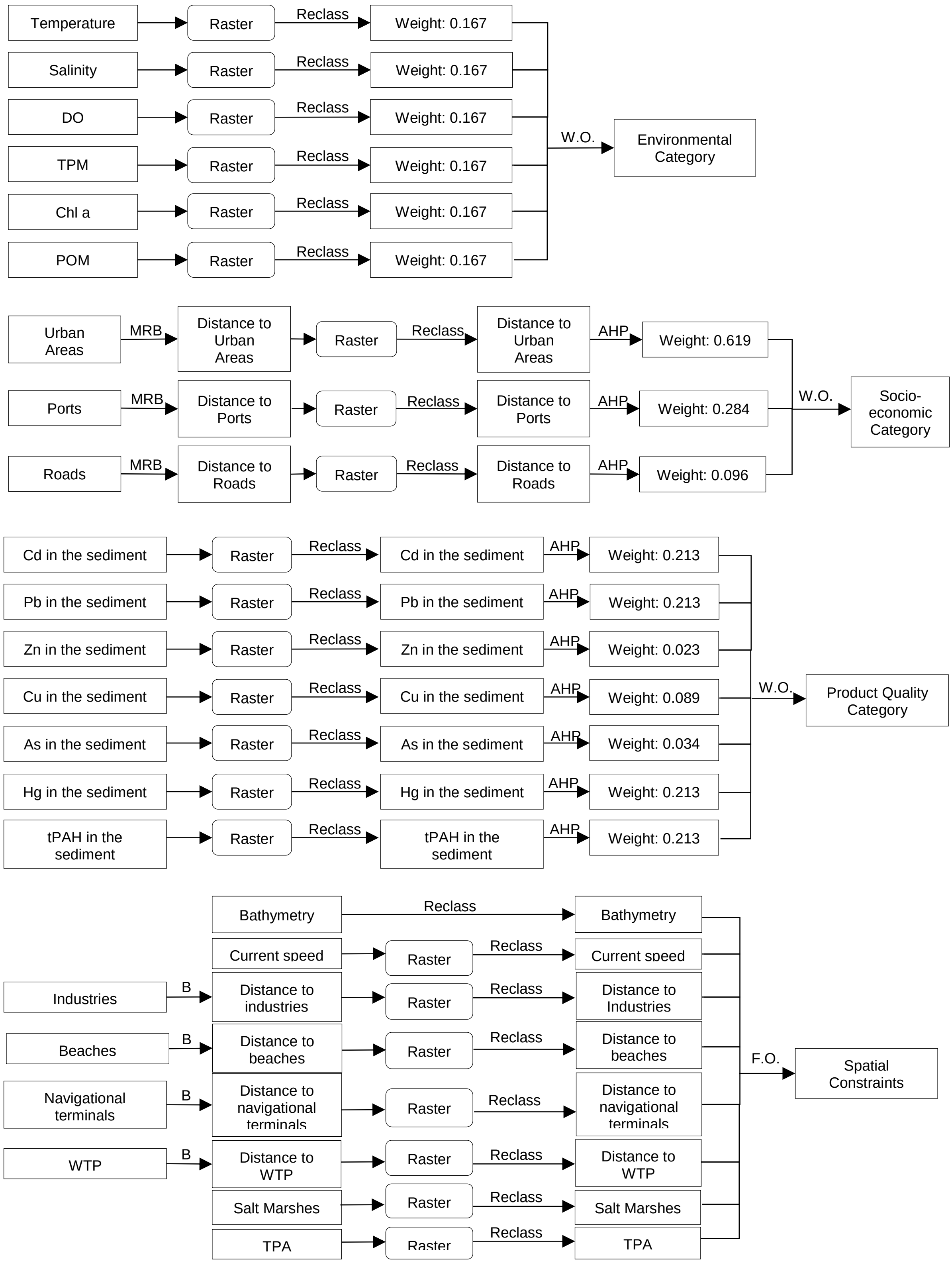


Figure 6: GIS methodology used in Stage 2. B – Buffers; MRB – Multiple Ring Buffers; AHP –Analytic Hierarchy Process; W.O. – Weighted Overlay; F.O. – Fuzzy Overlay;

As shown in the figure above (Fig. 6), thematic maps based on water and product quality (Environmental and Product Quality categories, respectively) were achieved through the Inverse Distance Weighted (IDW) tool; this interpolation determines cell values using a linearly weighted combination of a set of sample points (Phillip & Watson, 1982). It implements the assumption that things closers to one another are more alike than those farther apart (Nagalakshmi et al., 2016).

The IDW tool is a simple interpolation tool used in many fields, as its outputs are influenced by two factors: i) the distance between known to unknown points; and ii) is proportional to the inverse distance raised to a power value, which is adjustable in GIS software's (Musashi et al., 2018; Pham & Van, 2016).

For this study, was used the IDW standard power value of 2 (ArcGIS "p value"), due to the computing system used to elaborate the maps; by defining a higher power value, more emphasis can be put on the nearest points (Watson & Phillip, 1985). Thus, nearby data will have the most influence, and the surface will have more detail (be less smooth), implying more storage for highly detailed outputs, which the software could not support. Supporting this decision (i.e. power value of 2), according to the studies of Musashi et al. (2018) and Pham & Van (2016), using IDW interpolation method with the same values of other factors, a value of 2 provided more accurate results when studying values from equal number of sampling points, when compared to power values wavering from 1 to 6.

As for Buffers and Multi-Ring Buffers, these were applied to several thematic maps in order to define unsuitable areas (for Spatial Constraints) or to define distances with different importance concerning the site selection (Socio-economic category).

Afterwards, all the thematic maps were converted to raster format and reclassified to a common scale, based on literature review. Finally, indicator and category weights were calculated according to a weighting methodology used in previous aquaculture studies (i.e. Analytical Hierarchic Process).

3.3.2.1 Application of Buffer and Multiple Ring Buffer

Buffers and Multiple Ring Buffers (MRB) were applied to study socio-economic factors and spatial constraints. These tools are important to create a specific distance(s) from selected input features which, in this work, are the human activities that effect shellfish aquaculture activities (i.e. Distance to Urban Areas, Ports and Roads) or that might represent an obstacle to other current activities (i.e. Distance to Navigational Terminals and Beaches). Table 13 shows the detailed explanation for the application of buffering tools for each socio-economic factor and specific spatial constraint.

Table 13: Buffer application and respective justification.

Indicator	Buffer application
Urban areas	Along the Sado Estuary margins, there are small villages (e.g. Carrasqueira, Murça and Gâmbia) which fisheries and aquaculture represent important activities for its economy. Additionally, the city of Setúbal is the most populated area within the estuary. These urban areas can represent valuable labour and market sources, therefore, important to study when selecting a site for aquaculture. Even though studies like Giap et al. (2005) consider population density and market assessment as different criteria, in this work, both are included in urban areas criterion, and suitability was analysed through MRBs with values adapted from Falconer (2016) and Giap et al. (2005).
Roads	Roads are here addressed in terms of access and transportation networks for aquaculture products (e.g. Falconer, 2016; Hossain et al., 2008). As other site selection studies (e.g.. Giap et al., 2005; Falconer, 2016; Hossain et al., 2008) only major roads were accounted, and MRB values were defined according to the literature previously mentioned. Such as urban areas, suitability for farm location is higher once closer to roads, decreasing with higher distances.
Ports	Ports or piers are infrastructures that provide boat transportation of people and products to places within the country or overseas (Serra, 2017). This way, ports are here addressed as means to commercialize aquaculture products, and a MRB was applied to illustrate specific distances to these areas. Values were adapted from Lin (2010) and Saunders et al. (2017).
Industry	As mentioned before, the Sado Estuary contains an industrialized belt along the northern margin, whose discharges have negative impacts in the ecosystem (Caeiro et al., 2005; Coutinho, 2003; Portela, 2016). Industries represent a high input of metals

	and organic matter, which might have a negative impact in aquaculture species when compound values are over their threshold limits. This way, a safety buffer is applied to these industrialized areas, to prevent product contamination by industrial effluents. Buffer value was gathered from Saunders et al. (2017).
Beaches	The Tróia bar is composed by beaches with high cultural and touristic value, therefore, there is a need of preservation and prevention from farm pollution (Dapueto et al., 2015). The same safety distance was applied by Serra (2017), but in terms of avoiding theft situations.
Navigational terminals	Aquaculture activities should not interfere with boat transportation within the estuary (APA, 2014). This way, navigational terminals are considered as all the areas along the estuary margins reachable by boat. The applied buffer distance was adapted from Saundres et al. (2017).

Moreover, to illustrate the suitability score of the created buffers, each indicator was converted to raster format and then reclassified into common values (1 – 4), found on literature.

3.3.2.2 Reclassification

To evaluate suitability, each thematic map (displayed in raster format) was reclassified into a common scale. As stated by Falconer et al. (2016), a fundamental part of model development is deciding the most appropriate reclassification method to use; therefore, for this work, the selected reclassification methods were: i) a user-defined classification: values are specified within suitability classes (Eastman, 2012); and ii) Boolean method, that displays all land uses in a binary format method (1 – Suitable; 0 – Not Suitable) (Eastman, 1999);

User-defined classification is one of the most used reclassification methods in aquaculture studies (e.g. Giap et al., 2005; Falconer et al., 2016; Hossain et al., 2009), and it is useful as it provides a clear view of suitability classes, supporting the decision-making process (Falconer et al., 2016). Suitability values were defined according to the literature in Table 14, and suitability scores according to Giap et al. (2005):

- **Not Suitable (1):** Data whose values are above or under the specified thresholds for oyster growth, survival and quality. It also represents socio-economic factors which require considerable cost and time in aquaculture operations and, therefore, worthless for farm siting;

- **Moderately Suitable (2):** Values are between the threshold limits, however, far from optimal for oyster growth, quality and production;

- **Suitable (3):** Provides good conditions for oyster aquaculture in the study area, where values are between a scale considered good for oyster growth, quality and production;

- **Highly Suitable (4):** Represents the optimal values for oyster aquaculture. Describes the environmental values that enhance oyster growth, less contamination from existing pollutants and proximity to places that provides the necessary needs related with farm operations;

Reclassification of spatial and regulatory constraints was based on a Boolean method. This method was used to screen out all the areas within the estuary where oyster farms cannot be located due to other land uses and, consequently, take knowledge on the maximum areas where aquaculture can be practised:

- **Not suitable (0):** Unsuitable areas for oyster farming are represented by a thematic map gathering all the identified constraints within the study area;

- **Suitable (1):** Suitable areas are represented as the maximum possible areas where oyster aquaculture can be practised without legal or spatial interferences.

Table 14: Reclassification table of Categories and respective suitability scores.

Variable	Units	Maps data range	Data source	Suitability score 1	2	3	4	Suitability source
Environmental								
Water temperature	ºC	13.7 – 23.7	1	< 10	10 – 18	18 – 22	22 – 27	4, 5, 7, 11
Salinity	psu	27.6 – 37.8	1	< 8	8 – 28	35 – 42	28 – 35	4, 7, 11, 15
DO	mg L^{-1}	5.1 – 9.6	1	< 1.4	1.4 – 4.8	> 4.8	-	19, 16
TPM	mg L^{-1}	3.9 – 74.4	1	> 192 and < 5	50 – 192	25 – 50	5 - 25	8, 20
Chl a	µg L^{-1}	0.7 – 8.3	1	< 1 and > 55	1 – 5	5 – 12	12 – 50	4, 15, 10
POM	mg L^{-1}		1	< 1 and > 55	1 – 5	5 – 12	12 – 50	4, 15, 10
Product quality								
Cd in the sediment	ppm	0.2 – 8	2	> 4.21	0.68 – 4.21	-	< 0.68	2,
Pb in the sediment	ppm	2 – 68.7	2	> 112	30.2 – 112	-	< 30.2	2, 21
Zn in the sediment	ppm	2.4 – 502.5	2	> 271	124 – 271	-	< 124	2, 21
Cu in the sediment	ppm	1.1 – 190	2	> 108	18.7 – 108	-	< 18.7	2, 21
As in the sediment	ppm	1.2 – 57.6	2	> 41.6	7.24 – 41.6	-	< 7.24	2, 21
Hg in the sediment	ppm	0.02 – 0.65	2	> 0.7	0.13 – 0.7	-	< 0.13	2, 21
tPAH in the sediment	ppb	19.6 – 1,077	3	> 16 770	1,684 – 16,770	-	< 1684	3, 22
Socio-economic								
Distance to urban areas	km	-	-	< 1 and 10 – 15	4 – 10	2 – 4	1 – 2	12, 14, 20
Distance to roads	km	-	-	> 1.5	1 – 1.5	0.5 – 1	< 0.5	6, 14
Distance to ports	km	-	-	> 8 and < 0.5	6 – 8	4 – 6	0.5 – 4	20, 6
Spatial constraints				**Boolean variables (0 – Not suitable; 1 – Suitable)**				
Bathymetry	m	0.4 – 3.6		Not suitable: < 0.4 and > 3.6; Suitable: 0.4 – 3.6				9, 18
Current speeds	m s^{-1}	0.01 – 0.52		Not suitable: < 0.02 and > 1; Suitable: 0.02 – 1				3, 18
Distance to industry	km	-		Not suitable: > 1; Suitable: < 1				20
Distance to beaches	m	-		Not suitable: < 500; Suitable: > 500				13
Distance to navigational terminals	m	-		Not suitable: < 500; Suitable: > 500				n/d
Distance to WTP	m	-		Not suitable: < 500; Suitable: > 500				13, 20
Natura 2000	-			*				21
Salt Marshes	-			Excluded				21
TPA	-			Excluded				21

*not included in the site selection thematic map

[1] BarcaWin 2000
[2] Caeiro et al. (2005)
[3] Silva et al. (2011)
[4] Kobayashi et al. (1997)
[5] Portela (2016)
[6] Lin (2010)
[7] Batista (2007)
[8] Bayne et al. (2017)
[9] Longdill et al. (2008)
[10] Roland & Brown (1990)
[11] Mann et al. (1991)
[12] Falconer et al. (2016)
[13] Dapueto et al. (2015)
[14] Giap et al. (2005)
[15] Cho et al. (2012)
[16] Vaquer-Sunyer and Duarte (2008)
[17] Ferreira et al. (2007a)
[18] Vincenzi et al. (2006)
[19] Weber et al. (2011)
[20] Saunders et al. (2017)
[21] ICNF (2007)
[22] Carreira et al. (2013)

3.3.2.2.1 *Spatial Constraints*

Spatial constraints were reclassified by values of 0 and 1, screening out areas that are, respectively, unsuitable and suitable for aquaculture site selection. Highly sensitivities areas, such salt marshes and total protected areas, possess favourable environmental conditions for shellfish, yet, in the Sado Estuary these are excluded by law and farms cannot be included in them.

Effluents from industries and WTP might represent pollution inputs for shellfish, therefore, according to literature review, farms should not be located within a specified distance to these infrastructures. Above that distance suitability is achieved, as farms should be safe from contamination.

Culture management practices were reclassified according to the extensive type of shellfish aquaculture. Suitable depths for oyster extensive culture ranged from 0.4 to 3.6 m. The purpose was to outline intertidal areas, as reclassification values were achieved from the Tide Table of 2018, published by Porto de Setúbal (Setúbal's port management institution). Value feasibility was proved by literature review and contacted oyster producers in the estuary.

3.3.2.2.2 *Environmental Category*

Environmental thresholds were adapted to both Portuguese and Pacific oysters, not only due to hybridization and taxonomical relation, but since survival factors are mostly studied for the *M. gigas* species, in contrast with the *M. angulata*, which lacks on studies concerning its survival and growth limits. This way, both oysters were used as a single model and reclassification values are equal among them. Some of the defined thresholds were already addressed in Table 7. Regarding:

i) **Water Temperature:** under 10 ºC (score 1) shell growth and gamete development is highly affected, as oyster metabolic function would cease (Batista, 2007; Mann et al., 1991). Optimal temperatures (score 4) ranged from 22 to 27ºC since, according to the studies of Buitrago et al. (2005) and Kobayashi et al. (1997). These stated that survival and reproductive rates are higher within these values;

ii) **DO:** adult hard clams can maintain metabolic functions to concentrations down to 1.4 mg L^{-1} (score 1), yet, aerobic metabolism is declined at levels under 4.8 mg L^{-1} and anaerobic metabolism becomes increasingly important (Weber et al., 2011). Above the mentioned these valuables was applied a score of 3;

iii) **Salinity:** oysters can survive a broad range of salinity levels (Batista, 2007); according to Brown (1986), concentrations below 8 psu are critical for oyster growth and studies have revealed mortality events in larvae and juveniles under these levels. According to Mann et al. (1991) and Batista (2007), 28 to 35 psu is considered optimum for larvae rearing and growth of *angulata*; being 35 psu the optimum value (4) for *gigas* growth;

iv) **Chl a and POM:** both are considered food sources for shellfish and were reclassified according to the Habitat Suitability Index (HSI) defined by Roland & Brown (1990). Chl a and POM levels below 1 ug L^{-1} and mg L^{-1}, respectively, represent low concentrations of available food for oysters and will highly compromise their growth. Hence, areas comprising these values are considered unsuitable (score 1), since food availability is not significant enough to guarantee proper oyster feeding (Roland & Brown, 1990).

iv) **TPM:** corresponds to suspended particulate matter (SPM) since oysters are filter feeders. This encompasses both inorganic and organic matter and will, consequently, influence available food sources. TPM concentrations below 5 mg L^{-1} will affect oyster growth as well as above to 192 mg L^{-1}, due to clogging and cession of filtration rate (Bayne et al., 2017).

3.3.2.2.3 *Socio-economic Category*

Reclassification of social and economic factors was solely based on literature review; Distance to ports was the only adaption to the studied buffers because the main port in the estuary comprises several boat terminals and, therefore, important to pinpoint the fact that boat transportation can be affected. This way, a distance of 500 m was considered unsuitable to ports, as applied to navigational terminals.

3.3.2.2.4 *Product Quality Category*

To assess product quality, reclassification was adapted from the Sediment Quality Guidelines (SQG) defined in Macdonald et al. (1996). Studies in the estuary (i.e. Caeiro et al., 2005 and Carreira et al.,

2013) also use these guidelines to determine sediment metal pollution, so, this reclassification method was selected to provide results in accordance with the previous mentioned studies. In addition, reclassification scores using PEL and TEL values followed the approach used by Serra (2017) and can be found in Table 15.

Table 15: Product quality reclassification and description (adapted from Serra, 2017).

Range of PEL and TEL values	Reclass value	Description
< TEL	4	As stated by McDonald et al. (1996) below the TEL there are no toxicity effect on benthic organisms, hence, was attributed a score of 4, outlining where the healthiest communities can be found, as well as the less contaminated areas on which the culture can be performed;
TEL – PEL	2	Reclassification of values between the TEL and PEL followed the precision used by Serra (2017) and, as stated by the same author, these can be considered controversial; the guidelines stipulate 3 classification methods where toxicity can be effective at levels above the PEL, but represent no harm to benthos when these are below the TEL. Hence, these where considered to be Moderately Suitable to avoid possible contaminated areas that could be classified as Suitable (3) (Serra, 2017).
> PEL	1	As mentioned above, PEL concentrations represent adverse effects to aquatic organisms. Therefore, was given a reclassification value of 1, being considered unsuitable for shellfish production since water and sediment might be contaminated.

Despite studies on Pacific oyster aquaculture (e.g. Silva et al., 2011) addressed product contamination using the thresholds defined in NOAA Guidelines (i.e. Long & Morgan, 1991); the ERM and ELM levels use the 10 and 50% of metal concentration that might affect the benthic communities, representing much lower thresholds (Long & Morgan, 1991).

3.3.2.3 Analytic Hierarchy Process (AHP)

The Analytical Hierarchy Process (AHP), created by Saaty (1980), is an effective tool to decompose a problem into several criteria and develop a set of relative weights, that represent the importance given by the decision-maker to each criterion, in order to make it easier to understand and evaluate (i.e. higher weights mean higher relative importance) (Saaty, 1980, 2008); for each factor, weights are achieved through pairwise comparisons among other factors of the same hierarchic levels (Nath et al., 2000; Hossain et al., 2007; Saaty, 1980).

This method has been used in many aquaculture site selection studies over the years (e.g. Falconer et al., 2016; Nath et al., 2000; Hossain et al., 2007, 2009; Salam et al., 2003; Serra, 2017), due to its ability to provide a logical framework for comparison of different criteria, supporting the decision-making process (Nath et al., 2000; Salam et al., 2003). In addition, the AHP allows the validation of the consistency of the selected evaluations, reducing the bias from the process (Hossain et al., 2007, 2009).

For the purpose of this work, the AHP is divided in two parts: i) to weight all indicators, from each category, and generate category suitability maps; and ii) weight of each category and assemble the final suitability map (this second part will be described in Stage 3);

3.3.2.3.1 *Environmental Indicators*

Studied environmental criteria were credited equal importance (16.7%), since all have a crucial role for oyster growth and survival. Consequently, the AHP was not needed to calculate the weights for these criterions.

3.3.2.3.2 *Socio-economic Indicators*

Relative importance for Socio-economic factors was based off literature review and the opinion of oyster producers in the study area (Table 16): Distance to ports was credited with highest relative importance due to boat transportation of fishermen and product to places within the country or overseas; despite product transportation, within the estuary, being mostly done by car, Distance to Roads was credited the lowest importance since the estuary holds shortage of roads along its margins. Urban areas weighted in-between of both factors, since they represent valuable sources of labour and marketing of the product.

Table 16: AHP concerning socio-economic factors.

	Distance to Ports	**Distance to Urban Areas**	**Distance to Roads**	**Weights**
Distance to Ports	1	3	5	0.619
Distance to Urban Areas	1/3	1	4	0.284
Distance to Roads	1/5	1/4	1	0.096
Consistency Ratio (CR) = 0.07				

A Consistency Ratio of 0.07 (Table 10) is below the 10% recommended by Saaty (1980), proving the viability of the achieved weights.

3.3.2.3.3 *Product Quality Indicators*

Credited importance to metals influencing product quality was mostly based off the Priority List of Hazardous Substances (ATSDR, 2015), developed by ATSDR (Agency for Toxic Substances and Disease Registry Division of Toxicology and Human Health Sciences) and EPA (Environmental Protection Agency). A Substance Priority List consists of organizing, in order of priority, the substances that are most commonly found at facilities on the National Priorities List (NPL) and which are determined to pose the most significant potential threat to human health due to their known or suspected toxicity and potential exposure at these NPL sites (ATSDR, 2015).

However, some adaptions were made according to the results of Caeiro et al. (2005) and Magro (2016), in order to provide a more accurate overview of the product contamination scenario in the estuary. The table below describes the methodology behind each pair-wise comparison (Table 17).

Table 17: Relative importance given to the pollutants in study.

Pollutants	**Description**	**Relative importance**
Cd, Pb, Hg, tPAH	Cadmium, Lead, Mercury and PAH's are within the first 9 scores of the SPL list, representing the most toxic elements to human health (ATSDR, 2015). In addition, the Portuguese agency IPMA classifies bivalve production areas and controls its harvest through the analysis of these four compounds on samples acquired in these production areas. To achieve this, the agency follows the EU legislation which: i) sets guidelines for sampling methods (Order nº 853/2004; Order nº 854/2004); and ii) limits for heavy metals (Order nº 1881/2006); and iii) PAH's (Order nº 1125/2015);	Highest ↓
Cu	The estuary comprises high concentrations of copper and, according to Magro (2016), high concentrations of this compound were found on samples of both *Magallana* oysters in the main beds. Even though it represents the least toxicity of the all studied	Lowest

	metals (rank 118 in the SPL), was credited a higher relative importance, when compared to the ones below, due to the reasons explained above and their capacity to damage human health when in high concentrations.	Highest
As	Despite scoring the number 1 on the SPL rank and being one of the main pollutants of the estuary (i.e. Caeiro et al., 2005), no legislation stipulates maximum levels of this metal in fisheries products, as its toxicity on *M. gigas* and *M. angulata* could not be assessed in Magro (2016). Due to this uncertainty, arsenic was credited the least importance, followed by zinc.	
Zn	As arsenic and copper, zinc is processed by the human organisms. *M. gigas* and *M. angulata* samples from the Sado Estuary (i.e. Magro, 2016) are rich in zinc, and the large consumption of this element lowers cadmium levels in the organism, concluding that consumption of these species arises a lower risk to human health. In these terms, was attributed with the lowest relative importance. To support this, zinc scored the 75th rank in the SPL, representing the least toxic element when compared with the ones above (except for copper) (ATSDR, 2015).	Lowest

Established the relative importance for each criterion, pair-wise comparisons were performed in order to achieve the specific weights, as shown in Table 18. Further explanations on how the AHP works can be found in Annex C.

Table 18: AHP for Product Quality category.

	Cd	**Pb**	**Zn**	**Cu**	**As**	**Hg**	**tPAH**	**Weight**
Cd	1	1	8	4	6	1	1	0.213
Pb	1	1	8	4	6	1	1	0.213
Zn	1/8	1/8	1	1/6	1/2	1/8	1/8	0.023
Cu	1/3	1/3	6	1	5	1/4	1/4	0.089
As	1/6	1/6	2	1/4	1	1/6	1/6	0.034
Hg	1	1	8	4	6	1	1	0.213
tPAH	1	1	8	4	6	1	1	0.213
Consistency Ratio (CR) = 0.04								

The Consistency Ratio of 0.04 is within the ratio of equal to or less than 0.10 recommended by Saaty (1980), suggesting a small probability that the weights were developed by chance.

3.3.2.4 Weighted and Fuzzy Overlay tools

Achieved all criteria weights, each criterion was combined through weighted linear combination (WLC) tools, and final category maps were generated. According to Dapueto et al. (2005), the WLC is one of the most used decision methods in GIS studies, since it is easy to apply using map algebra and geospatial overlay. Even though it can be performed to vector and raster files, for this work, all thematic maps were converted to raster format (if they weren't in this format already) because GIS software's hold more information while in this format (Dapueto et al., 2005).

The WLC evaluates criterion suitability through function (5), as described in Malczweski (2000).

$$S = \sum_j w_i \, x_{ij} \quad (5)$$

Where:
w_i = criterion normalized weight, achieved through the AHP;
X_i = respective suitability score (1, 2, 3 or 4);
S = Criteria suitability;

Spatial Constraints criteria were reclassified through a Boolean method and combined by a Fuzzy Overlay tool in ArcGIS; was applied an "AND" operator which returns the minimum value of the sets the cell location belongs to.

3.3.3 Stage 3: Site Selection

The third stage of the MCE methodology focus on the generation of the final site selection map. To achieve this, an AHP (Part two) was performed to determine the specific weights at the category level, followed by Weighted Overlay tool and the intersection with the identified constraint in the study area.

3.3.3.1 Analytical Hierarchic Process – Part two

The second part of the AHP methodology followed the same procedure applied in the first part, but this time, pairwise comparisons were performed at the level of the category in order to achieve a relative weight.

Importance given to each category was accomplished by literature review, as well as, the opinion of queried oyster producers. Every farmer and stakeholder agreed that the environmental factors of the estuary are the main reason to guarantee that oyster can grow, and business can maintain. Therefore, was credited with the highest relative importance.

Following, the Socio-economic category was given a relative weight an influence of 30% (weight equal to 0.3), because they highly influence operations in aquaculture activities and evaluate the distance to infrastructures upon which aquaculture activities depend, such as roads or piers. Both are very important for an efficient transportation of harvested product and fishermen, as well as to reduce transportation costs; urban areas comprise people able to participate in labour activities, including as well, local markets where the product can be sold;

Product Quality category evaluates anthropogenic points of pollution within the Sado Estuary that influence the quality of the shellfish harvesting and production areas. This category was attributed the least importance since it is the easiest one to avoid or minimize: shellfish aquaculture siting just must avoid contaminated areas. In addition, the uncertainty of the values, as well as their reclassification method, supports the relative importance attributed.

Table 19: AHP concerning all identified categories.

	Environmental	**Socio-economic**	**Product Quality**	**Weights**
Environmental	1	2	6	0.575
Socio-economic	1/2	1	5	0.343
Product Quality	1/6	1/5	1	0.082
Consistency Ratio (CR) = 0.03				

Consistency Ratio of 0.03 proves the feasibility of the judgements in study (<10%), according to the statements of Saaty (1980).

3.3.3.2 Site Selection map

The final step of the GIS procedure was the application of a Weighted Overlay tool to the weighted category, followed by the intersection with the results of the Boolean constraints. This procedure is displayed in the following figure (Fig. 7).

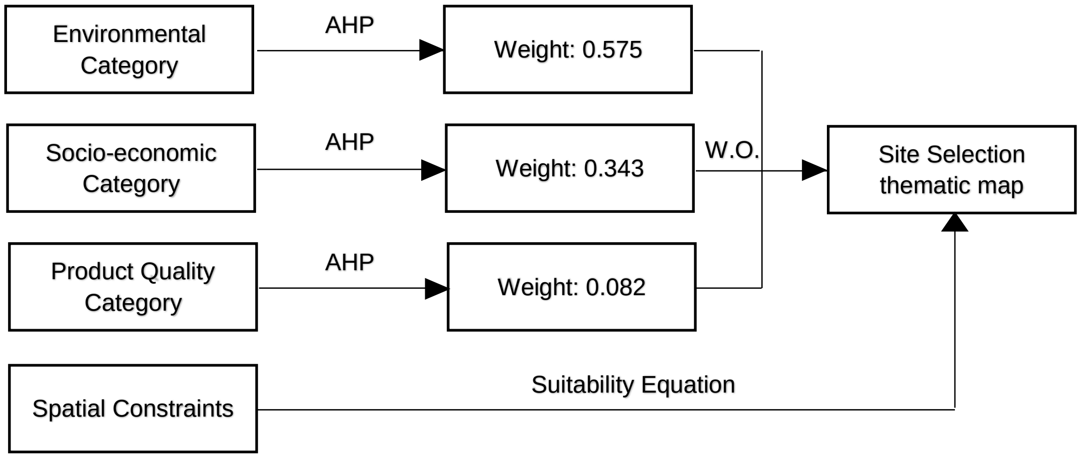


Figure 7: Stage 3 used methodology for obtaining the final site selection map for shellfish aquaculture; W.O – Weighted Overlay.

Suitability was achieved by the intersection of the Weighted Linear Combination (WLC), otherwise defined as Weighted Overlay, and the product of Boolean constraints (Eastman, 1999), as represented in Eq. (6).

$$\text{Suitability} = \sum w_i X_i * \prod C_j \tag{6}$$

Where:
w_i = weight assigned to factor i;
X_i = criterion score of factor i;
C_j = constraint j;

This way, Eq. (6) can be divided into two different parts, where the first one focus on the multiplication of each category to its relative weight and the second one adds the Boolean multiplication (0 to the unsuitable areas and 1 to the suitable ones).

Since all Spatial Constraints were mixed together using a Fuzzy Overlay, the second part is not exactly as defined in the equation, and can be rewritten as, Eq. (7):

$$\text{Suitability} = \sum w_i X_i * \text{SC} \tag{7}$$

Where:
w_i = weight assigned to factor i;
X_i = criterion score of factor i;
SC = Spatial Constraints;

By applying the Suitability Equation (Eq. 7), through GIS tools, Suitability is going to be equivalent to final the site selection map. In ArcGIS, this was achieved using the Raster Calculator tool.

3.3.4 Stage 4: Dynamic modelling

The last stage of the whole methodology focused on the application of the FARM model (Chapter 2.7) on potentially suitable sites retrieved from the site selection thematic map. Despite this work addressing site suitability for both Pacific and Portuguese oysters, the dynamic model could only be tested for *M. gigas*, since no individual growth models are included in FARM regarding *M. angulata*.

This way, the model for Pacific oyster production was applied in those areas considered to be Suitable for aquaculture (i.e. score 3 in the suitability scale), since these represent less polluted areas (i.e. heavy metal pollution), gather the best environmental conditions for growth and are, generally, less resource intensive (i.e. require least investment when compared to unsuitable or moderately suitable areas).

Henceforward, the first step of this analysis resumed in identifying the possible areas where the conceptual farms could be established. According to Shumway (2011), a farm is an integrated production unit subjected to specific pressures and impacts. For each farm, the number of sections and dimension were selected, though, according to Ferreira et al. (2007a), the total area should not exceed 5000 m^2 per farm.

In order to include environmental drivers on FARM (Water temperature, DO, Salinity, Chl, POM, TPM and DIN), data was gathered from two different B2K stations (#8A and IH3, respectively) (Fig. 8). Only superficial samples taken from a depth of 0.5 to 1.5 m were considered and used in the calculations, since only intertidal cultures are being addressed.

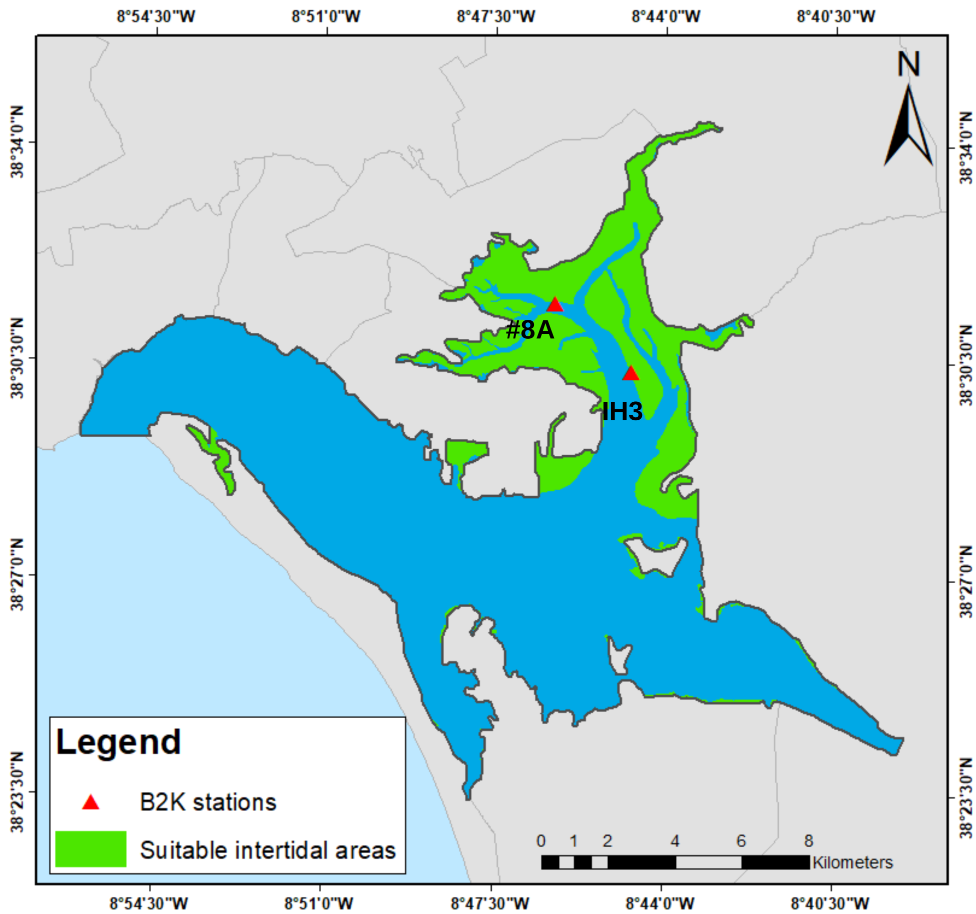


Figure 8: Location of both B2K stations used to extract environmental drivers.

The model was simulated for (intertidal) bottom culture for a stocking density of 100 ind m^{-2} (standard value), over a culture period of 365 days. Selected values for seed cost per kg and sale price per kg were the default ones, as well as seed and harvest TFW. Natural mortality was assumed to be 35% per year. Semi-diurnal tides were also applied. Biodepositional effects were not considered for the study.

Data on peak current at spring and neap tide was adapted from Rosa (2010), as well as the tidal ranges (Table 20). Environmental inputs for both test farms are displayed in Annex D.

Table 20: FARM drivers for each test farm and respective type of tide.

FARM drivers	Test Farm A	Test Farm B
Latitude (N)	38º31’	38º30'
Longitude (W)	8º46'	8º44'
Length (m)	180	180
Width (m)	25	25
Total area (m^2)	4500	4500
Depth (m)	1.3	1.5
Nº of sections	3	3
Peak current at spring tide ($m\ s^{-1}$)*	0.189	0.213
Peak current at neap tide ($m\ s^{-1}$)*	0.102	0.134
Spring tidal range (m)*	1.6	2.7
Neap tidal range (m)*	0.9	1.2
Mid-tide height above datum (m)	1.2	1.3

*adapted from Rosa (2010)

Model outputs were previously discussed in Chapter 2.7 (see also Ferreira et al., 2007a). In the scope of this work, was applied an adapted version of FARM to: i) estimate production and return of investment of the cultivated population, expressed as Total Physical Product (TPP) and Average Physical Product (APP), a proxy for return of investment (Cubillo et al., 2015; Ferreira et al., 2007a); and ii) evaluate environmental externalities by calculating carbon removal for food assimilated by the oysters, from the energy balance; afterwards, carbon is converted to nitrogen according to the Redfield ratio and then to population equivalent (PEQ). Population equivalent (PEQ) is the load (e.g. nitrogen) corresponding to the emissions of one person, regardless the origin of the source (e.g. agriculture, industry or livestock) (Silva et al., 2011).

Finally, the optimal production, income and expenditure in each suitable area were determined in the socio-economic analysis, using Eq. (4) (see Chapter 2.7).

4. Results and discussion

Results, and further discussion, for the components of the four-staged methodological approach are presented in the following order:

1) Stage 2: Category final suitability maps are discussed in accordance with the most important features from each respective thematic map (created in Stage 1), as these are displayed in Annex B; the only exception to this approach was the Environmental Category;
2) Stage 3: Site selection map, created through weighting of category suitability maps, combined with the identified spatial constraints;
3) Stage 4: FARM application to the identified sites and carrying capacity analysis;

All GIS thematic and final maps were exported from ArcMap (version 10.3) with 600 dpi resolution and colour mode of 24-bit True colour. All data used for the creation of the thematic maps is displayed in Annex A.

4.1 Stage 2

Spatial constraints final thematic map was created by means of a Fuzzy Overlay tool, accounting for every identified legal and spatial constraint, screening out areas considered as unsuitable for by, at least, one thematic map (i.e. since the Fuzzy Overlay, using the “AND” operator, returns the minimum value).

Each Category’s suitability map was obtained by means of Weighted Overlay, based on the calculation of relative weights in the AHP. Total areas were calculated according to each suitability score in order to provide a quantitative analysis of the different classes achieved for shellfish aquaculture.

4.1.1 Spatial constraints

The Spatial Constraints thematic map (Fig. 9) accounted for approximately 25 km^2 of suitable areas (16% of the estuary total area), with the remaining unsuitable areas totalling 135 km^2 and being considered prohibited for aquaculture practice (Table 21). The results show that the estuary is subject to a wide variety of uses (Caeiro et al., 2005; Freitas et al., 2008) and legal constraints (ICNF, 2007), since these unsuitable areas represented approximately 84% of the estuary area.

Table 21: Total suitable areas for shellfish aquaculture.

Suitability	Total area (km^2)
Not suitable (0)	135.37
Suitable (1)*	24.63

*Not considering the areas below the Marateca Channel.

Bathymetry was the most important constraint to the spatial site selection process, since it restricted the existing areas to those suitable for intertidal aquaculture. In accordance, the areas considered unsuitable for bathymetry accounted 57% of the estuary (91 km^2 of the total area).

Available intertidal flats for aquaculture siting were identified in the upper part of the estuary, along the Marateca Channel, while the flats in the southern area of the estuary were mostly excluded by the presence of Total Protected Areas and salt marshes (e.g. Comporta Channel and near Carrasqueira village [1]) with a special protection status (Type I). In front of Carrasqueira port [2], intertidal areas were excluded, within 500 m, to not interfere with boat transportation.

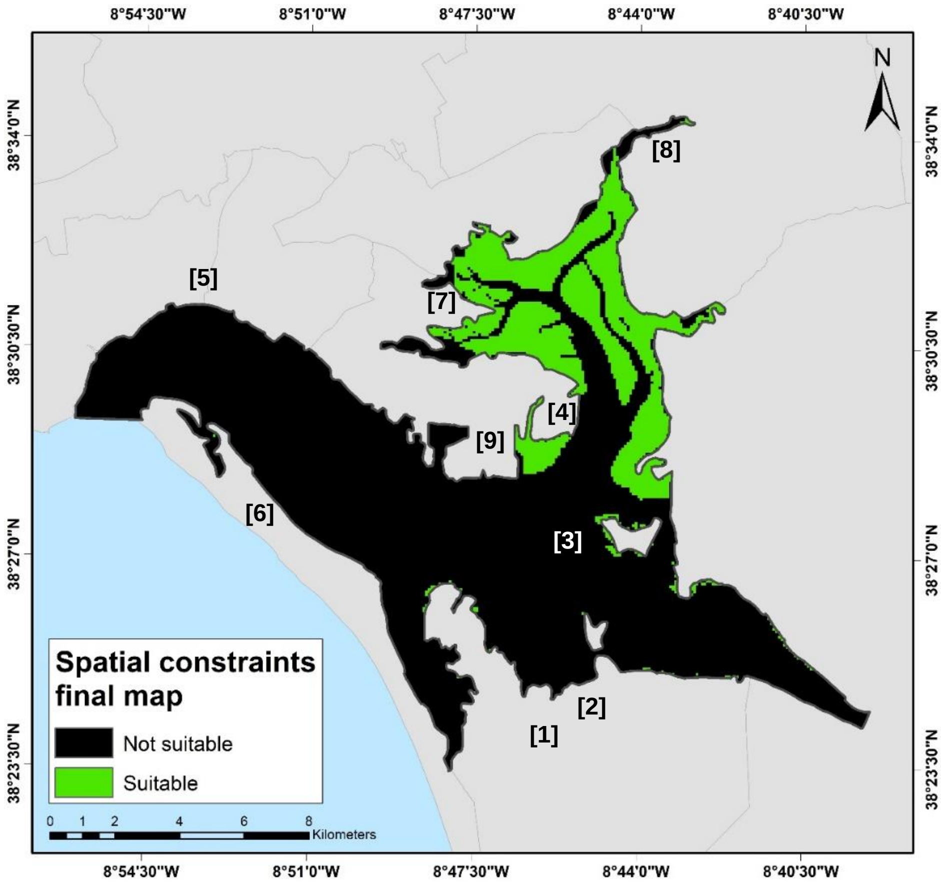


Figure 9: Spatial constraints final thematic map. [1] – Carrasqueira village; [2] – Carrasqueira port; [3] – Ilha do Cavalo (Horse Island); [4] – Mitrena Peninsula; [5] – Setúbal; [6] – Tróia; [7] – Praias do Sado; [8] – upper Marateca Channel; [9] – Lisnave shipyard;

Ilha do Cavalo (Horse Island) [3] and the salt marsh in the Mitrena Peninsula [4] were classified as TPA, being excluded due to their high ecological sensitivity (ICNF, 2007). In addition, the base map (i.e. used estuary mask for the study) on which the site selection procedure was performed had already excluded these areas, explaining why these are shown in grey. Concerning the areas in front of Ilha do Cavalo, these should not be considered suitable for aquaculture siting because, according to the ICNF (2007), the totality of the flats included on the island have a total protection status: its suitability was achieved due to the bathymetry map and the extent of the layer used to classify TPAs, which did not include these areas previously mentioned. The same applies to the areas at the inlet of the Álcacer Channel, which are classified a legal constraint (i.e. TPA) and should not comprise aquaculture activities.

Other spatial constraints such Distance to Navigational Terminals, Beaches and WTP's did not played a crucial part in the site selection process, since these mostly restricted areas along the corridor between the city of Setúbal [5] and Tróia [6], which were already excluded by the bathymetry. However, the identified industries in the upper area of the estuary were close enough (<1 km) to the flats in Praias do Sado and Faralhão [7] and the inlet of the Marateca Channel [8], excluding them for farm siting due to the probability of damaging cultured species with industrial effluents. This way, Distance to Industries thematic map excluded 9% of the upper intertidal flats, corresponding to an area of 2.4 km^2.

The Setúbal industrialized belt, located in the northern margin, from the estuary mouth to the Lisnave shipyard, was the core area excluded by the infrastructures previously mentioned (total of 13.4 km^2): Distance to Industries excluded all areas within 1 km, encompassing the areas restricted by Distance to Navigational Terminals and Beaches. In front of Lisnave shipyard [9], areas within a 500 m radius where excluded due to the presence of a WTP;

Regarding the Tróia sand bar, around its urban area, areas were excluded due to proximity to industries, as well as the presence of navigational terminals which provide transportation between Tróia and the city of Setúbal. Furthermore, at the entrance of the Comporta Channel, a buffer area of 500 m was excluded due to a WWTP which is still to be finished, as currently, discharges are made directly into the estuary (Público, 2017). Henceforth, areas excluded in the Tróia bar accounted 8.6 km^2 (without considering the ones excluded by Salt Marshes, as previously mentioned).

For this study, water current speeds were considered a physical constraint since, according to Silva et al. (2011), such as bathymetry, current speeds are inherent to the type of culture applied; these were always within the acceptable levels and did not limit any areas of the estuary for extensive oyster culture. The only exception was in front of the city of Setúbal, which was already restricted by bathymetry and other spatial constraints, such Distance to Navigational Terminals and Industries, as well as some socio-economic factors (i.e. Distance to ports and Distance to urban areas), as seen further in this work.

In conclusion, according to DGRM geoportal of marine cultures (https://eaquicultura.pt/) the identified suitable areas match the current placement of aquaculture activities in the estuary, proving the feasibility of the results.

4.1.2 Environmental

In contrast with the other categories, Environmental category results were discussed separately, and each thematic and reclassified map is displayed side-by-side; environmental indicators were credited the same level of importance for oyster growth and survival, meaning that all of them had the same impact on the environmental suitability map, therefore, worth to be discussed individually.

Furthermore, the category encompasses the highest relative importance (when compared to the other weighted categories), as it displays, almost, one single suitability score for the whole estuary (Suitable), as seen further in this chapter (Fig. 15). Thus, discussing each environmental factor separately might avoid loss of content and provide a more detailed view of the environmental conditions of the estuary.

The only exception to this approach was chlorophyll a and POM maps, that were discussed together in terms of better understanding food accessibility to shellfish in the estuary.

4.1.2.1 Stage 1 – Thematic maps

Concerning water temperature, the estuary score ranged from moderately to highly suitable (scores 2, 3 and 4), concluding that no unsuitable areas were identified. Most of the estuary is classified as Suitable, with the downstream area, between Setúbal [1] and Tróia [2] urban areas, representing the biggest part of moderately suitable values, since temperatures tend to decrease as closer to the ocean. As for Highly Suitable values (score 4), only a few and isolated were identified, specifically near the Lisnave shipyard [3], Comporta village [4] and at the inlet of the Alcácer Channel [5].

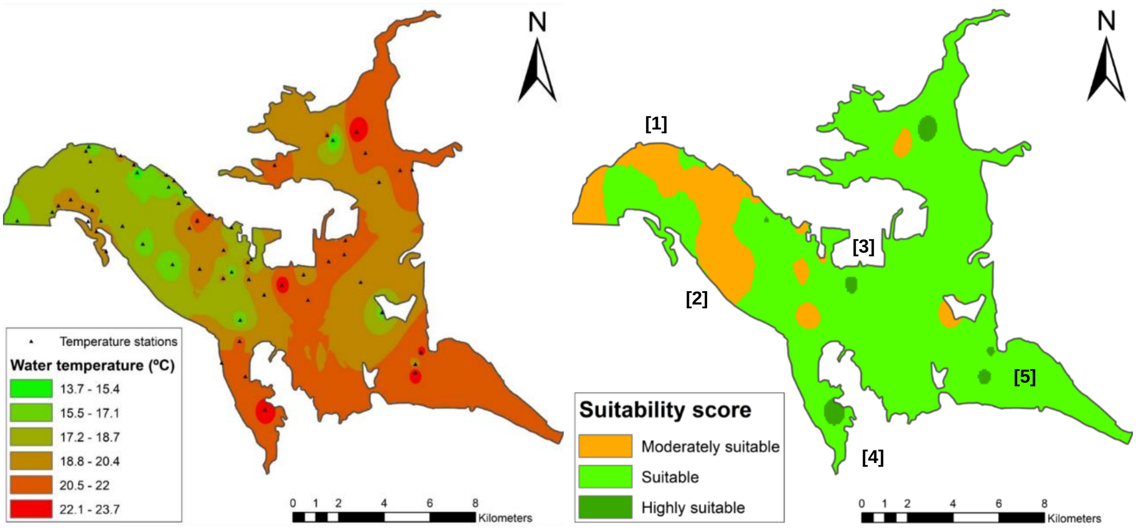


Figure 10: Water temperature values and reclassification. [1] – Setúbal; [2] – Tróia; [3] – Lisnave shipyard; [4] – Comporta; [5] – Alcácer Channel;

As water temperature, no unsuitable areas were identified for salinity and the estuary score ranged, as well, from Moderately suitable to Highly suitable. In contrast with the previous indicator, salinity tend to decrease along the downstream area to the interior of the estuary, nonetheless, most of the estuary scored Highly suitable, since oysters can tolerate a broad range of salinity levels.

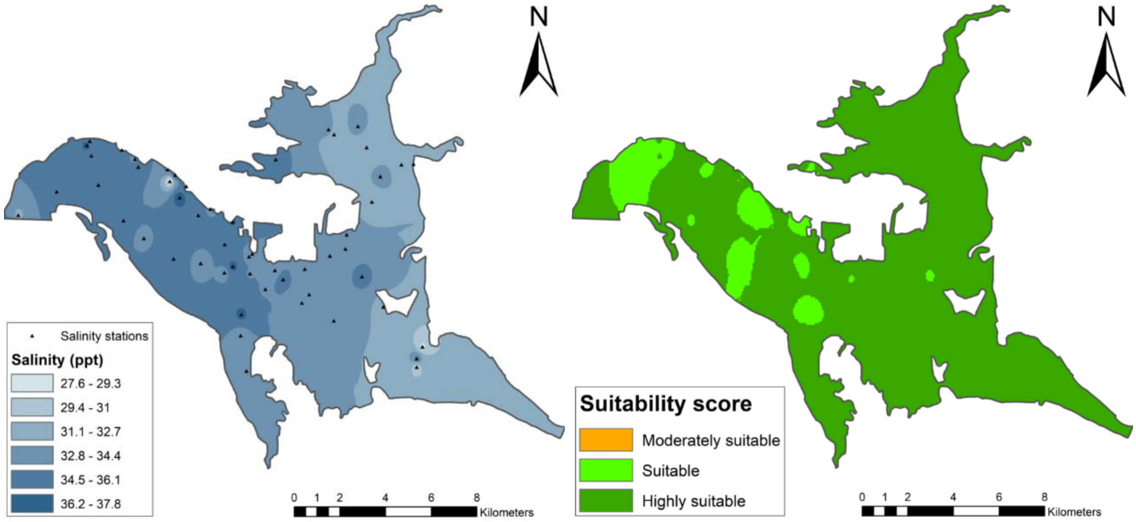


Figure 11: Salinity concentrations and reclassification.

DO levels in the estuary are considered Suitable for oyster respiration. No unsuitable areas were identified regarding this factor, as well as Moderately suitable or Highly suitable areas. The highest values were found at the estuary mouth, next to Setúbal's port [1], decreasing slightly along the corridor between the Setúbal industrialized belt and the Tróia peninsula [2]. The lowest values were found on the upper limit of the estuary [3], where the bulk of aquaculture activities currently take place. In conclusion, DO should not limit oyster respiration and, consequently, growth and survival.

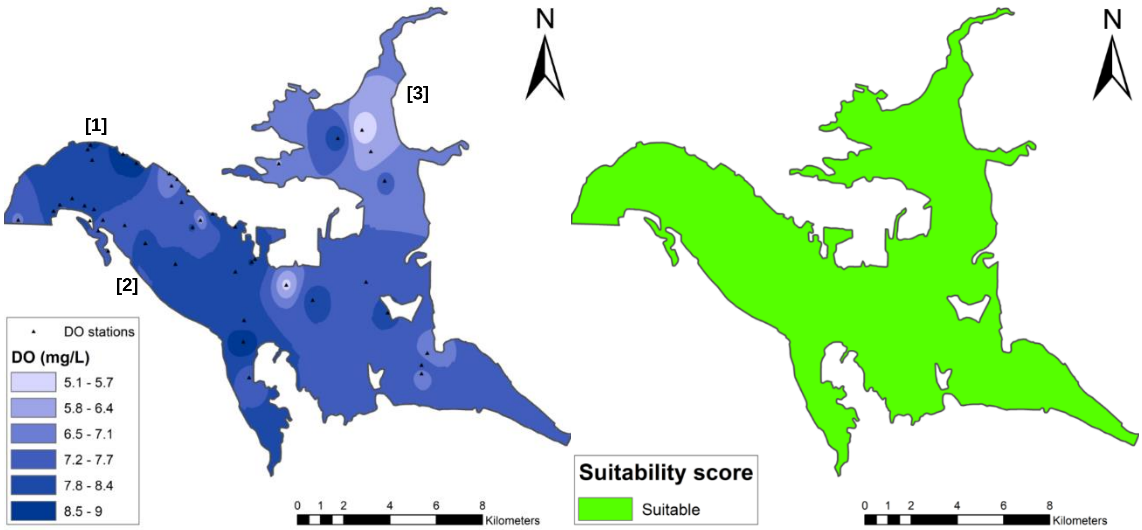


Figure 12: Dissolved oxygen concentrations and reclassification. [1] – Setúbal; [2] – Tróia; [3] – upper Marateca Channel;

TPM was the only environmental indicator encompassing all four suitability scores: the highest values were identified in the upper limit of estuary and considered as Suitable and Moderately suitable; The southern area of the estuary, whose values ranged from 3.9 to 27.4 mg L^{-1}, was identified as the most favourable area, with a Highly suitable score. The only unsuitable areas were identified in front of Setúbal city [1] due to concentrations below 5 mg L^{-1}.

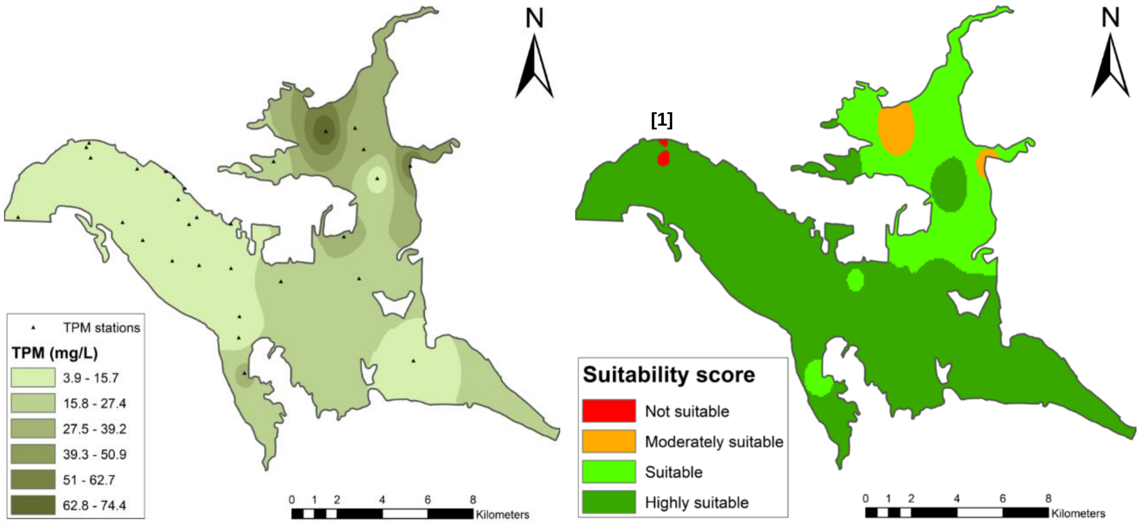


Figure 13: TPM concentrations and reclassification. [1] – Setúbal;

In terms of food accessibility, Chl a and POM reclassification results differ much from each other (Fig. 14). As previously mentioned, both indicators were reclassified according to the same Habitat Suitability Index (HSI) (defined by Roland & Brown, 1986), concluding that, regarding POM, the totality of the estuary is considered to be unsuitable for oyster growth and survival, whereas Chl a values scored from Not suitable to Suitable (score equal to 1, 2 and 3).

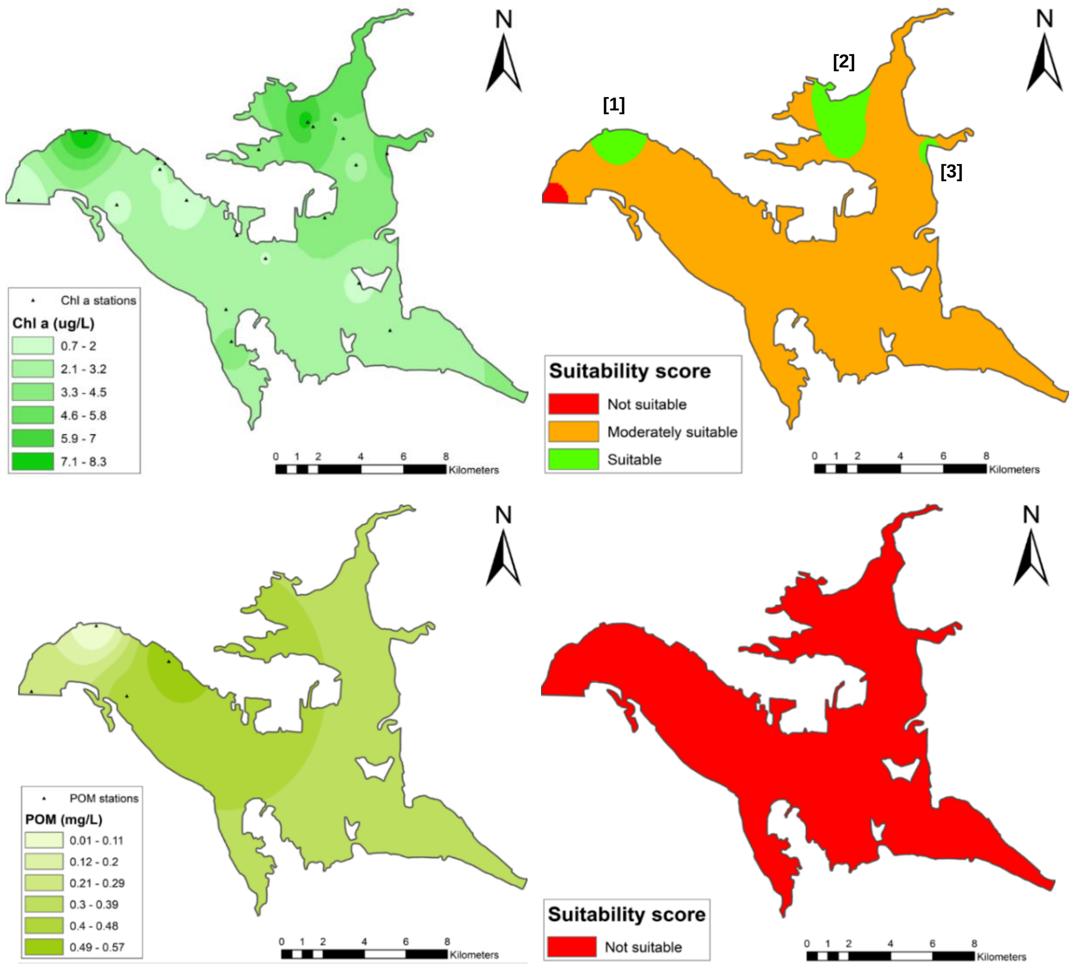


Figure 14: Concentrations of food indicators (Chl a correspond to the two upper images, whereas POM to the two lower images) and respective reclassification. [1] – Setúbal; [2] – Gâmbia; [3] – Herdade do Pinheiro

It is crucial to mention that POM values, for the whole estuary, were achieved using only four stations at the estuary mouth, due to data scarcity. This means that, once the interpolation is performed, values for the areas near both channels will not correspond to reality. Despite this fact, all the existing values were under 1 mg L^{-1}, concluding that POM might represent a limitation for oyster growth, according to the GIS results.

In contrast, Chl a concentration was achieved using several stations in different parts of the estuary; however, its biggest part is considered to be Moderately suitable (score 2). Only a few exceptions were categorised as Suitable for oyster culture, specifically Setúbal port and city [1], Gâmbia [2] and in the vicinities of Herdade do Pinheiro [3]. No Highly suitable areas were identified, concluding that food availability might arise a constraint for shellfish in the estuary.

4.1.2.2 Environmental suitability map

The Sado Estuary is known for being a favourable place to grow shellfish and this is proven by the results achieved with the Environmental final suitability map (Fig. 15): most of the estuary is classified as suitable (99% of the total area), except for the areas in front of the Setúbal city and port [1], as well as in the upper Marateca Channel [2], which were characterized as Moderately Suitable. Meanwhile, no unsuitable or Highly suitable areas were found (score 1 and 4, respectively), as shown in Table 21.

Table 22: Total area of both suitability scores.

Suitability	Total area (km^2)
Moderately suitable (2)	1.6
Suitable (3)	141.14

According to the results previously discussed, food sources (i.e. Chl a and POM) were identified as the main possible constraints for oyster growth in the estuary. As stated before, Chl scored most of the estuary as Moderately suitable, while POM concentrations were below the studied thresholds over the whole estuary, classifying it with a score 1, related to Not suitable.

Chl a concentrations representing suitable areas for oyster growth are over 5 µg L^{-1} and followed the conclusions achieved by Portela (2016): higher concentrations of *M. angulata* individuals and larvae were found in the summer months, when Chl a values ranged from 4 to 9 mg/m^3; Portela's results are, as well, equivalent to other studies performed on the estuary regarding Chl distribution, such: i) Oliveira & Coutinho (1992); ii) Cabeçadas et al. (1994); iii) Coutinho (1994); and iv) Coutinho (2003); This means that, despite the fact Chl distribution being driven from an interpolation of existing values, they can be considered reliable. However, the same can't be concluded for POM, due to the reasons explained in chapter 4.1.2.1. Even though POM values score the estuary as being unsuitable for oyster development, these weren't powerful enough to classify any areas as being unsuitable, when the overlay is performed. Yet, since areas reported to have growing populations were classified as unsuitable, Chl a can be attributed higher importance for oysters' feeding process.

Overall, current areas in the estuary containing the majority of aquaculture activities (i.e. Marateca Channel) and natural populations of *M. angulata* (i.e. Alcácer channel), scored a value of 3, being favourable for oyster rearing. Despite all the beds within the estuary mask scored the same suitability score, Portela (2016) findings showed that natural *M. angulata* populations are expanding in the Álcacer Channel beds [A], as it displays a large number of individuals, when compared to Marateca Channel [B] and Carrasqueira beds [C]; concluding that environmental conditions are more favourable in the lower inlet (i.e. Alcácer Channel). However, in this study, the stated areas comprised the same environmental conditions for growth and reproduction of the Portuguese and Pacific oysters and couldn't be concluded which beds could provide the highest number of individuals and juveniles. Regarding the Pacific species, the results achieved are considered more precise when compared to the Portuguese species, since the studied survival thresholds focused mainly on this first one.

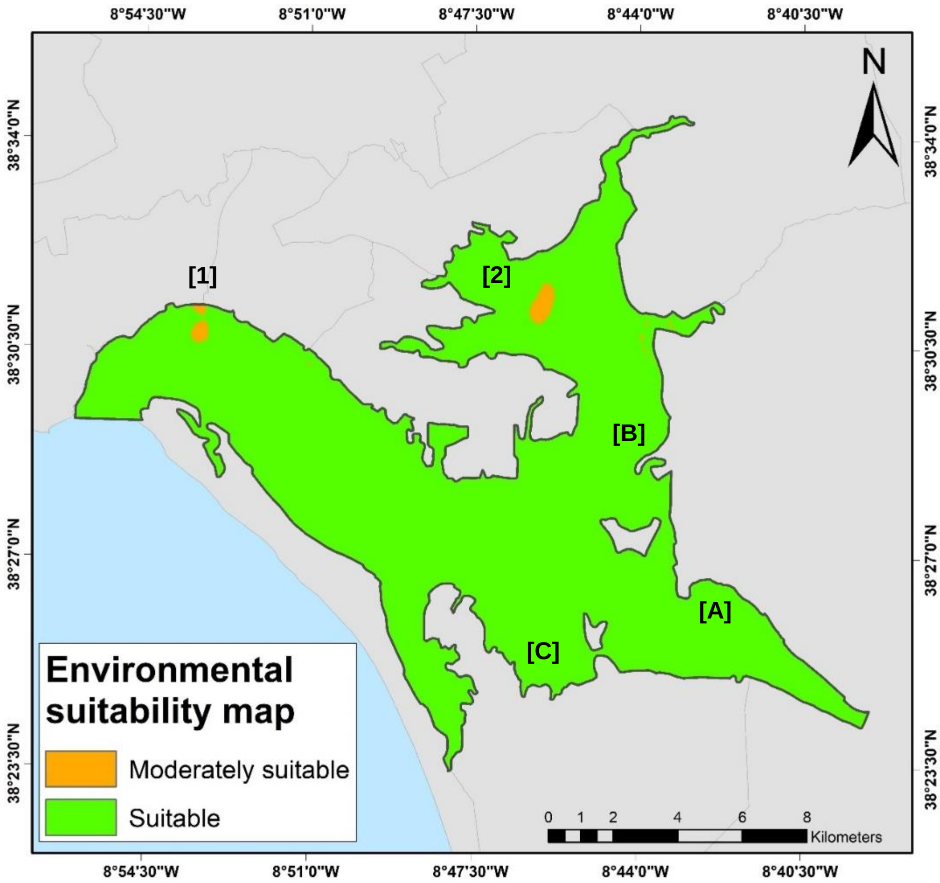


Figure 15: Environmental suitability map. [1] – Setúbal; [2] – upper Marateca Channel; [A] – Alcácer Channel oyster beds; [B] – Marateca Channel oyster beds; [C] – Carrasqueira oyster beds;

Currently, as no legal aquaculture framework or management practices are being ensured (Portela, 2016), species production reflects only on the environmental factors (i.e. no site selection procedures are being performed). Since the studied growth and survival thresholds focused mainly on the *M. gigas* species, which crossbreeds with the Portuguese species, local aquaculturists might find a problem with species feasibility, becoming hard to implement a business of Portuguese oyster, whose product value is higher when compared to its homologue, as shown in Table 23.

Table 23: Oyster production in Portugal and commercialization income in 2016 (Source: INE, 2018).

Species	Production (t)	Income (k €)
Pacific oyster	710	1385
Portuguese oyster	274	1013
TOTAL	984	2398

In 2016, production of *M. angulata* was slightly over a third of *M. gigas*, yet, the income was barely the same (i.e. difference of 372,000€). Product value is not only reason to implement *M. angulata* culture: currently, there is a governmental objective of returning the native species production, in terms of resuming the exportation values of the 1960s and 1970s decades; However, there is still a lack of relevant studies regarding the Portuguese species, as well as the competition with the existing exotic species. Further studies should inquire current *M. angulata* producers in terms of better understanding the species dynamics and the sector needs.

Another way to address this category could be through a time-series analysis of the environmental factors of the estuary, since these tend to change over the seasons and, consequently, the suitability achieved (e.g. water temperature is higher in the summer months rather than winter, thus, oysters grow better during the summer months and suitability would be higher).

4.1.3 Socio-economic

The discussion of socio-economic results followed the same approach as the Product Quality and Spatial Constraints categories: only the results of Stage 2 are displayed and the three thematic maps, elaborated through buffer tools, were discussed in accordance with the final suitability map;

4.1.3.1 Socio-economic suitability map

The city of Setúbal [1] represents the biggest and most populated area in the estuary, including, as well, the most important port (i.e. Porto de Setúbal). Other ports and urban areas, such the Carrasqueira fishing dock and village [2], Tróia [3] and Comporta [4], do not hold the same amount of people and trade chain opportunity, yet, were credited with the same level of importance in order to include places where aquaculture and fisheries are relevant for local economy (Fig. 16).

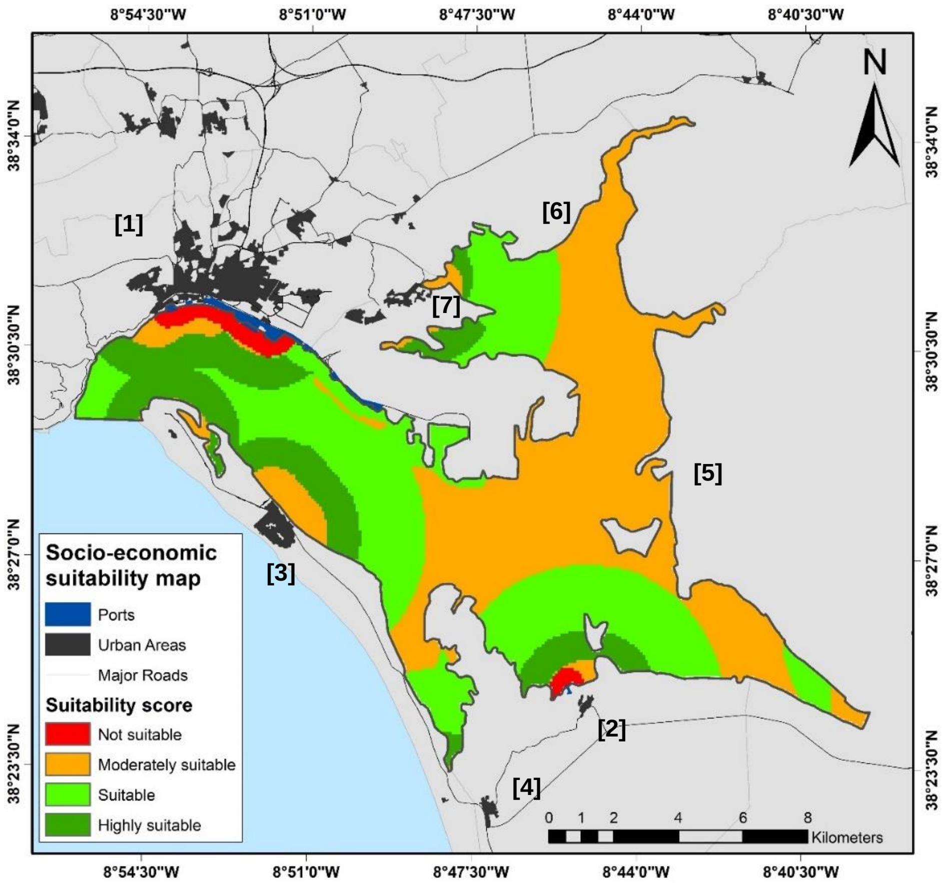


Figure 16: Socio-economic suitability map. [1] – Setúbal; [2] – Carrasqueira; [3] – Tróia; [4] – Comporta; [5] – Herdade do Pinheiro; [6] – Gâmbia; [7] – Praias do Sado;

Ports and Urban Areas were obtained from DGT's soil occupation chart (COS, 2015): i) selected urban areas corresponded to the "continuous urban tissue", since these would hold more people and market opportunities; and ii) ports, displayed as a polygon file, were selected in terms of product marketing and transportation in the estuary;

The socio-economic suitability map is highly influenced by both indicators mentioned above. As shown in Fig. 17, areas within 500 m of port areas, as well as the urban areas of Setúbal city [1] and Carrasqueira village [2], were excluded for oyster farm siting. This is due to the importance given to ports and urban areas (influence of 62% and 28%, respectively), which established this safety buffer in order to avoid landscape impacts problems. Aquaculture siting guidelines (e.g. Saunders et al., 2017) and other aquaculture site selection studies (e.g. Falconer et al., 2016) address that suitability is as higher as the proximity to port areas, however, for this study, a safety distance of 500 m was established for areas in front of ports since they are also considered as navigational terminals and boat transportation can be compromised. Nevertheless, these areas were already excluded in the Spatial Constraints thematic map (i.e. Distance to Navigational terminals).

The Distance to Ports thematic map excludes, not only areas within 500 m, but areas over 8 km as well, since these would represent high transportation costs. However, the Distance to Urban Areas thematic map only excludes areas within 1 km, meaning that once the overlay is performed, areas such Herdade do Pinheiro [5], are considered as moderately suitable for oyster culture siting and not excluded as in Distance to Ports and Distance to Roads thematic maps (see Annex B).

Major Roads were obtained from OSM's database (2018) and used on this study for its purposes of product transportation (generally by car) and labour. Nevertheless, since most of the transportation in the estuary is made by boat, this indicator was given the lowest importance, with a respective influence of 10%. Selected roads are classified as primary, secondary and tertiary: primary roads correspond to major traffic movement between centres of population and economic activity on a regional and national levels, also linking strategic roads to residential streets or industrial roads; secondary roads provide access to properties within a residential area, while tertiary roads are not usable by motor vehicles and may include footways, footpaths or cycleways;

The Distance to Roads thematic map (Annex B) shows that most of the estuary is considerable as unsuitable for farm siting, especially important areas for aquaculture development, such as Gâmbia [6] and Praias do Sado [7]. However, Moderately suitable to Highly suitable areas were identified in front of urban centres and ports, since roads closer to the estuary margins are located with the purpose of connecting these infrastructures. Additionally, the overlay with the other social and economic factors allowed the areas in front of Tróia [3] and Praias do Sado [7] not be excluded for site selection, being considered Moderately Suitable.

Suitable and Highly Suitable areas (score 3 and 4, respectively) for farm siting followed the results achieved with the Distance to Urban Areas thematic map, even though ports have a higher relative importance. Highly suitable areas (22 km^2) for shellfish farm siting are mostly located within 1 to 2 km of urban areas and, consequently, from both selected ports as well. As for suitable areas (36 km^2), these are located at 2 to 4 km from these infrastructures.

Table 24: Total area of each suitability score achieved in Socio-economic category.

Suitability	Total area (km^2)
Not suitable (1)	2.90
Moderately suitable (2)	64.21
Suitable (3)	35.98
Highly suitable (4)	21.83

Overall, and according to the reclassification map, the estuary seems to gather enough socio-economic conditions to comprise aquaculture activities. The map (Fig. 16) shows that the closer to urban areas, ports, facilities and population, the better for shellfish production: 29% of the estuary scored a value of 3 on the suitability scale, with 17% being classified as Highly suitable (score value of 4). Unsuitable areas accounted 2% of the total estuary area, while the Moderately suitable areas represented 51%. These last ones were identified, mostly, in the areas of the northern and southern channel, as well in the heart of the estuary (Central Bay), due to the bulky distance to the infrastructures, yet, the overlay did not exclude them for farm siting.

This work focuses on addressing the main infrastructures that allow fishermen transportation to harvesting/production locations (e.g. roads and piers), as well as their trip back, with the harvested product. Some aquaculture site selection studies (e.g. Giap et al., 2005; Falconer et al., 2016) include local markets as a single indicator to assess product commercialization, yet, for this study, markets are included in the identified urban areas.

4.1.4 Product Quality

Product Quality results and discussion follow the same approach as the Spatial Constraints and Socio-economic categories and only the most important features were discussed. The main reason for this approach was the fact that the Product Quality suitability map was attributed with the lowest relative importance, when compared to the other weighted categories and, therefore, representing less influence on the final suitability map.

It should be highlighted, once again, that the reclassification according to the PEL and TEL values reduces suitability down to three scores: less polluted areas are considered as Highly suitable (score 4), while levels above the PEL levels are considered as unsuitable (score 1). Values in-between the TEL and PEL levels are attributed with a score 2 and defined as Moderately suitable, to avoid possible product contamination.

4.1.4.1 Product Quality suitability map

Results achieved show that metal concentrations in the estuary should not contaminate shellfish populations, as no unsuitable areas (score 1) were identified. The estuary score ranged from Moderately suitable (score 2) to Highly suitable (score 4), even though reclassification methods only addressed three suitability scores (i.e. without a score 3, related to Suitable areas, not being one of them).

As shown in Fig. 18, the southern area of the estuary is classified as the least contaminated of them all, encompassing all the Highly suitable areas identified. This is due to the fact that the studied pollutants are mostly driven from industrial discharges and the bulk of the industries, within the estuary margins, being located in the northern area of the estuary, respectively along the city of Setúbal [1] and Mitrena peninsula [2], in contrast with the southern area, which is less industrialized. Highly suitable areas represented 48% of the estuary with the healthiest locations (i.e. less contaminated) being in front of Carrasqueira [3], Comporta [4], Tróia [5] and at the inlet of the Alcácer Channel [6].

As for the upper area of the estuary (i.e. Marateca Channel), it is mostly classified as Suitable and should not affect product quality. It is important to notice that values used to achieve metal concentrations, for the whole estuary, were driven from sampling points (Caeiro et al., 2005) along the corridor between Setúbal city and the Tróia sand bar, meaning that, once the interpolation is performed, values within these areas will be more accurate than the ones achieved for the upper limit of estuary, where the bulk of aquaculture activities take place, as well as the southern channel of the estuary, where the beds with more abundance of oyster individuals are located. Nevertheless, Suitable areas correspond to 51% of the total area, meaning that metal concentrations should not harm the product and consequently human health (Table 25).

Table 25: Total area of each suitability score achieved in Product Quality category.

Suitability	Total area (km^2)
Moderately suitable (2)	1.81
Suitable (3)	72.85
Highly suitable (4)	67.87

Moderately suitable values (score 2) were identified in front of Lisnave shipyard [7] and Setúbal city and port [1]. The first, Lisnave shipyard, holds the highest heavy metal concentrations found on the estuary: concentrations of Cd, Cu and Zn were over the acceptable levels as natural shellfish populations might be contaminated; other metals scored a value of 2 on the suitability scale, yet, there might a chance that these pollute oyster populations; The only exception was PAH's, whose concentrations don't seem to be high enough to contaminate the product on this area, as for the whole estuary, scoring a value of 4 on the suitability scale, being in accordance with the results achieved by Carreira et al. (2013).

In front of the city of Setúbal and port [1], the values ranged from unsuitable (score 1) to Highly suitable (score 4), yet, the majority scored a value of 2, linked to moderate suitability: Cd, As, Cu and Zn scored a value of 1, while Hg and Pb scored a value of 2. Since these last ones were attributed the highest relative importance (21% of influence), as Cd and PAH's, the overlay classified these areas as

Moderately suitable, excluding all unsuitable values; Concluding, Moderately suitable areas only accounted 1% of the estuary area.

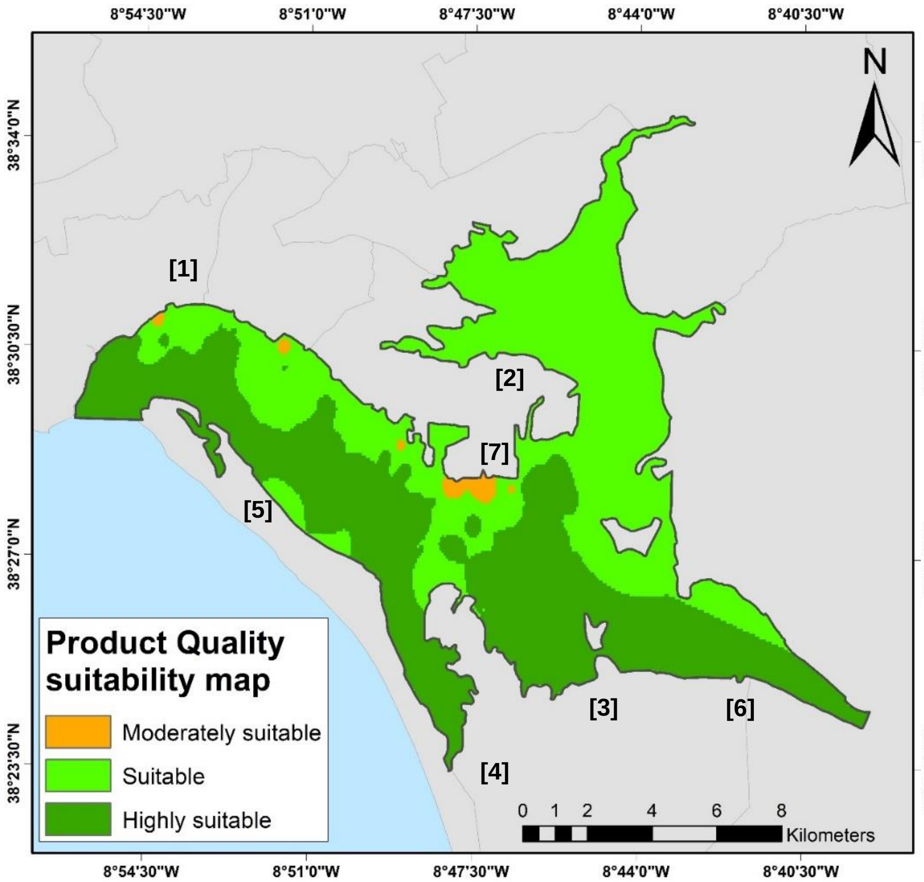


Figure 17: Product quality suitability map. [1] – Setúbal; [2] – Mitrena peninsula; [3] – Carrasqueira; [4] – Comporta; [5] – Tróia; [6] – Alcácer Channel; [7] – Lisnave shipyard;

This way, no constraints were identified regarding product quality, despite some punctual areas, previously mentioned, whose values are in-between the PEL and TEL levels. Henceforth, Product Quality suitability map can be deceiving, as it can give the illusion that "suitable" areas are pollution free, which is not the case. Since weights were given for each metal, suitable areas are merely indicative of which areas are less contaminated (e.g. an area can be heavily contaminated by copper and still have an overall suitability score of 4, even though high concentrations of copper would reduce the product's quality). More trustworthy comparisons and conclusions cannot be made, due to the larger scope of this work and the author's expertise, as the final suitability map should only be understood as an overall state.

As for today, according to contacted producers in the area and Order nº 2018/3996 (Portuguese Institute of the Sea and Atmosphere – IPMA), harvest of *M. angulata* is totally forbidden due to cadmium contamination of the production areas, in contrast the *M.* gigas, which is harvested and conducted to cleansing facilities to be destined to human consumption. Supporting these conclusions, Oliveira (2012) results showed that Portuguese oysters, gathered from the Sado Estuary, comprised cadmium concentrations above the EU limits (Order No. 1881/2006/EC), which can damage human health. Yet, regarding the other metals in study, these didn't exceed the values imposed by the EU legislation, being cadmium the biggest concern in consumption of bivalves from the estuary. These statements followed the studies of Silva & Batista (2008) and Caeiro et al. (2005), proving the feasibility of Oliveira (2012) results.

Problems associated with the consumption of shellfish grown in waters contaminated with microbiological pathogens are mainly due to food-borne diseases, including heavy metal and PAH contaminations, toxins from harmful algal blooms or contamination from pathogenic microorganisms

(WHO, 2010). Thus, they represent a significant human health risk, which can be reduced by depurating the harvested shellfish in tanks.

Table 26: EU classification of bivalve production areas (Source: Order nº 2018/3996).

EU class	Description	Microbiological standard (*Escherichia coli/100 g*)
A	In Class A production areas, bivalves can be harvested and directly consumed without any necessary treatment.	≤ 230
B	Class B areas allow the collection of bivalves, yet, in order to be placed in the market for human consumption, these must be transferred to depuration centres or other industrial facilities with the same purpose.	≥ 230 to ≤ 4600
C	In Class C production areas, harvested bivalves must be conducted to depuration facilities for longer periods of time (minimum two months).	≥ 4600 to ≤ 46000
Prohibited	Totally forbidden areas for collection of bivalves destined to human consumption.	≥ 46000

According to Order No. 4022/2015 and later Order No. 3996/2018, both being included in the scope of Regulation (EC) No. 854/2004 and Ordinance No. 1421/2006, after three years of monitoring and microbiological quality control of bivalve molluscs, production areas should be reclassified. Currently, IPMA divides the Sado Estuary into two production areas, namely ESD1 (Sado Estuary and Marateca Channel) and ESD2 (Alcácer Channel), both classified as B and C (Table 26), being the harvest of the Portuguese species totally forbidden in the ESD2.

Concluding, further studies on metal contamination should be performed in order to achieve a more precise and up-to-date overview of the contaminated areas in the estuary (i.e. the used metal concentrations from Caeiro et al. (2005), are the most up-to-date data available). Another limitation of this study is that metal contamination was only studied for the most industrialized areas, as the concentration of metals in both inlets of the estuary could not be assessed; and this is important due to the entrance of metals sourced from mining activities along the Sado watershed.

4.2 Stage 3

Stage 3 focused on the creation of the final site selection thematic map, which followed the same approach used in Stage 2: each category was attributed with a weight (defined through an AHP approach) and combined through a Weighted Overlay tool;

Afterwards, weighted categories were incorporated with the identified spatial constraints (through Eq. 6) to screen out unsuitable areas, either because of legal hindrance or anthropogenic disturbances. The results are displayed in the figure below (Fig.18), with the weighted categories on the left, and their union with the spatial constraints on the right side.

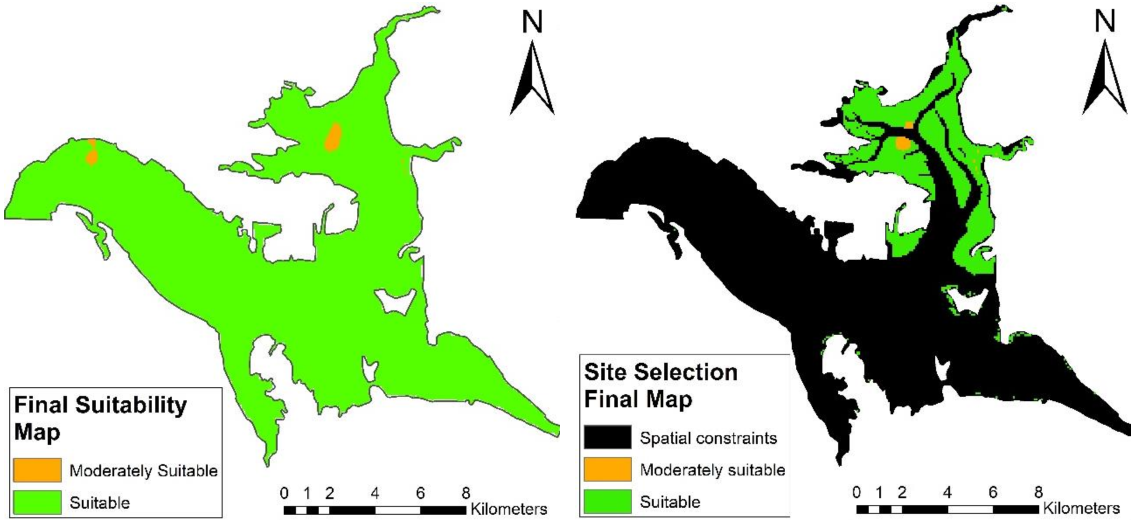


Figure 18: Final suitability map (left) and Site Selection map (right).

Suitable sites are illustrated in Fig. 19: by combining each category (suitability values wavering from 1 to 4), a final Suitability map was generated, consisting of only two suitability scores: Moderately Suitable areas occupy 2% of the total area, with Suitable areas occupying the remaining 98%; next, by combining the Spatial Constraints thematic map and the final suitability map, Moderately Suitable areas were down to 0.5 km^2 (0.2% of the total area) and Suitable areas to 24 km^2 (9% of the total area), as illustrated in Table 27.

Table 27: Suitability scores for both final suitability map and site selection map.

	Total area (km^2)	
Suitability	**Final Suitability map**	**Site Selection map**
Spatial constraints	n/i	135.37
Moderately Suitable (2)	3.20	0.49 (-85%)
Suitable (3)	156.8	24.14 (-84%)

n/i – not included

By superimposing the Spatial Constraints thematic map, both Moderately Suitable and Suitable areas were reduced by 85 and 84%, respectively. This further validates that the estuary is subject to conflict uses, such fisheries, industries, urban growth and boat related activities, including, as well, areas protected by law (e.g. Coutinho, 2003; ICNF, 2007; Portela, 2016).

According to the results achieved, oyster culture siting is mostly defined by the spatial constraints and the environmental factors of the estuary (Fig. 19). Despite socio-economic and product contamination features being included in the study, these did not influence the site selection map, as the results displayed the same suitability scores achieved with the Environmental map and barely the same percentage of scores (e.g. Moderately suitable areas increased 1% when compared to the Environmental suitability map). Since the Environmental category did not classified any areas as being Not suitable (score 1), unsuitable areas for shellfish culture siting corresponded, singularly, to the identified legal and spatial constraints in the area.

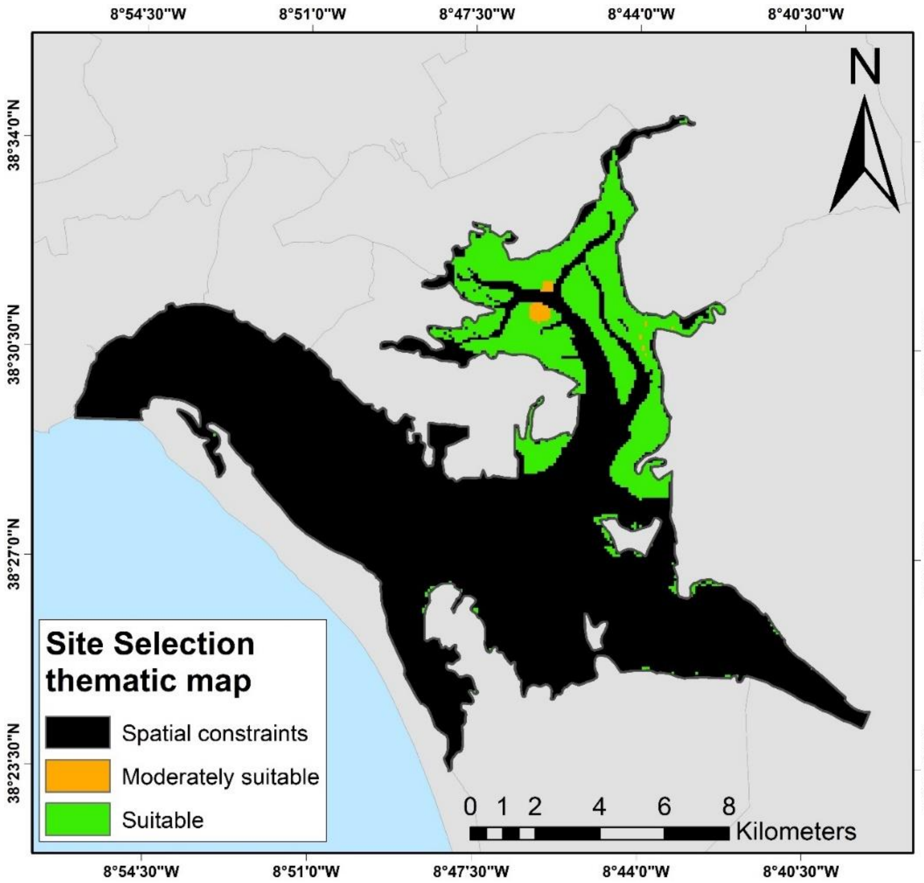


Figure 19: Site selection map.

Henceforth, in contemplation with what was previously discussed in each final suitability map:

- The Sado estuary gathers optimal environmental conditions for growth and survival of *M. gigas* and *M. angulata* oysters, which is supported by the studies that have reported the colonization of both species (e.g. Batista, 2007; Portela, 2016; Silva & Batista, 2008);
- The Sado Estuary possesses enough infrastructures and labour to support the legalization and further development;
- The results achieved with metal contamination could not be considered the most feasible as the extent of the used data did not include sampling points on the identified suitable areas (i.e. along the Marateca Channel); Nonetheless, these were considered Suitable for aquaculture and metal contamination should not arise a constraint to product quality;

The Sado Estuary is in need for proper management plans to control the harvest and production of the Portuguese species. The current estuary status for oyster production implies challenges to the monitoring of pollutants, which disturbs the success of a sector which could be more profitable. According to Portela (2016), further management plans should focus on: i) the sustainable use of the oyster natural beds; ii) implementation of maternities; iii) use of collectors for seed harvest; and iv) the production of the Portuguese species, singularly, instead of other species (e.g. *M. gigas*); If seed imports could be avoided, the introduction of alien species would be avoided as well, and the balance and resilience of the Nature Reserve could be maintained.

The following step will be the application of the FARM carrying capacity model to the identified suitable areas for oyster aquaculture in the final site selection map. This way, environmental data from these selected sites is going to be extracted and incorporated to run the model.

4.3 Stage 4

In the previous stage, a site selection thematic map was developed by means of GIS tools, where the whole estuary scored suitability values of 2 and 3, related to Moderately suitable and Suitable areas respectively. As previously mentioned, in Chapter 3.3.4, FARM only focused on the areas considered to be "Suitable", since those gather the best conditions for individual farm siting, as the overall suitability score represent the highest one achieved (i.e. no Highly suitable areas were identified on the final map, as these would potentially hold better conditions than the Suitable ones, thus, being selected to evaluate production and environmental externalities). In the scope of this work, farms will be addressed as "test farms".

This way, two test farms were selected from two different Suitable areas of the estuary (Fig. 20): farm A's location was selected since it is in the vicinities of shipping routes, though far enough to not disturb or be disturbed by ships; farm B was sited in a location defined as having largest oyster populations within the identified suitable areas (Magro, 2016; Oliveira, 2012; Portela, 2016).

Both farms are located within the areas influenced by the selected B2K stations, where the environmental drivers were extracted to run the FARM model: Farm A corresponds to station #8A, whereas Farm B to station IH3; Both test farms are located in intertidal areas and included in the estuary Nature Reserve (consequently on Natura 2000 areas as well), where bottom culture with FARM's standard density stocking of 100 ind m^{-2} was modelled for a culture period of 365 days.

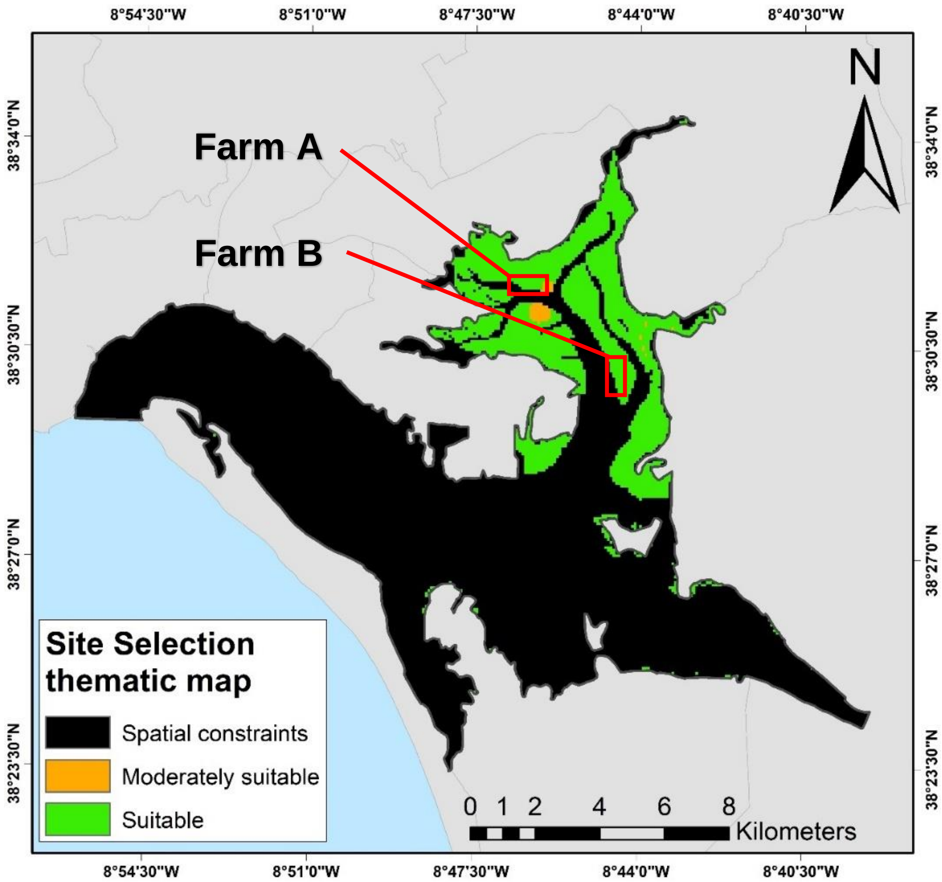


Figure 20: Location of both "test farms" within the estuary.

Environmental drivers (namely Temperature, Salinity, DO, Chl a, POM and TPM) were used to simulate individual growth of Pacific oyster. For each driver, monthly spot values were gathered and used to evaluate potential production, environmental externalities and economic performance. The table below (Table 28) shows the value range of environmental drivers according to farm, as the rest of the dataset is displayed in Annex D.

Table 28: Main environmental characteristics of the suitable sites.

Environmental drivers	Test Farm A	Test Farm B
Temperature (ºC)	13.7 – 26.2	12.9 – 25.2
Salinity (psu)	27.2 – 33.7	22.2 – 36.4
DO (mg L^{-1})	6.0 – 8.9	6.0 – 8.8
Chl a (µg L^{-1})	1.9 – 10.7	0.9 – 5.9
POM (mg L^{-1})*	5	4
TPM (mg L^{-1})	19.4 – 123.2	3.3 – 13.5

*constant values based off data gathered from the Tagus Estuary.

Data displayed on the table above was used to simulate, and further compare production and environmental impacts in both farms, with nitrogen removal being one of the FARM outputs; by this fact, nitrogen removal was assessed even though the main purpose of this work is to study optimal production of oyster aquaculture, in the Sado Estuary. Furthermore, there is no market in the Sado Estuary for nutrient trading (as of March 2019), as no farmer will implement a shellfish culture solely based off its purposes of nutrient removal, as it is not cost-effective, unless subsidized (Rose et al., 2015).

According to Smaal et al. (2019), shellfish can provide multiple ecosystem services, such: i) provisioning (e.g., aquaculture); ii) cultural (tourism and recreation); iii) supporting (cycling of nutrients); and iv) regulating (water quality maintenance by reducing eutrophication symptoms); being the last one of special relevance in the environmental evaluation carried by FARM.

By removing nitrogen from the waterbodies, shellfish aquaculture may reduce eutrophication symptoms, improving water quality in estuaries (Lubet et al., 1994; Rose et al., 2015; Smaal et al., 2019). FARM evaluates the mass balance of carbon and nitrogen that measures the difference between inputs, such as phytoplankton and detritus, measured in carbon units, kg C, further converted to nitrogen based on the Redfield ratio (Ferreira et al., 2007a; Rose et al., 2015); and outputs, namely excretion and faeces that are deposited to the seabed, transferring the organic nitrogen present in the inputs to the sediments (Dame et al., 1989; Rice, 2008). The difference is negative as shellfish remove nitrogen and can be further converted into population equivalent (PEQ).

Once converted to PEQ, the potential economic return is evaluated according to each farm's nitrogen removal, by considering nitrogen credits (see Ferreira & Bricker, 2015), within the scope of EPA's water quality/nutrient trading (EPA, 2013): a "credit" is defined as a unit of pollutant reduction (e.g. nitrogen); More information about nutrient trading can be consulted in: e.g. Ferreira & Bricker, 2015; Newell, 2004; Newell & Mann, 2012; Rose et al., 2015; Smaal et al., 2019)

Regarding shellfish production of the defined test farms, it was achieved by the evaluation of TPP, APP, expenditures and profit; Profit is calculated by accounting for TPP and sale price per kg (P_y), as well as total quantity of seeds used and its cost per kg (P_x). As previously mentioned in Chapter 3.3.4, used values for both P_y and P_x were FARM's default ones (4.45 € and 0.89 €, respectively), as they tend to fluctuate with market conditions.

The table below (Table 29) illustrates the FARM results for both farms, based on the environmental drivers displayed in Table 28, at a standard density of 100 ind m^{-2}. Outputs were displayed side-by-side in order to provide a comparative approach among them.

Table 29: Production outputs and environmental impacts at a standard density stock of 100 ind m^{-2}.

FARM outputs	**Test Farm A**	**Test Farm B**
Production		
Seed (t TFW)	0.9	0.9
TPP (t TFW)	6.6	15.4
APP	7.3	17.1
Harvest profit (k €)	28	68
PEQ (y^{-1})	44	70
Shellfish farming income (k €)	29.2	68.6
Nutrient treatment (k €)	1.8	2.8
Total Income (k € y^{-1})	31	71.4
Environmental impacts		
Carbon removal (kg C y^{-1})		
Phytoplankton removal	385	481
Detritus removal	2316	3783
Nitrogen removal (kg N y^{-1})		
Algae	-60	-75
Detritus	-360	-588
Excretion	22	31
Faeces	249	398
Mortality	3	5
Mass Balance	-147	-230
ASSETS score inflow	Good	Good
ASSETS score outflow	Good	Good

Even though both farms being located within suitable areas achieved with the GIS site selection procedure, production results showed differences at a standard seed density of 100 ind m^{-2}, considering a test farm area of 4500 m^2, culture period of 365 days, a seed weight of 0.65 g TFW, a harvest weight of 90 g TFW and a natural mortality of 0.35 y^{-1}.

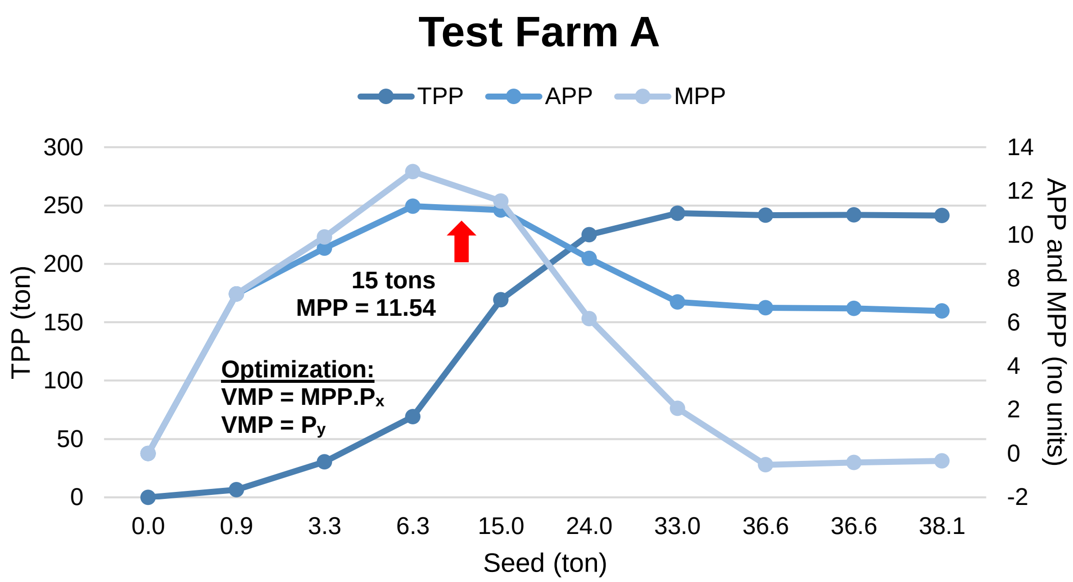
Farm B presented the highest production with a TPP of 15.4 t TFW and an APP of 17.1 after the cultivation period. At Farm A, production was lower with a TPP of 6.6 t TFW and APP of 7.3. These results suggested that Farm B is more promising for Pacific oyster aquaculture than Farm A at standard densities, with fast growth and return on investment, as shown by the APP and the predicted income, at the end of the cultivation period (31 000 € for Farm A and 71 400 € for Farm B).

Regarding environmental externalities, Farm B also showed the highest net nitrogen removal from the water through the filtration of algae and detritus by oysters, with annualized net removals in the standard scenario of 230 kg N y^{-1}, corresponding to a profit of 2 800 € in nutrient treatment and a nitrogen input of 81 population equivalents per year (PEQ y^{-1}). Farm A displayed the lowest nitrogen removal with annual gross of 147 kg N y^{-1} and an equivalent value of 1 800 € in nutrient treatment.

Results from the application of the ASSETS model implemented in FARM provide a eutrophication indicator at the local scale and where applied to both farms in study. However, the eutrophication score showed that studied oyster farms do not have significant effects on water quality, since the quality status of the inflowing water is “Good”, being no effect in the outflowing water quality.

Since the present work focuses mainly on production and profit maximization, Eq. 4 (Chapter 2.7) was applied to provide a detailed analysis of optimal production and seed density.

In order to obtain a production function by FARM, the TPP was simulated over a variable range of seeding effort, depending on the site. According to Ferreira et al. (2007a), the analysis of the interaction of the resulting TTP, APP and MPP curves can be divided in three stages: Stage I, the MPP curve is above the APP, crossing when the APP becomes negative; the farmer should consider increasing the seeding density in this stage, while the APP is still increasing; Stage II represents the region where profit is maximized and is maintained until the MPP = 0; Stage III begins once the MPP equals 0; Afterwards, the TPP decreases despite the increase in seed input, which is undesirable on a financial and resource conservation basis (Fig. 21).



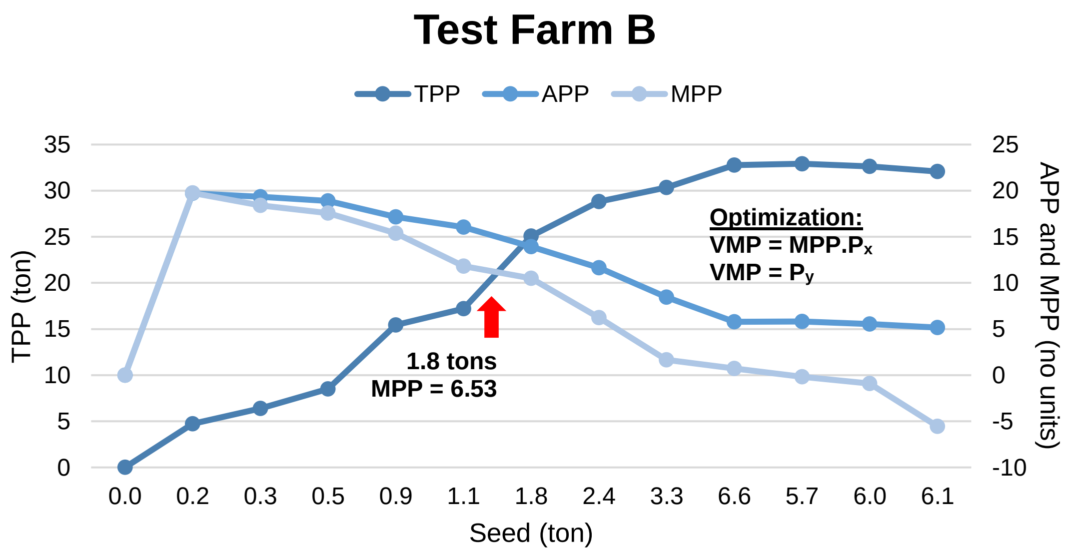


Figure 21: Economical analysis for Sado Estuary aquaculture test farms using FARM model.

Socio-economic outputs from the marginal analysis of the optimal profit for each farm and a comparison with the standard seed density farming are shown in Table 30. Additionally, environmental impacts of both optimized farms were also assessed.

Table 30: Optimization analysis at the two potential Pacific oyster farms in the estuary and further comparison with results at standard density (100 ind m^{-2}).

FARM outputs	Farm A	Farm A optimized	Farm B	Farm B optimized
Production				
Seed (t TFW)	0.9	15	0.9	1.8
TPP (t TFW)	6.6	169	15.4	25
APP	7.3	11	17.1	14
Harvest profit (k €)	28	757	68	82.6
PEQ (y^{-1})	44	879	70	133
Shellfish farming income (k €)	29.2	753.8	68.6	111.6
Nutrient treatment (k €)	1.8	35.2	2.8	5.3
Total Income (k € y^{-1})	31	788.9	71.4	116.9
Environmental impacts				
Carbon removal (kg C y^{-1})				
Phytoplankton removal	385	6709	481	903
Detritus removal	2316	46 748	3783	7261
Nitrogen removal (kg N y^{-1})				
Algae	-60	-1044	-75	-140
Detritus	-360	-7272	-588	-1130
Excretion	22	402	31	60
Faeces	249	4962	398	762
Mortality	3	51	5	9
Mass Balance	-147	-2900	-230	-439
ASSETS score inflow	Good	Good	Good	Good
ASSETS score outflow	Good	Good	Good	Good

At optimized densities Farm A would be more profitable than Farm B. According to the table above (Table 30) and Fig. 21, the point of profit maximization for Test Farm A was achieved giving an MPP = 11.54, corresponding to a seed input density of 15 tons and a profit of 757 000 € with harvest. As shown by the APP curve on Farm A graph (Fig. 22), seeding density should be increased until 15 tons, when it starts to become negative and crosses the MPP curve.

As for Test Farm B optimal profit occurred at a seed density of 1.8 tons and MPP = 6.53, totalling 82 600 € with harvest profit, over the cultivation period. However, results achieved for Farm B can be considering deceiving, as profit maximization is achieved when the harvestable biomass (APP) is already decreasing (Fig. 22). This way, in contrast with Farm A, seeding density should be increased until 1.8 tons in order to obtain the maximum profit, despite the APP being lower when compared to standard densities.

Concerning environmental impacts at optimized densities, Farm A showed the highest net nitrogen removal with 2900 kg N y^{-1}, a profit of 35 200 € in nutrient treatment and a nitrogen input of 879 population equivalents per year (PEQ y^{-1}). These results were roughly 19x over the environmental impacts at standard densities. Farm B displayed the lowest nitrogen removal with annual gross of 439 kg N y^{-1} and an equivalent value of 5 300 € in nutrient treatment. At optimized densities, environmental externalities in Farm B were approximately 2x over the ones achieved for standard densities.

Moreover, the application of the ASSETS model presented that, such as standard densities, optimal densities of Pacific oyster do not have significant effects on water quality, since the quality status of the inflowing water is equal to the outflowing water quality (i.e. ASSETS score: “Good”). This means that, such in standard and optimized densities, the consumption of chlorophyll a and dissolved oxygen do not fall into concentrations below 5 µg L^{-1} and 6 mg L^{-1} respectively, which according to the original paper (i.e. Ferreira et al., 2007a) would improve water quality and achieve a “High” score.

In conclusion, the application of the FARM model showed a high variability among the carrying capacity of both sites. The results have shown that Pacific oyster aquaculture in Farm A is considered to be economically viable at a farm-scale, being more profitable when compared to Farm B. Optimized harvest profit in Farm B was restricted by the available food sources, namely Chl a and POM, whose concentrations are lower when compared to Farm A; by increasing seeding density, less food will be available for each individual, compromising its growth. Consequently, the harvestable biomass would decrease, as well as the profit.

It is vital to highlight, once again, that the available water quality data for the Sado Estuary is scarce and represented a limitation for the carrying capacity study performed by FARM. No POM or POC concentrations were found for the identified suitable areas, thus, was assumed an annual constant value of 5 and 4 mg L^{-1} for Farm A and B respectively, based off an adaption of the values present in the Tagus Estuary and the paper of Rosa (2010): POM tend to be more concentrated in areas where current speeds are lower, thus, concentrations were gathered from areas within the Tagus estuary with same environmental and current speeds conditions; At first, POC was simulated using a % of TPM based off the concentrations in the Tagus Estuary (both are considered mesotidal well-mixed estuaries, therefore, environmental conditions are similar), however, this proxy would provide concentrations of POM under 1 mg L^{-1} for the whole cultivation period, compromising individual growth and production, drifting the results from the current situation (see Annex D).

Additionally, and regarding the rest of water quality factors, the bulk of monthly values were driven from one single monthly value; for instance, TPM concentrations for Farm A during the months of June and July were over 120 mg L^{-1}, which is most likely related to an error during sampling. A hypothesis might be that the high TPM is a bottom sample and the weight attached to the sampling bottle might have struck the sediment, resuspending particulate matter. However, there was no information regarding the depth the sample was taken, being considered for the study since these were the only available values for the mentioned months.

Lastly, the assessment of production and profit maximization was only achieved for the exotic species (Pacific oyster), being the native species (Portuguese oyster) excluded from this part of the study. Despite the study of Ferreira et al. (2012) using the Pacific oyster growth model to evaluate production and growth of Portuguese oyster, growth of the latter is slower when compared to its homologue; e.g. according to the study of Batista (2007), when oysters reach favourable market sizes (around 65 g of individual total weight) the individual weight of *M. gigas* was two times higher than *M. angulata*; meaning that individual growth rate are not equal for both species. Nevertheless, since both are very close related and, according to the results achieved and the available food sources, Pacific oyster production is higher in Farm A, it can be concluded that production of *M. angulata* would be more profitable in Farm A rather than Farm B, as well.

5. Conclusions

The present work is reliant on the trustworthiness of the used GIS sources. Only the latest files concerning each source were selected for the study, however, this was not possible for all indicators (e.g. Corine Land Cover 2012). This way, some areas defined as existent and accounted for the study, might not exist today (as of 2019), where beaches and industries should be highlighted.

Industries, considered one of the major constraints in the estuary and in the study, can have significant impacts in the constraints and site selection maps if, for example, inactive industries in 2019 were accounted for. This might be of special relevance in the Mitrena area and the vicinity of Setúbal city, where the bulk of industries are located.

Beaches, located in the estuary, possess ecologic and touristic standards that must be preserved. In CLC 2012, was only identified the Albarquel and Tróia beaches, both facing the ocean and being the only ones accounted for the study. Nevertheless, the Tróia bar still holds a large belt of sand faced to the interior of the estuary (i.e. estuarine beach), which should have the same protection status as the ones mentioned before. In order to overcome this problem, was used the buffer performed for the Tróia beach which excluded it for aquaculture siting, in conjunction with the bathymetry.

Piers were considered key infrastructures for transportation of fishermen to more inaccessible areas and harvested products. Even though was used the latest version of Portugal soil occupation chart (COS 2015) to screen out existing piers on the estuary, the Gâmbia port (in the upper area) was not included in COS and, therefore, not accounted for the study. The same applies to the Gâmbia urban area. This is crucial to mention since, the inclusion of Gâmbia infrastructures would influence the socio-economic suitability scores achieved for the upper estuary and, possibly, the results achieved with the site selection map.

Despite being important factors in urban aquaculture, the establishment of safety distances from industries and WTP seem to be lacking on peer reviewed studies, which might be attributed to: i) polluted areas are disregarded by common sense, due to health and hygiene problems (typically on developed countries); or ii) lack of space and spatial management (i.e. China), as well as contaminated water by sewage and industrial waste, which then might have a synergy effect with the existing aquaculture farms' wastewaters (Bricker, 2018); Future aquaculture projects in the estuary are recommended to avoid siting near pollution sources (i.e. by assessing each area's sanitary and health risks by developing a sanitary program to the estuary).

Metal concentrations used to assess Product Quality category were collected in the early 2000s, meaning that it might drift apart from the current situation in the estuary. The same goes to the B2K water quality data, which corresponded to samples taken in the 60s to the early 2000s. In contrast, samples to evaluate PAH contamination were taken in 2011, however, these did not cover the whole estuary and were based on only 5 stations, meaning that the interpolation results were not as accurate as the 71 samples used to assess product contamination. In case this work is used for any project that aims to develop aquaculture in the Sado Estuary, it is recommended to use more recent data or, if possible, collect new samples.

Water quality data for the Sado Estuary is scarce, for instance, there are more than 81 thousand water quality results for the Tagus Estuary, in comparison with the 24 thousand for the Sado Estuary (Ferreira et al., 2005); and, as previously discussed, POM (based off POC concentrations using a conversion ratio of 0.38 POM:POC) represented a major constraint to the study, as only 4 stations at downstream could be used for the GIS study. Since these were sampled at downstream, oceanic currents influenced the deposition of organic matter, meaning that POM concentrations were much lower when compared to other areas less influenced by current speeds, such as the ones selected for aquaculture siting. Nonetheless, and since no studies include POC or POM concentrations for the areas along the Marateca Channel (as of 2019), the results achieved were based from the existing values and drifted far from the current situation, displaying concentrations under 1 mg L^{-1} POM, meaning that food availability for bivalves is low, in areas where several species have been reported to grow.

Despite data scarcity, results achieved from the evaluation of environmental factors support that the estuary provides good conditions for the establishment of oyster populations, even though there are two aspects that need proper attention: i) Survival thresholds must always be respected, as there should be more studies regarding the Portuguese species; and ii) the existing competition between the exotic (e.g. Pacific oyster) and native species (e.g. Portuguese oyster), and the declining of the latter, can lead to its extinction and should be properly managed;

The absence of POM concentrations brought constraints not only for the site selection process, but for the evaluation carried by FARM model as well. FARM classifies POM as phytoplankton and detritus that can be ingested by the oysters, representing one of the main inputs for individual growth. Without POM values, FARM could not be applied. Thus, FARM was performed based on constant values of POM for the whole cultivation period. In order to achieve more precise and realist values of production and environmental impacts of oyster culture, it is recommended to collect new samples regarding the factors that lead oysters to grow (e.g. POC, a proxy to assess POM).

The application of FARM model, although not considered a limitation, should be only seen as indicative of what benefits and impacts may lie in the application of Pacific oyster aquaculture in the estuary. If further developments are seen in Portuguese aquaculture, more specifically in the Sado estuary, more efficient and complex models must be applied (e.g. the inclusion of Portuguese oyster individual and production models), in order to properly evaluate the environmental and socio-economic effects.

In short, the thematic map showed the most important criteria for aquaculture site selection. However, alternative variables and/or classification might produce different outcomes. The application of FARM illustrates the value of dynamic models in providing detailed information on oyster culture feasibility. This is illustrated by the contrast between test farms A and B: the former is at a location where extensive intertidal aquaculture will provide significant profit and associated ecosystem services, whereas the latter will not be viable, despite being flagged as suitable using the GIS tool.

In conclusion and compliance with the questions established in Chapter 1:

- The major spatial constraints identified for shellfish aquaculture were bathymetry and distance to industries;
- Overall, the Sado Estuary displays suitable conditions for oyster aquaculture to prosper, which was expected since oyster populations have been reported to be expanding in the estuary;
- The vicinities of urban areas and ports (>1 km) scored the highest suitability values for production, decreasing as both get more distant;
- The areas identified as most likely to be contaminated followed the conclusions of the original paper (Caeiro et al., 2005): Setúbal port and Lisnave shipyard; However, due to the extent of the data used, some areas reported to be contaminated (i.e. Alcácer Channel) were classified as suitable and comprised pollutant concentrations under the studied limits;
- Identified suitable areas for aquaculture are inserted in the Nature Reserve and Natura 2000, therefore, in the case of farm implementation, environmental impacts must be properly assessed;

Therefore, it is possible to conclude that Portuguese and Pacific oyster aquaculture is viable in the Sado Estuary, showing good prospects regarding environmental and productions conditions.

5.1 Recommendations

In order to enforce an eventual management framework regarding oyster aquaculture in the Sado Estuary, the author provides the following recommendations:

- Detailed information about the oyster production sector in the estuary should be gathered, as of 2019, information is scarce, possibly because producers do not report all the aspects of the sector to the respective agencies. This way, surveys to the current producers in the estuary should be performed in order to better understand the sector needs and enhance production;

- Samples to evaluate water quality should be performed regularly (e.g. annually) on the areas where oysters grow and are produced (i.e. Marateca Channel). Adding to the fact that available data is short and outdated, the estuary is subject to multiple uses, being the projected dredges (TUPEM 030/01/2019 DGRM) of major concern, since these will cause harmful particles to regroup and spread to a larger area in the water column. In addition, a more wide and precise study of sediment contamination should also be performed.

- A more detailed GIS-based site selection should be performed, by using the most recent data and establishing a team with different experts (e.g. GIS, marine pollution and biology), in order to increase the trustworthiness of aquaculture siting. It is advised to evaluate only the areas that respect the survival thresholds of the respective oysters, since it would reduce the chances of an inferior siting.

- The bathymetry used for the study was the best available, but given the nature of sediment movement, once again, with special focus to the projected dredges to increase navigational routes to Setúbal port, the use of an updated bathymetry for hydrodynamics evaluation and identification of available culture areas is highly needed. A regular update of the estuary bathymetry should be performed by an accredited agency, such the Portuguese Hydrographic Institute;

- A more throughout knowledge of the distribution of the Portuguese oyster (*M. angulata*) should assessed, in order to identify other areas (national wide) where these are able to grow. The current pollution situation of the estuary imposes challenges to the monitoring of pollutants (naturally or anthropogenic sourced), which disturbs the success of a sector that could be more profitable. This way, by identifying other suitable areas for growth and survival of the native species, the sector could be boosted;

- Implementation of management guidelines based on: i) the sustainable use of the oyster natural beds; ii) creation of maternities; iii) use of collectors; and iv) the focus on native species production, instead of exotic ones (e.g. Pacific oyster); by avoiding importation of Pacific oyster seed, the introduction of diseases in the estuary could be reduced and the resilience of the native species and the Nature Reserve could be maintained (as also discussed in Portela, 2016);

- An appropriate economic analysis for larger areas should be conducted in the scope of an ecosystem approach to aquaculture, by considering the different types of carrying capacity (Inglis et al., 2000; McKindsey et al., 2006). The author further recommends an assessment of regulatory carrying capacity (Ferreira et al., 2012), in order to create a management plan and enforce its compliance;

Before deciding how to proceed, this problematic in the estuary must be seen from all the possible perspectives: Should Portuguese authorities treat the invasion and expansion of the Pacific oyster as an invasive alien species and protect the native species at all costs? Or should they take advantage of its economic value, as it has been done over the years? The answer seems very ambiguous and, as a serious issue in the estuary, it should not be taken lightly. As such, adding to the lack of data concerning both species' populations in the estuary, more studies should be done in this regard, in order to support, as best as possible, the decision-makers. By this fact, the author gives the following recommendations, based off the paper of Caddy & Deffeo (2003):

- Monitor both species' populations to evaluate their respective numbers and which areas have the highest densities;

- Control of predators; this aims to level the difference between both species' populations;

- Creation of a native species hatchery in the vicinities of the estuary that would help to maintain its wild stock;

Enhancement of the native oysters' wild stocks with seeds raised on hatchery or laboratory-based larvae spawning and rearing (genetic implications should be considered);

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7. Appendix

7.1 Appendix A

In Appendix A, all used data for the creation of each Category's thematic maps is displayed. The tables follow the same sequence as the one used and mentioned in the methodology: Spatial Constraints, Environmental, Socio-economic and Product Quality;

Setúbal port tide table for 2018, used for bathymetry reclassification, available at URL: https://www.portodesetubal.pt/files/Mares_Site.pdf; Reclassification values corresponded to the highest and lowest tide value of 2018 being, respectively, 3.6 and 0.4 m.

Used discharge points and respective coordinates. Retrieved from APA (2018) – Sniamb (i.e. Spatial Constraint – Distance to WTP).

Station name	Description	Latitude (N)	Longitude (E)
WTP1	Sapec	38.5083	-8.8525
WTP2	Cidade de Setúbal	38.523	-8.8863
WTP3	Praia de Alberquel	38.5113	-8.9146
WTP4	Outão (Fab. Secil)	38.4944	-8.931
WTP5	Outão (Fab. Secil)	38.493	-8.9323
WTP6	Zona Industria da Mitrena	38.4902	-8.7944
WTP7	Porto de Setúbal - Eurominas	38.4727	-8.7847
WTP8	Comporta	38.3896	-8.7886
WTP9	Comporta	38.3939	-8.776
WTP10	Pinheiro (RNES)	38.4634	-8.72
WTP11	Mitrena (Santo Ovidio)	38.5227	-8.8091
WTP12	Mitrena (Santo Ovidio)	38.5275	-8.8101
WTP13	Gâmbia	38.5486	-8.7729
WTP14	Tróia (em construção)	38.4393	-8.8306

Obtained data for current speed (m s-1); median was done to see if it would fit in the reclassification values. From Barcawin2000 (Spatial Constraints – Current Speed).

Station name	Latitude (N)	Longitude (E)	MEDIAN Current Speeds (m s-1)
#11A	38.51722222	-8.751388889	0.14
#13A	38.48277778	-8.761111111	0.12
#25	38.4875	-8.818333333	0.16
#26	38.50138889	-8.841666667	0.06
#27	38.47111111	-8.834166667	0.12
#28	38.48083333	-8.862777778	0.24
#29	38.50888889	-8.865833333	0.09
#30	38.51305556	-8.889444444	0.01
#6B	38.44277778	-8.813888889	0.19
#8A	38.52416667	-8.770555556	0.16
#WFix Outão	38.48944444	-8.925833333	0.41
#WFix Sapec	38.50138889	-8.841666667	0.42
#WFix Setúbal	38.51888889	-8.890277778	0.37

(cont.) Obtained data for current speed (m s-1)			
#Wfix Central	38.50333333	-8.85	0.26
#WFix Troia	38.48777778	-8.873055556	0.52

Environmental indicator based off data gathered from Barca2000Win database: Chlorophyll a;

Station name	Latitude (N)	Longitude (E)	MEDIAN Chl a (ug L-1)
#10-00	38.475	-8.808333333	2.8
#10-97	38.52555556	-8.755833333	4.4
#11-97	38.465	-8.792777778	1.9
#11A	38.51722222	-8.751388889	4.4
#12-00	38.52222222	-8.767777778	5.1
#12A	38.51083333	-8.727777778	5.3
#13-97	38.49	-8.835555556	1.3
#13A	38.48277778	-8.761111111	4.3
#4B	38.42888889	-8.810833333	3.7
#6B	38.44277778	-8.813888889	2.2
#8A	38.52416667	-8.770555556	8.3
#9-00	38.45444444	-8.7425	1.6
#9A	38.51222222	-8.796944444	3.5
#RFM	38.50583333	-8.847222222	2.4
#TFM	38.50805556	-8.851111111	2.7
#WFix Outão	38.48944444	-8.925833333	0.7
#WFix Setúbal	38.51888889	-8.890277778	8.1
#WFix Central	38.50333333	-8.85	1.4
#WFix Tróia	38.48777778	-8.873055556	1.7
IH2	38.43416667	-8.725555556	2.4
IH3	38.50583333	-8.744444444	2.4

Environmental indicator based off data gathered from Barca2000Win database: Water Temperature;

Station name	Latitude (N)	Longitude (E)	MEDIAN Water temperature (ºC)
#10-00	38.475	-8.808333333	16.8
#10-97	38.52555556	-8.755833333	23.7
#11-97	38.465	-8.792777778	23.2
#11A	38.51722222	-8.751388889	21.0
#12-00	38.52222222	-8.767777778	13.6
#12A	38.51083333	-8.727777778	20.6
#13-97	38.49	-8.835555556	22.3
#13A	38.48277778	-8.761111111	21.1
#24	38.48722222	-8.839444444	20.1
#25	38.4875	-8.818333333	12.9
#26	38.50138889	-8.841666667	14.6
#27	38.47111111	-8.834166667	14.0
#28	38.48083333	-8.862777778	16.4
#29	38.50888889	-8.865833333	14.3
#30	38.51305556	-8.889444444	17.5
#3B	38.41583333	-8.800833333	22.4

(cont.) Water Temperature;			
#4B	38.42888889	-8.810833333	21.5
#5B	38.43416667	-8.822777778	20.9
#6B	38.44277778	-8.813888889	20.8
#8A	38.52416667	-8.770555556	21.1
#9-00	38.45444444	-8.7425	16.7
#9A	38.51222222	-8.796944444	21.5
#RFM	38.50583333	-8.847222222	18.5
#TFM	38.50805556	-8.851111111	17.2
#WA1	38.51888889	-8.890277778	17.7
#WA10	38.47444444	-8.769444444	20.8
#WA11	38.47722222	-8.761666667	21.2
#WA12	38.51055556	-8.733888889	21.3
#WA2	38.50166667	-8.885833333	17.2
#WA4	38.47111111	-8.834166667	19.7
#WA5	38.47861111	-8.822222222	18.9
#WA6	38.4675	-8.822222222	19.0
#WA7	38.46722222	-8.809444444	19.1
#WA8	38.46111111	-8.801666667	19.1
#WA9	38.46916667	-8.781944444	19.7
#WB1	38.51555556	-8.874166667	19.2
#WB10	38.45916667	-8.779722222	21.2
#WB11	38.47388889	-8.81	19.7
#WB12	38.4925	-8.829444444	20.9
#WB13	38.51194444	-8.8675	19.1
#WB2	38.51888889	-8.890277778	18.5
#WB3	38.43888889	-8.722777778	22.3
#WB8	38.43083333	-8.725555556	23.1
#WFix Outão	38.48944444	-8.925833333	15.7
#WFix Sapec	38.50138889	-8.841666667	16.1
#WFix Setúbal	38.51888889	-8.890277778	14.8
#Wfix Central	38.50333333	-8.85	15.4
#WFix Troia	38.48777778	-8.873055556	18.3
IH2	38.43416667	-8.725555556	19.1
IH3	38.50583333	-8.744444444	19.6
LNETI 1	38.47777778	-8.881111111	19.8
LNETI 2	38.48555556	-8.886111111	19.7
LNETI 3	38.48944444	-8.890277778	19.1
LNETI 4	38.48972222	-8.883888889	18.5
LNETI 5	38.49388889	-8.888333333	18.9
LNETI 6	38.49527778	-8.893055556	18.8
LNETI 7	38.49805556	-8.899166667	19.1
LNETI 8	38.49555556	-8.905277778	19.0
LNETI 9	38.49305556	-8.908333333	18.3
Vertical 1	38.4875	-8.818333333	17.5
Vertical 10	38.46638889	-8.753333333	19.0
Vertical 2	38.51722222	-8.891666667	18.0
Vertical 3	38.49694444	-8.845	18.9
Vertical 4	38.47277778	-8.847777778	15.5

(cont.) Water Temperature;			
Vertical 8	38.47	-8.818055556	16.0
Vertical 9	38.45111111	-8.813611111	16.0

Environmental indicator based off data gathered from Barca2000Win database: Salinity;

Station name	Latitude (N)	Longitude (E)	MEDIAN Salinity (psu)
#10-00	38.475	-8.808333333	34.3
#10-97	38.52555556	-8.755833333	33.3
#11-97	38.465	-8.792777778	35.2
#11A	38.51722222	-8.751388889	33.6
#12-00	38.52222222	-8.767777778	31.3
#12A	38.51083333	-8.727777778	32.5
#13-97	38.49	-8.835555556	35.5
#13A	38.48277778	-8.761111111	33.4
#25	38.4875	-8.818333333	34.4
#26	38.50138889	-8.841666667	33.2
#27	38.47111111	-8.834166667	34.8
#28	38.48083333	-8.862777778	34.9
#29	38.50888889	-8.865833333	35.3
#30	38.51305556	-8.889444444	35.2
#4B	38.42888889	-8.810833333	34.2
#6B	38.44277778	-8.813888889	33.6
#8A	38.52416667	-8.770555556	33.3
#9-00	38.45444444	-8.7425	32.4
#9A	38.51222222	-8.796944444	36.1
#RFM	38.50583333	-8.847222222	35.0
#TFM	38.50805556	-8.851111111	35.1
#WA1	38.51888889	-8.890277778	34.8
#WA10	38.47444444	-8.769444444	33.4
#WA11	38.47722222	-8.761666667	33.3
#WA12	38.51055556	-8.733888889	32.4
#WA2	38.50166667	-8.885833333	34.7
#WA4	38.47111111	-8.834166667	34.4
#WA5	38.47861111	-8.822222222	34.4
#WA6	38.4675	-8.822222222	34.5
#WA7	38.46722222	-8.809444444	34.3
#WA8	38.46111111	-8.801666667	34.2
#WA9	38.46916667	-8.781944444	33.5
#WB1	38.51555556	-8.874166667	34.7
#WB10	38.45916667	-8.779722222	32.7
#WB11	38.47388889	-8.81	33.9
#WB12	38.4925	-8.829444444	33.8
#WB13	38.51194444	-8.8675	33.9
#WB2	38.51888889	-8.890277778	34.6
#WB3	38.43888889	-8.722777778	29.0
#WB8	38.43083333	-8.725555556	29.9
#WC10	38.44888889	-8.767222222	33.1

(cont.) Salinity;			
#WC11	38.45583333	-8.783333333	33.8
#WC12	38.46111111	-8.801666667	34.3
#WC17	38.50166667	-8.885833333	35.1
#WC8	38.43083333	-8.725555556	31.0
#WF10	38.49583333	-8.748611111	31.6
#WF11	38.51722222	-8.751388889	33.3
#WF2	38.49888889	-8.906666667	35.6
#WF3	38.50166667	-8.885833333	35.1
#WF5	38.47111111	-8.834166667	34.4
#WF6	38.4675	-8.822222222	33.7
#WF7	38.46861111	-8.796944444	33.5
#WF8	38.47444444	-8.769444444	33.3
#WF9	38.47722222	-8.761666667	33.4
#WFix Outão	38.48944444	-8.925833333	33.8
#WFix Sapec	38.50138889	-8.841666667	33.6
#WFix Setúbal	38.51888889	-8.890277778	32.8
#Wfix Central	38.50333333	-8.85	28.2
#WFix Troia	38.48777778	-8.873055556	33.9
IH2	38.43416667	-8.725555556	32.5
IH3	38.50583333	-8.744444444	33.2
Vertical 1	38.4875	-8.818333333	37.8
Vertical 10	38.46638889	-8.753333333	35.0
Vertical 2	38.51722222	-8.891666667	37.5
Vertical 3	38.49694444	-8.845	36.6
Vertical 4	38.47277778	-8.847777778	36.5
Vertical 8	38.47	-8.818055556	35.6
Vertical 9	38.45111111	-8.813611111	35.9

Environmental indicator based off data gathered from Barca2000Win database: Dissolved Oxygen;

Station name	Latitude (N)	Longitude (E)	MEDIAN Dissolved oxygen (mg L-1)
#10-00	38.475	-8.808333333	7.8
#10-97	38.52555556	-8.755833333	5.1
#11-97	38.465	-8.792777778	5.6
#11A	38.51722222	-8.751388889	5.7
#12-00	38.52222222	-8.767777778	8.3
#13-97	38.49	-8.835555556	6.1
#24	38.48722222	-8.839444444	7.9
#28	38.48083333	-8.862777778	8.0
#30	38.51305556	-8.889444444	7.8
#4B	38.42888889	-8.810833333	7.4
#6B	38.44277778	-8.813888889	9.0
#9-00	38.45444444	-8.7425	8.0
#9A	38.51222222	-8.796944444	6.4
#RFM	38.50583333	-8.847222222	6.9
#TFM	38.50805556	-8.851111111	6.5
#WB1	38.51555556	-8.874166667	9.0

(cont.) Dissolved Oxygen;			
#WB10	38.45916667	-8.779722222	8.0
#WB11	38.47388889	-8.81	8.6
#WB12	38.4925	-8.829444444	8.4
#WB13	38.51194444	-8.8675	9.0
#WB2	38.51888889	-8.890277778	9.1
#WB3	38.43888889	-8.722777778	6.8
#WB8	38.43083333	-8.725555556	6.9
#WFix Outão	38.48944444	-8.925833333	7.0
#WFix Sapec	38.50138889	-8.841666667	7.6
#WFix Setúbal	38.51888889	-8.890277778	9.3
#Wfix Central	38.50333333	-8.85	6.5
#WFix Troia	38.48777778	-8.873055556	7.2
IH2	38.43416667	-8.725555556	7.5
IH3	38.50583333	-8.744444444	7.2
LNETI 1	38.47777778	-8.881111111	7.7
LNETI 2	38.48555556	-8.886111111	7.5
LNETI 3	38.48944444	-8.890277778	7.8
LNETI 4	38.48972222	-8.883888889	7.7
LNETI 5	38.49388889	-8.888333333	7.9
LNETI 6	38.49527778	-8.893055556	8.0
LNETI 7	38.49805556	-8.899166667	7.8
LNETI 8	38.49555556	-8.905277778	8.0
LNETI 9	38.49305556	-8.908333333	7.8
Vertical 1	38.4875	-8.818333333	7.8
Vertical 10	38.46638889	-8.753333333	7.5
Vertical 2	38.51722222	-8.891666667	7.6
Vertical 3	38.49694444	-8.845	7.7
Vertical 4	38.47277778	-8.847777778	8.1
Vertical 8	38.47	-8.818055556	8.1
Vertical 9	38.45111111	-8.813611111	8.0

POM transformation: POC values were multiplied to TPM (for each station), then converted to mg L-1 by dividing by 10000 and finally POC to POM conversion ratio was used, 0.38. POC concentrations were gathered from Barca2000Win database.

Station name	Latitude (N)	Longitude (E)	MEDIAN POC (mg m-3)	POM (mg L-1)
#WFix Outão	38.48944444	-8.925833333	267.105	0.267
#WFix Setúbal	38.51888889	-8.890277778	14.447	0.014
#Wfix Central	38.50333333	-8.85	571.053	0.571
#WFix Troia	38.48777778	-8.873055556	413.158	0.413

Environmental indicator based off data gathered from Barca2000Win database: Total Particulate Matter;

Station name	Latitude (N)	Longitude (E)	MEDIAN TPM (mg L-1)
#10-97	38.52555556	-8.755833333	36.1
#11-97	38.465	-8.792777778	26.7
#11A	38.51722222	-8.751388889	30.3

(cont.) Total Particulate Matter;			
#12A	38.51083333	-8.727777778	57.3
#13-97	38.49	-8.835555556	12.6
#13A	38.48277778	-8.761111111	29.6
#24	38.48722222	-8.839444444	7.8
#25	38.4875	-8.818333333	25.4
#26	38.50138889	-8.841666667	9.6
#27	38.47111111	-8.834166667	8.2
#28	38.48083333	-8.862777778	6.7
#29	38.50888889	-8.865833333	8.4
#30	38.51305556	-8.889444444	4.3
#4B	38.42888889	-8.810833333	30.7
#6B	38.44277778	-8.813888889	12.5
#8A	38.52416667	-8.770555556	74.5
#9A	38.51222222	-8.796944444	21.9
#RFM	38.50583333	-8.847222222	14.0
#TFM	38.50805556	-8.851111111	12.0
#WFix Outão	38.48944444	-8.925833333	8.5
#WFix Sapec	38.50138889	-8.841666667	8.0
#WFix Setúbal	38.51888889	-8.890277778	3.9
#WFix Troia	38.48777778	-8.873055556	11.1
IH2	38.43416667	-8.725555556	5.0
IH3	38.50583333	-8.744444444	6.5
Vertical 1	38.4875	-8.818333333	6.0
Vertical 10	38.46638889	-8.753333333	23.0
Vertical 2	38.51722222	-8.891666667	7.0
Vertical 3	38.49694444	-8.845	11.5
Vertical 4	38.47277778	-8.847777778	10.0
Vertical 8	38.47	-8.818055556	12.0
Vertical 9	38.45111111	-8.813611111	10.0

Product Quality – Metal concentrations in the study area, gathered from Caeiro et al. (2005).

Station	LAT (N)	LON (E)	Cd	Pb	Zn	Cu	As	Hg
			ppm					
1	38.515475	-8.9042	5.80	64.00	206.00	59.00	22.00	0.43
2	38.513867	-8.90761	2.80	24.00	98.00	30.00	15.00	0.19
4	38.509299	-8.91226	1.30	28.00	34.00	7.00	7.20	0.07
8	38.497203	-8.92063	0.90	2.00	4.00	4.00	3.00	0.07
10	38.496356	-8.9118	0.30	3.50	7.40	1.00	4.50	0.06
11	38.499553	-8.9109	0.20	3.60	6.40	1.00	3.60	0.07
14	38.506219	-8.90729	3.50	17.00	110.00	31.00	21.00	0.21
16	38.510272	-8.90173	1.10	6.20	32.00	10.00	7.50	0.08
17	38.51608	-8.89589	3.20	26.00	149.00	46.00	21.00	0.45
19	38.512548	-8.89519	3.90	21.00	130.00	48.00	21.00	0.28
21	38.505777	-8.89656	1.00	5.10	34.00	9.00	7.60	0.07
23	38.500605	-8.8988	1.00	3.50	24.00	5.00	21.00	0.06
24	38.497316	-8.90198	1.10	2.00	9.00	4.00	8.00	0.07
25	38.494646	-8.90519	0.40	3.40	2.10	10.00	21.00	0.06

(cont.) Product Quality – Metal concentrations.

26	38.494907	-8.9087	0.30	3.60	3.30	1.00	7.90	0.07
31	38.507414	-8.88392	0.50	3.30	6.30	2.00	1.10	0.06
32	38.509641	-8.87906	0.50	3.10	7.90	3.00	3.10	0.06
33	38.514177	-8.8789	0.20	8.90	59.00	21.00	12.00	0.20
34	38.507899	-8.85925	8.00	36.00	272.00	149.00	54.00	0.65
35	38.502622	-8.84814	6.00	28.00	213.00	98.00	33.00	0.50
36	38.495857	-8.84084	2.00	8.90	67.00	24.00	13.00	0.12
37	38.490599	-8.83161	1.60	9.40	56.00	15.00	9.40	0.36
39	38.48577	-8.82379	2.50	16.00	104.00	42.00	16.00	0.22
40	38.481075	-8.81775	6.50	35.00	273.00	92.00	41.00	0.65
43	38.469192	-8.79903	6.40	69.00	507.00	191.00	37.00	0.41
52	38.444132	-8.77592	1.20	5.00	57.00	6.00	10.00	0.08
53	38.454023	-8.77958	2.10	8.30	79.00	15.00	12.00	0.07
55	38.459643	-8.7918	1.30	5.00	49.00	5.00	7.00	0.07
56	38.462575	-8.79794	1.50	8.40	52.00	13.00	9.10	0.18
57	38.465469	-8.80622	2.20	13.00	69.00	15.00	11.00	0.10
58	38.47003	-8.81323	2.30	11.00	74.00	22.00	12.00	0.16
59	38.474003	-8.8161	1.30	5.30	20.00	7.00	4.00	0.07
60	38.477864	-8.82267	0.60	3.30	12.00	4.00	3.30	0.06
61	38.482811	-8.82815	1.80	10.00	56.00	16.00	11.00	0.21
63	38.49226	-8.84416	0.40	3.70	19.00	3.00	3.70	0.07
65	38.502591	-8.85887	1.20	7.00	42.00	14.00	9.00	0.07
70	38.484527	-8.8484	1.40	8.00	47.00	11.00	9.00	0.08
74	38.462572	-8.81098	0.60	3.00	12.00	3.00	7.00	0.06
75	38.465627	-8.81418	0.80	4.00	28.00	4.00	3.00	0.08
82	38.452687	-8.79966	1.00	4.00	34.00	6.00	9.00	0.08
86	38.46953	-8.82786	0.70	19.00	85.00	3.00	8.00	0.06
90	38.497099	-8.86364	3.30	23.00	131.00	31.00	23.00	0.50
93	38.476838	-8.84499	0.80	5.00	28.00	6.00	58.00	0.06
95	38.474998	-8.8317	0.60	4.00	57.00	11.00	2.00	0.06
98	38.45939	-8.81627	1.20	6.00	58.00	9.00	9.00	0.06
102	38.446438	-8.80493	6.30	2.00	199.00	43.00	38.00	0.26
105	38.455778	-8.82148	1.50	7.00	65.00	11.00	10.00	0.06
113	38.49795	-8.89071	1.40	7.00	41.00	9.00	7.00	0.07
116	38.481928	-8.86748	0.60	3.00	13.00	3.00	7.00	0.06
117	38.477504	-8.86008	0.80	4.00	18.00	4.00	9.00	0.08
118	38.472153	-8.85474	0.60	3.00	19.00	3.00	7.00	0.06
119	38.467559	-8.84475	1.40	7.00	47.00	8.00	9.00	0.08
125	38.453284	-8.84027	5.60	22.00	162.00	39.00	29.00	0.24
128	38.465744	-8.85914	1.00	5.00	37.00	10.00	7.00	0.27
131	38.496686	-8.88351	1.80	9.00	58.00	14.00	11.00	0.08
132	38.490556	-8.88624	0.70	2.00	4.00	4.00	3.00	0.07
136	38.458199	-8.84154	1.80	10.00	70.00	12.00	14.00	0.09
138	38.450147	-8.82596	0.60	2.00	17.00	3.00	2.00	0.06
139	38.469104	-8.78838	5.90	48.00	295.00	94.00	39.00	0.35
147	38.457967	-8.76749	0.80	3.00	22.00	4.00	6.00	0.06
148	38.464734	-8.76708	0.60	2.00	20.00	3.00	7.00	0.06
149	38.469116	-8.77018	0.60	3.00	15.00	3.00	7.00	0.06

(cont.) Product Quality – Metal concentrations.									
150	38.469084	-8.77785	7.40	33.00	219.00	70.00	45.00	0.35
151	38.469512	-8.77309	0.80	3.00	14.00	3.00	6.00	0.06
153	38.460737	-8.75828	3.00	10.00	86.00	20.00	14.00	0.02
156	38.46558	-8.75714	1.70	7.00	74.00	12.00	13.00	0.07
157	38.463655	-8.74958	6.20	24.00	221.00	49.00	41.00	0.29
800	38.445627	-8.78736	0.60	2.00	5.00	3.00	7.00	0.06
1110	38.487541	-8.88048	0.60	3.00	12.00	3.00	7.00	0.06
1111	38.490433	-8.87457	1.70	6.00	40.00	10.00	9.00	0.09
1240	38.448167	-8.8283	1.30	5.00	32.00	6.00	8.00	0.07

Note: Sampling stations coordinates were not available in the original paper, being achieved using Google Earth Pro.

Product Quality – PAH's concentrations from Carreira et al. (2013).

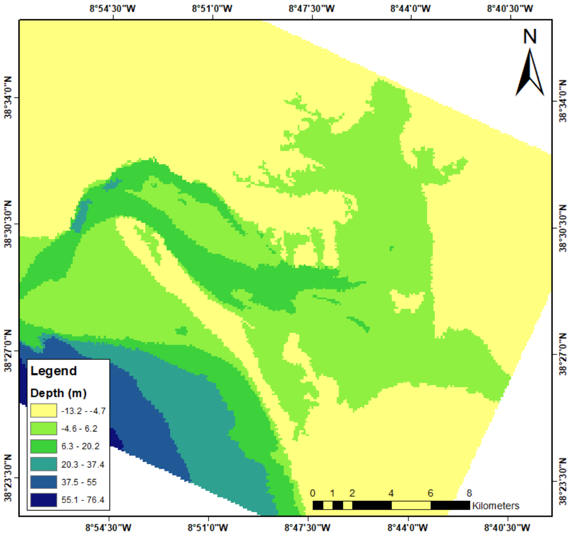
Station Number	LAT (N)	LON (E)	tPAH (ppb)
S1	38.497667	-8.863598	23.9
S2	38.484127	-8.857107	19.6
S3	38.481924	-8.833032	1077.0
S4	38.418803	-8.697143	215.0
S5	38.415083	-8.682446	82.5

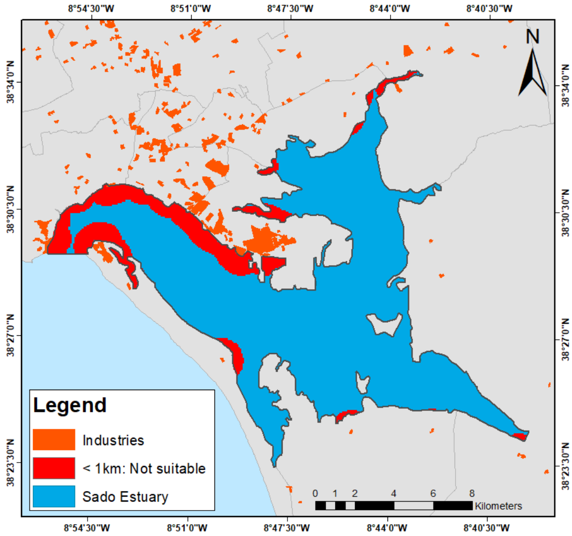
Note: Sampling stations coordinates were not available in the original paper, being achieved using Google Earth Pro.

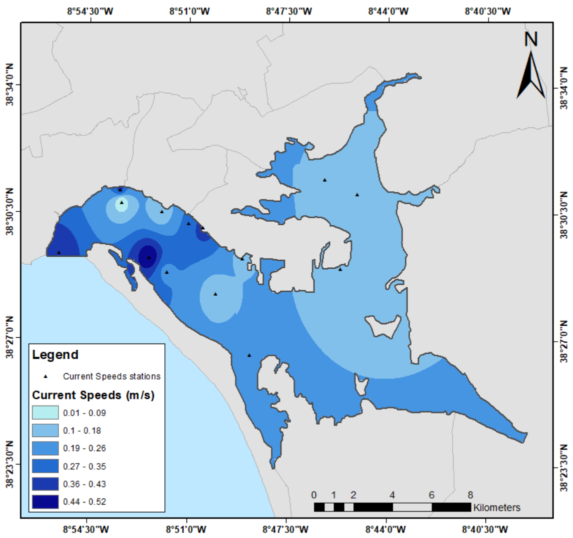
7.2 Appendix B

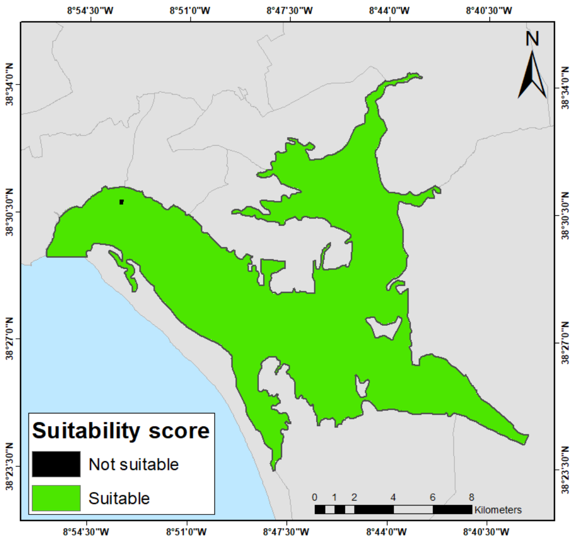
In the presented, thematic maps created in Stage 1 are displayed in the following order: i) Spatial Constraints; ii) Socio-economic; iii) Product Quality; thematic maps (on the left) are displayed side-by-side with the respective reclassification map (on the right).

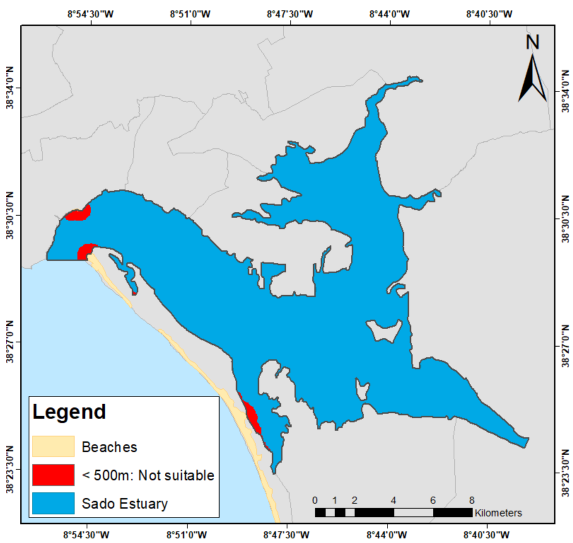
Spatial Constraints.

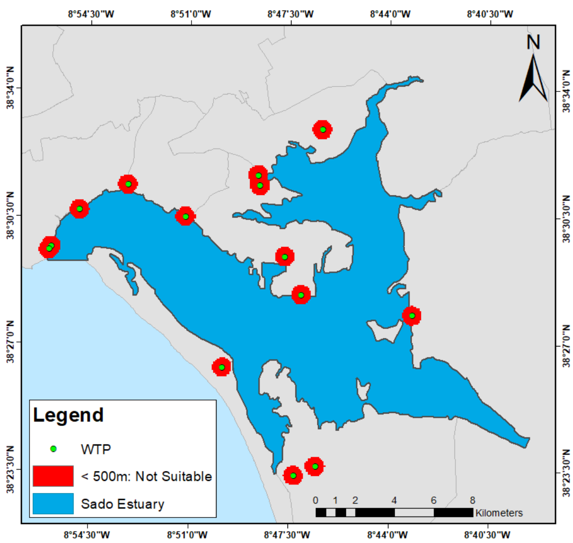


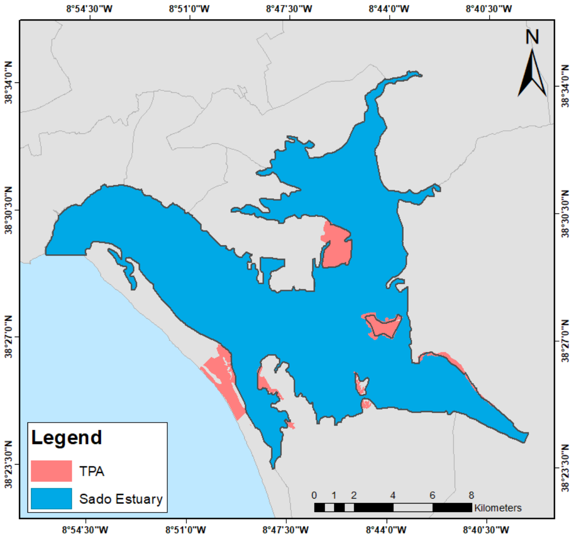


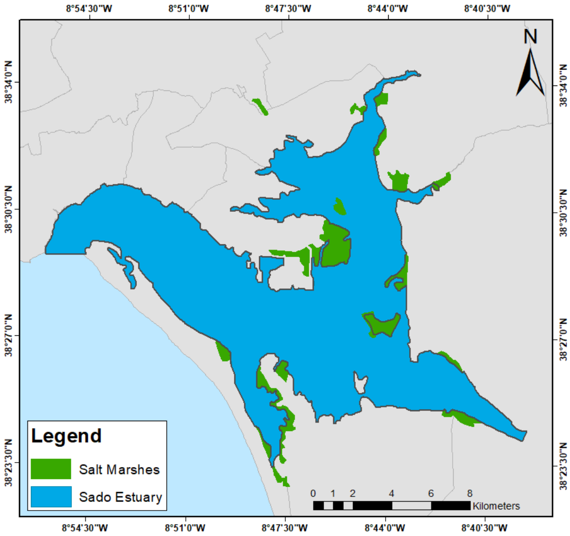




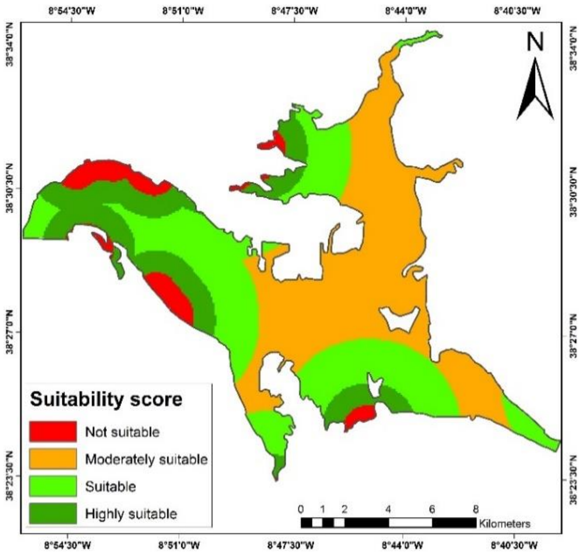


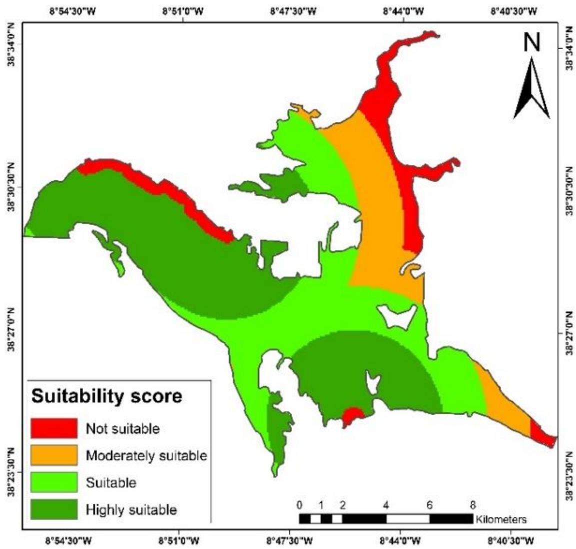


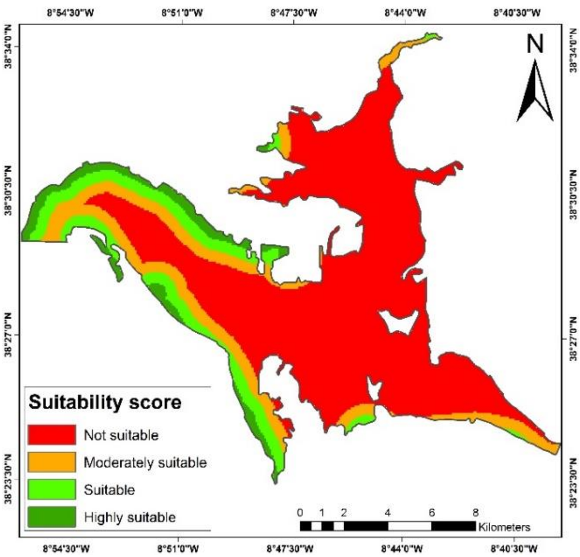




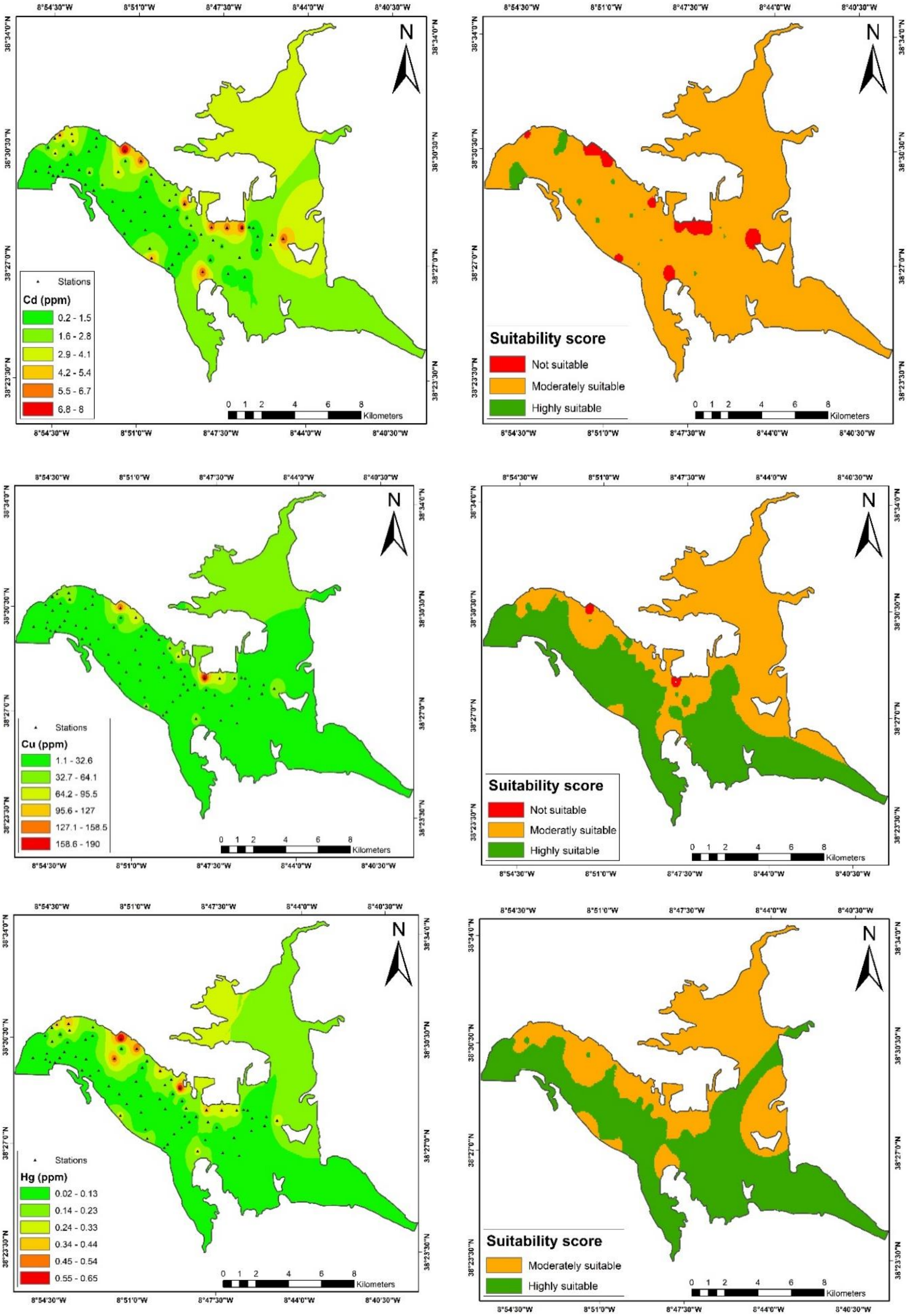
Socio-economic factors: this category represent the only exception to the “side-by-side” approach. Here are only displayed the reclassification maps, as the polygons (i.e. Ports and Urban Areas, which are represented by the upper right and left figures, respectively) and line (i.e. Roads, at the bottom) files, were already displayed in Chapter 4.1.3.1.

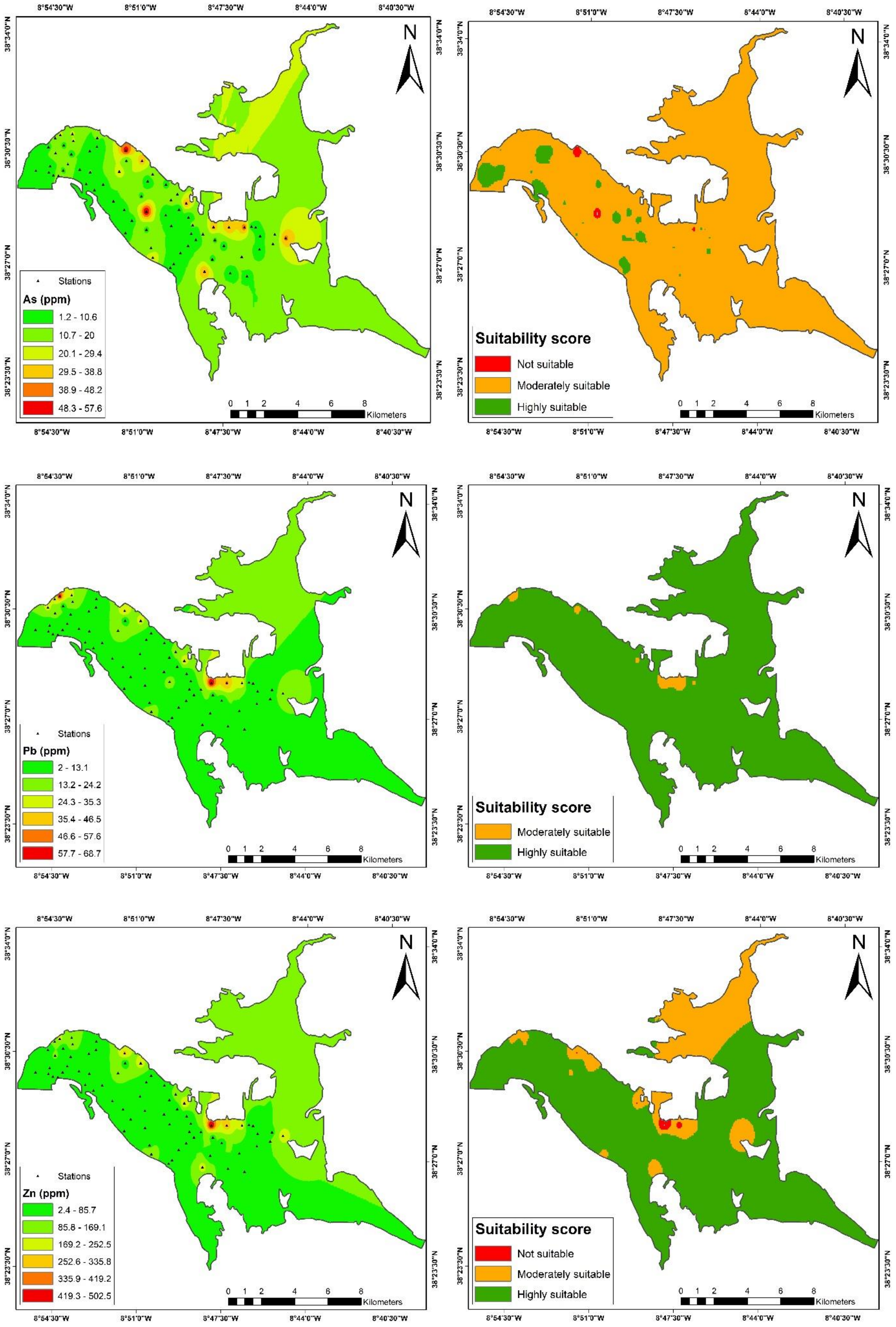


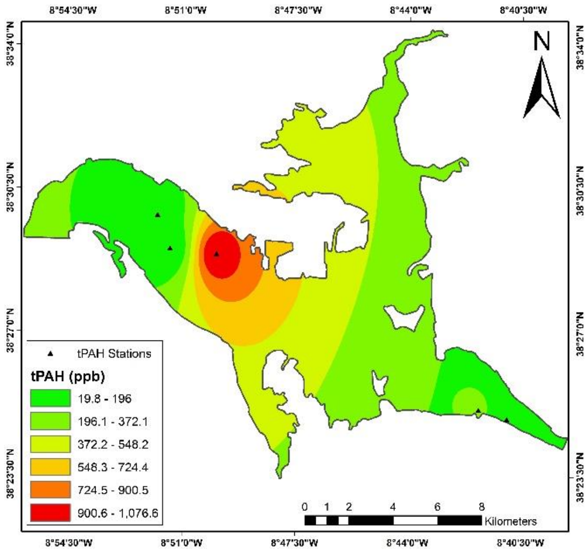


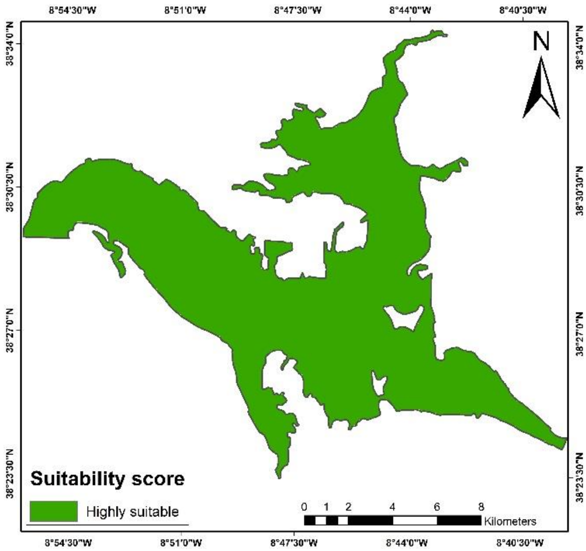


Product Quality thematic (on the left) and respective reclassification maps (on the right).




Stations
As (ppm)
1.2 - 10.6
10.7 - 20
20.1 - 29.4
29.5 - 38.8
38.9 - 48.2
48.3 - 57.6
Suitability score
Not suitable
Moderately suitable
Highly suitable
Stations
Pb (ppm)
2 - 13.1
13.2 - 24.2
24.3 - 35.3
35.4 - 46.5
46.6 - 57.6
57.7 - 68.7
Suitability score
Moderately suitable
Highly suitable
Stations
Zn (ppm)
2.4 - 85.7
85.8 - 169.1
169.2 - 252.5
252.6 - 335.8
335.9 - 419.2
419.3 - 502.5
Suitability score
Not suitable
Moderately suitable
Highly suitable
N
0 1 2 4 6 8 Kilometers
8°54'30"W 8°51'0"W 8°47'30"W 8°44'0"W 8°40'30"W
38°34'0"N 38°30'30"N 38°27'0"N 38°23'30"N


8°54'30"W
8°51'0"W
8°47'30"W
8°44'0"W
8°40'30"W
38°34'0"N
38°30'30"N
38°27'0"N
38°23'30"N
N
tPAH Stations
tPAH (ppb)
19.8 - 196
196.1 - 372.1
372.2 - 548.2
548.3 - 724.4
724.5 - 900.5
900.6 - 1,076.6
0 1 2 4 6 8
Kilometers


8°54'30"W
8°51'0"W
8°47'30"W
8°44'0"W
8°40'30"W
38°34'0"N
38°30'30"N
38°27'0"N
38°23'30"N
N
Suitability score
Highly suitable
0 1 2 4 6 8
Kilometers

7.3 Appendix C

In the first part of the AHP, the general methodology was applied to each category (Environmental, Socio-economic and Product Quality and respective indicators). In the general methodology explanation, it is mentioned only each category. However, in Part One, each category's indicator was used in order to evaluate their weight. The step to step methodology explained here is based on Saaty (1980, 2008), with only a few minor adaptions. Criterion can be applied to either categories or indicators:

1) A hierarchy should be established, consisting of goal, criteria, sub criteria and alternatives: this is a fundamental step to the process of AHP. Hierarchy indicates a relationship between elements of one level with those of the level immediately below. This relationship percolates down to the lowest levels of the hierarchy and in this manner every element is connected to every other one, at least in an indirect manner. A hierarchy is a more orderly form of a network. An inverted tree structure is like a hierarchy. Saaty (1980) suggests that a useful way to structure the hierarchy is to work down from the goal as far as one can and then work up from the alternatives until the levels of the two processes are linked in such a way as to make comparisons possible (pairwise comparison).

2) After a proper hierarchy is defined, data are collected from experts or decision-makers corresponding to the hierarchic structure, in the pairwise comparison of alternatives on a quantitative scale: if the relative score in a comparison between criterion J and K is 7, that means that J is much more import than K. The comparisons are made for each criterion.

Table of relative scores between pairs (Criterion J and Criterion K).

Intensity of importance	Definition	Explanation
1	Equal Importance	Criterion J and K are equally important
3	Somewhat more important	Criterion J is slightly more important than K
5	Much more important	Criterion J is more important than K
7	Very much more important	Criterion J is strongly more important than K
9	Absolutely more important	Criterion J is absolutely more important than K
2,4,6,8	Intermediate values	Values in-between

3) The pairwise comparison of all the criteria generated in step 2 are organized into a square matrix (m x m, where m is the number of criteria). The diagonal elements of the matrix are 1. The criterion in the jth row is better than criterion in the kth column if the value of element (j, k) is more than 1; otherwise the criterion in the kth column is better than that in the jth row. Both (j, k) element of the matrix and the (k, j) element must satisfy the following constraint

$$(j, k) . (k, j) = 1$$

4) Priority vector is obtained by adding each column of the square matrix already created; afterwards, each element of the matrix is divided by the sum of its column (normalized relative weight), where the sum of each column is 1. The normalized principal Eigen vector can be obtained by averaging across the rows.

5) The consistency of the matrix of order n (number of evaluated criterion) is evaluated. Comparisons made by this method are subjective and the AHP tolerates inconsistency through the amount of redundancy in the approach. If this consistency index fails to reach a required level, then answers to comparisons may be re-examined. The consistency index, CI, is calculated as:

$$CI = \frac{\lambda_{máx} - n}{n - 1}$$

Where $\lambda_{máx}$ is the maximum eigenvalue of the judgement matrix. Afterwards, CI (Consistency Index) can be compared with the respective numbers in the random matrix (RI).

Random Consistency Matrix (RI).

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

The ratio between CI and RI is called the Consistency Ratio (CR), which is demonstrated below. Saaty (1980, 2008) suggests that the value of CR should be less than 10% (or 0.01).

$$CR = \frac{CI}{RI}$$

7.4 Appendix D

Appendix D displays FARM's environmental drivers for both test farms (Farm A and Farm B), as well various seeding density inputs to assess economic and production optimization.

Farm A environmental data (B2K Station #8A).

Month	Temp (ºC)	Salinity (psu)	DO (mg L-1)	POM (mg L-1)	Chl a (ug L-1)	TPM (mg L-1)	DIN (umol L-1)
1	13.65	27.19	9.30	5.00	2.28	27.50	57.20
2	13.66	32.41	7.02	5.00	1.90	19.42	49.88
3	18.53	32.58	8.90	5.00	3.58	54.36	63.75
4	20.96	33.41	7.78	5.00	8.54	74.02	58.29
5	23.39	33.66	7.71	5.00	9.66	96.13	45.42
6	22.89	33.32	6.23	5.00	8.97	123.20	32.67
7	24.96	33.53	6.53	5.00	10.68	121.57	37.77
8	26.16	33.45	6.02	5.00	8.97	87.85	23.13
9	20.20	33.21	7.16	5.00	7.49	68.23	32.88
10	18.87	31.62	7.27	5.00	6.03	50.14	40.98
11	16.26	32.40	7.73	5.00	6.01	66.81	45.10
12	14.96	33.01	8.56	5.00	8.96	48.33	38.02

Farm B environmental data (B2K Station IH3).

Month	Temp (ºC)	Salinity (psu)	DO (mg L-1)	POM (mg L-1)	Chl a (ug L-1)	TPM (mg L-1)	DIN (umol L-1)
1	13.55	30.97	8.71	4.00	1.24	5.42	23.21
2	12.85	31.86	8.83	4.00	1.58	4.50	24.80
3	17.03	30.05	7.71	4.00	2.38	5.25	26.39
4	18.96	31.49	7.51	4.00	3.00	8.38	24.29
5	20.90	32.93	7.31	4.00	3.62	13.50	23.24
6	21.83	22.19	6.90	4.00	7.07	10.33	22.19
7	23.49	29.31	6.45	4.00	5.90	8.17	25.76
8	25.15	36.42	6.00	4.00	4.73	6.00	27.55
9	22.00	29.33	6.61	4.00	2.27	6.33	29.33
10	19.35	30.51	7.34	4.00	2.05	5.17	24.68
11	16.70	31.69	8.06	4.00	1.83	6.00	22.36
12	14.25	30.09	8.58	4.00	0.90	6.33	20.04

Economic analysis for Farm A.

Seed (ton)	TPP (ton)	APP	MPP	VMP (€)	TR (€)	TC (k€)	Profit (k€)
0.0	0	0	0.00	0.00	0.0	0.0	0.0
0.9	7	7	7.30	32.47	29.2	0.8	28.4
3.3	30	9	9.90	44.06	145.4	2.9	142.5
6.3	69	11	12.89	57.34	361.3	5.6	355.7
15.0	169	11	**11.54**	51.35	770.3	13.4	**757.0**
24.0	225	9	6.16	27.43	658.4	21.4	637.0
33.0	243	7	2.07	9.20	303.7	29.4	274.3
36.6	242	7	-0.51	-2.29	-83.8	32.5	-116.3

(cont.) Economic analysis for Farm A.							
36.6	242	7	-0.41	-1.84	-67.5	32.6	-100.1
38.1	241	7	-0.33	-1.46	-55.8	33.9	-89.7

Economic analysis for Farm B.

Seed (ton)	TPP (ton)	APP	MPP	VMP (€)	TR (€)	TC (k€)	Profit (k€)
0.0	0	0	0.0	0.00	0.0	0.0	0.0
0.2	5	20	19.75	87.90	21.1	0.2	20.9
0.3	6	19	18.40	81.89	27.0	0.3	26.7
0.5	9	19	17.58	78.25	35.2	0.4	34.8
0.9	15	17	15.37	68.41	61.6	0.8	60.8
1.1	17	16	11.81	52.56	55.2	0.9	54.3
1.8	25	14	**10.51**	46.76	84.2	1.6	**82.6**
2.4	29	12	6.24	27.77	66.6	2.1	64.5
3.3	30	8	1.68	7.46	24.6	2.9	21.7
6.6	33	6	0.74	3.29	21.7	5.9	15.9
5.7	33	6	-0.16	-0.73	-4.2	5.1	-9.3
6.0	33	6	-0.91	-4.04	-24.3	5.3	-29.6
6.1	32	5	-5.54	-24.65	-150.4	5.4	-155.8