Project	AtlantOS – 633211
Deliverable number	8.2.
Deliverable title	Aquaculture site selection Report: Report on potential, selected sites for offshore aquaculture along the Spanish, Norwegian and Irish Atlantic coasts.
Description	European policy intends to expand the space available to aquaculture by cultivating sites that are offshore. This presents challenges in terms of building structures e.g. fish cages that withstand the effects of offshore weather conditions along the Atlantic coast. In order to establish possible future sites for offshore aquaculture production we intend to gather relevant wave, current velocity and water column structure measurements from the coasts of Ireland, Norway and Spain and use these data to validate site assessment models at ca. 200 m horizontal resolution of the potential new offshore aquaculture sites. This will result in a generic tool based on *in-situ* observations and model output over a hindcast period, coupled to existing site decision tools, so that potential license applicants can pinpoint sites for further exploration and site investigation.
Work Package number	8
Work Package title	Societal benefits from observing/information systems
Lead beneficiary	NIVA
Lead authors	Trine Dale, Caroline Cusack & Manuel Ruiz
Contributors	John Rune Selvik, Dag Hjermann, Tomasz Dabrowski, Kieran Lyons, Ramona Carr and Eleanor O'Rourke.
Submission data	31.08.2017
Due date	31.03.2017
Comments	Some of the datasets needed for product development was delayed due to the high demand for mapping services and data from external sources which is going far beyond the originally planned work.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement n° 633211.

Contents

1. Summary

The AtlantOS WP 8 “Societal benefits from observing/information systems” has an ambition to deliver a suite of new or improved products that are targeted at issues of societal concern in European Member States. The issues of concern overlap with the GEOSS societal benefit areas on biodiversity and ecosystem sustainability, disaster resilience, food security, transport management, and water resources management. The value and societal benefit of the existing observing system in the Atlantic will be demonstrated through seven pilot cases. The WP 8 pilot cases are tangible outputs from the integration of Earth observation, *in-situ* data systems and model analyses, reanalysis and forecasts presented as usable products, or demonstrations of potential products.

The use case “Offshore aquaculture siting” (AtlantOS task 8.5) will demonstrate the use of presently available oceanographic variables for aquaculture site selection products. Furthermore, the use case will point to the gaps between the data available and the requirements for aquaculture site selection demonstrating the interest of improved ocean observations.

Complete site selection involves the integration of data addressing all aspects of the intersection between planning needs and user requirements, spatial restrictions, operational requirements from the aquaculture industry (e.g. distance to port), animal welfare and growth, and environmental assimilative capacity (e.g. dilution of organic material and nutrients) as issues to consider. A comprehensive site selection analysis was outside the scope of the deliverable, and cases presented here focus on a few selected requirements related to wave, current velocity, temperature and chlorophyll *a*. In addition, some spatial restrictions such as protected areas and habitats, fisheries areas, and maritime activities (e.g. Ship Routes, Oil & Gas installations) were included. A geographical information system (GIS) approach was the chosen analytical tool. An analytical framework was set up for each case reflecting the area differences (e.g. data availability).

The report is a formal requirement of Deliverable 8.2, submitted in Month 24 of the project. It presents the outcome of GIS analysis in the form of maps to identify areas/sites suitable for offshore aquaculture production along the coasts of Ireland, Norway and Spain. This report focuses on new AtlantOS products to provide useful information and support to decision makers on aquaculture site selection.

Ocean data products (e.g. model outputs) throughout the ocean observing value chain were used to create and build GIS tools to develop targeted products for potential offshore aquaculture siting. The ocean based products were enhanced and supported by GIS data layers derived from satellites and/or administrative layers (e.g. Coastline, Infrastructure, Fishing Areas etc.). The simple flow diagram in Figure 1 presents the upstream essential ocean variables (ocean data), the midstream merged products (models, satellite and *in-situ*) and the additional administrative products. Since downstream product development is an iterative process, the next step will require a thorough assessment of the developed products by end-users. This will, in turn, drive the continued development and improvement of the products.

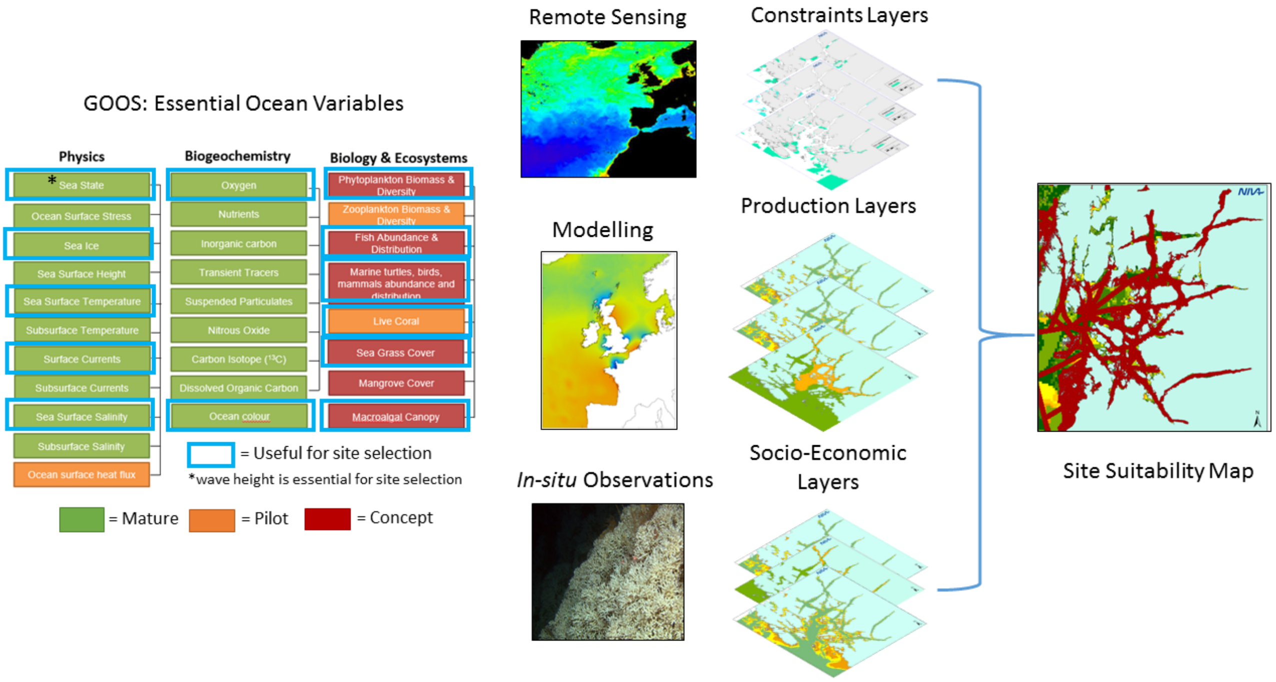

Figure 1. Conceptual model of the aquaculture site selection GIS approach. The left side of the figure presents the GOOS Essential Ocean Variables (EOVs) and indicates their potential use in the development of aquaculture siting tools.

2. Acronyms

Abbreviation	Description
FAO	Food and Agriculture organization of the United Nations
EEZ	Exclusive economic zone
GIS	Geographic Information System
MCE	Multi-criteria evaluation
GEOSS	Global Earth Observation System of Systems
MPA	Marine Protected Areas
HSE	Norwegian risk based legislation on Health, Safety & Environment
MSFD	Marine Strategy Framework Directive
HAB	Harmful algal bloom
SST	Sea surface temperature
WMS	Web Map Service
WFS	Web Feature Service

3. Introduction

The AtlantOS WP 8 “Societal benefits from observing/information systems” has an ambition to deliver a suite of new or improved products that are targeted at issues of societal concern in European Member States. The value and societal benefit of the existing observing system in the Atlantic will be demonstrated through seven pilot cases: HABs mapping, storm surge coastal hazard mapping, safe ship routing, oil spill hazards mapping, MSFD reporting, site selection for mariculture and forecast of North Atlantic albacore tuna populations.

The WP 8 pilot cases are tangible outputs from the integration of Earth observation, *in-situ* data systems and model analyses, reanalysis and forecasts to form usable products. These end-user focused products may be a contribution to the forthcoming EMODnet Atlantic Checkpoint Portal in terms of development of the algorithms and basic tools to evaluate fitness for purpose of the monitoring system. The present report describes use case 8.5, focused on offshore aquaculture siting.

Aquaculture is the fastest growing food production system in the world. Over the past 30 years, this industry has grown steadily by 8-10 % per annum and this trend is set to continue. An important milestone was reached in 2014: for the first time human food supply from aquaculture activities surpassed that of wild-caught fish (FAO 2016). Today, nearly all global aquaculture is carried out inshore. For example, a Google Earth-based study in the Mediterranean showed that 80 % of fish cages and pens were within a distance of 1 km from the coast (Trujillo *et al.* 2012). Despite the fact that offshore aquaculture has been a topic of interest for decades (e.g Wilcox 1982, Ryan, 2004, Benetti & Welch 2010, Simpson 2011) commercial offshore aquaculture practice is still in its infancy.

There are drivers both at local and global levels that incentivise aquaculture to move to the unprotected waters of the open sea. At the local level, competing claims on available space and resources exist. This is compounded by regulatory restrictions, water quality issues and negative public perception of aquaculture operations related to environmental and aesthetic impact concerns. At the global level, there is a need to maintain food security as the human population size increases – United Nations projections indicate that the global population will reach 9.7 billion by 2050 (United Nations, 2015). Furthermore, there is the conviction that the potential of the world’s oceans for food supply is vastly underutilised (Kapetsky *et al.* 2013).

Significant aquaculture growth is evident in some European countries such as Norway and Turkey. Other EU Member States have experience stagnated aquaculture production with little or no growth since 2000 (FAO 2016). However, a recent report issued by the European Market Observatory for Fisheries and Aquaculture Products indicates a positive trend in recent years[1]. Aquaculture is one of the key sectors expected to expand under the EU Blue Growth initiative (European Commission, 2012). Recent reports predict that EU aquaculture will expand and grow in the years ahead, however, the quantity of estimated versus expected growth vary greatly (Lane *et al.* 2014, OECD/FAO 2015). Competition for space from multiple sectors and ecosystem health concerns are considered key obstacles to future growth (Lane *et al.* 2014). In 2013, the EC distributed non-binding Strategic Guidelines for the Sustainable Development of EU Aquaculture (COM/2013/229) to guide Member States. These guidelines state that the lack of space often cited as a hindering factor for the expansion of EU marine aquaculture can be overcome by identifying the most suitable sites amenable for aquaculture, as the current surface and coastline occupation by aquaculture activities appears limited.

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[1] 2016 fish market report: www.eumofa.eu

Site selection is a key factor in any aquaculture operation and the same applies to offshore aquaculture. Proper site selection is a prerequisite for the economic sustainability of the operation, for animal welfare and for product quality (Figure 2). Furthermore, proper site selection can help to avoid and/or solve competing demands for access and use of areas, and prevent potential negative environmental impacts of the operations.

Several studies that have addressed the spatial aspects of offshore aquaculture, some in European waters (Macias-Rivero *et al.* 2003, Perez *et al.* 2005, Watson & Drum 2007, Falconer *et al.* 2013, Dabrowski et al 2016). Kapetsky *et al.* (2013) explored the offshore farming potential in Norway, Ireland and Spain for salmon (*Salmo salar*), blue mussels (*Mytilus edulis*) and cobia (*Rachycentron canadum*). Perez *et al.* (2005) presented a methodology for selecting suitable sites for offshore farming of seabream (*Sparus aurata*) and seabass (*Dicentrarchus labrax*) in floating cages in Tenerife Island, Canary Archipelago.

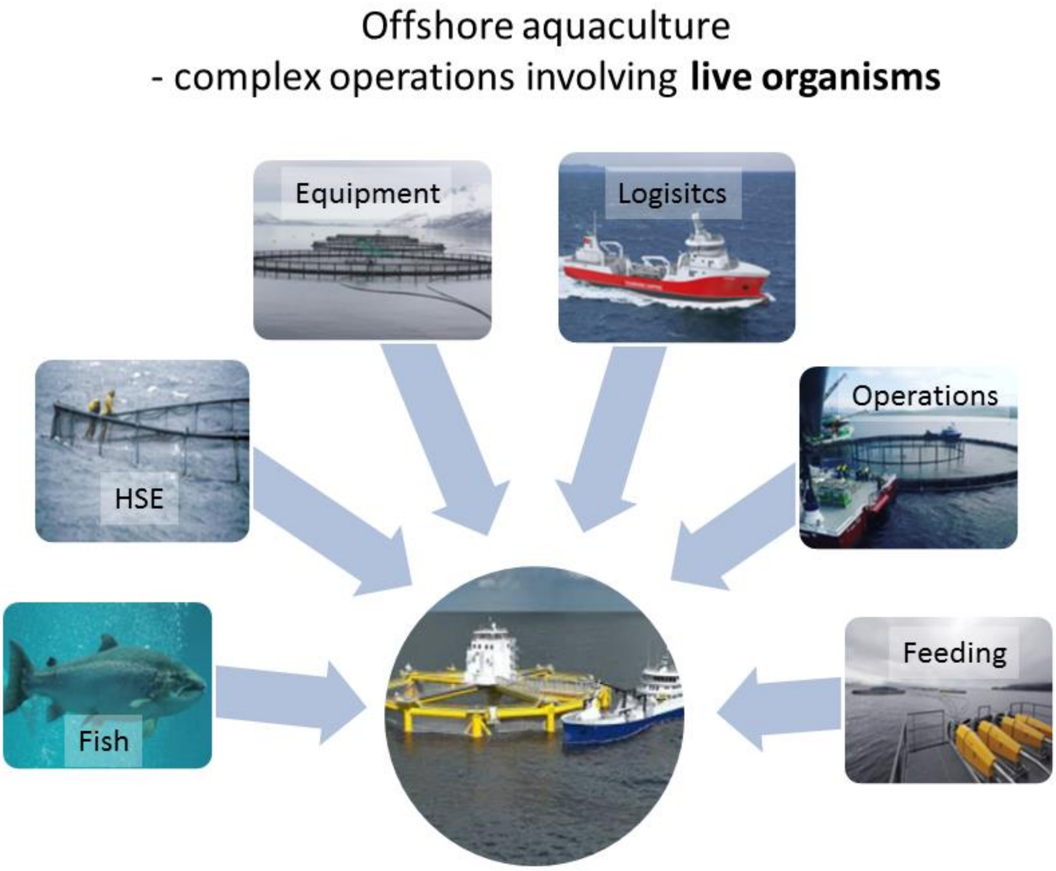

Figure 2. Schematic shows the various aspects to be considered when selecting sites for offshore aquaculture.

AtlantOS Task 8.5 “Aquaculture site selection” seeks to support EU Blue Growth. The main aim of this report is to describe an AtlantOS developed aquaculture site selection support tool that assesses regional oceanographic conditions in order to identify suitable aquaculture sites. A key challenge to European aquaculture development is the availability of suitable space for new farms. The main focus of this study was on waves, current velocities and water column structure in Norwegian, Irish and Spanish marine waters.

4. Approach

4.1 What is “Offshore aquaculture”

There is no internationally agreed definition for “offshore aquaculture”. A variety of terms are used in both the peer-reviewed and the grey literature. Some definitions are quite open such as the US definition “Rearing of marine organisms under controlled conditions in the EEZ — from the three mile territorial limit of the coast to two hundred miles offshore. Facilities may be floating, submerged, or attached to fixed structures”. Drum (2010) proposed that offshore aquaculture may be defined as “taking place in the open sea with significant exposure to wind and wave action, and where there is a requirement for equipment and servicing vessels to survive and operate in severe sea conditions from time to time. The issue of distance from the coast or from a safe harbour or shore base is often but not always a factor”. For site selection and GIS analysis, operational definitions are needed, such as the ones suggested by Holmer *et al.* (2010) and Lovatelli *et al.* (2013) presented in Table 1.

The Spanish, Irish and Norwegian coasts are very different, and it is not feasible to apply the same definition of “offshore” aquaculture in all three case studies. Therefore, regional specific criteria were used in each case.

4.2 The use of GIS analysis in site selection – general description

A Geographic Information System (GIS) approach was chosen to develop the AtlantOS products. This method offers useful tools to optimize and plan the location of marine aquaculture sites, and to provide a decision-support to resource managers, aquaculture industry representatives and local community stakeholders. The GIS approach offers a means to organise, process and analyse different data types such as administrative and physical factors, and data models. It also facilitates spatial multi-criteria evaluation (MCE). The MCE approach combines multiple variables in a structured model using a weighted overlay where weights are proportional to their importance of the variables (Nath *et al.* 2000). In the past, the GIS approach has been used to address various aspects of aquaculture site selection and suitability analysis (e.g. Nath *et al.* 2000, Longdill *et al.* 2008, Falconer *et al.* 2013, Kapetsky *et al.* 2013, Gimple *et al.* 2015, Dapueto *et al.* 2015).

Table 1. Criteria for defining coastal, off-the coast and offshore aquaculture (modified from Holmer *et al.* 2010, Lovatelli *et al.* 2013)

Parameters	Coastal Aquaculture	Off-The Coast Aquaculture	Offshore Aquaculture
Physical setting	< 500 m from the coast	500 m to 3 km from the coast	> 3 km from the coast, generally within continental shelf zones, possibly open ocean
	< 10 m depth at low tide	10-50 m depth at low tide	> 50 m
	Within sight from shore	Often within sight from shore	
	Usually sheltered	Somewhat sheltered	
Environment/exposure	(Hs) usually < 1m	Hs < 3-4 m	Hs 5 m or more, regularly 2 - 3 m oceanic swell
	Local winds	Localized winds	Ocean winds
	Strong tidal current	Weak tidal current	No tidal current
Note: Hs = Significant Wave Height	Sheltered	Partly exposed e.g. > 90 °	Exposed e.g. > 180 °
Access	100% accessible	90 % accessible on at least once daily basis	Usually > 80 % accessible
	Landings always possible	Landings usually possible	Landings may be possible, periodic e.g. every 3-10 days
Operation	Manual involvement, feeding, monitoring and more	Some automated operations e.g. feeding monitoring and more	Remote operations, automated feeding, distance monitoring, system function

5. Norwegian Case study

5.1 Background

The information product developed in this case study seeks to highlight potential offshore aquaculture sites in Norwegian Atlantic waters. Norway is the largest aquaculture producer in Europe. In 2015, 1.39 million tonnes was produced and salmonids accounted for > 80 % of the total aquaculture output. Strict animal welfare and health regulations, focus on safety for equipment and employees, environmental monitoring, and a strong political desire to grow the industry has been important factors for the growth the last decade. However, the excellent natural marine conditions remain the aquaculture industry's greatest asset. The country's large sea area, with > 82,880 Km of coastline, provides good conditions year-round to cultivate seafood. Several challenges must be addressed to allow continued sustainable growth with pressing environmental issues related to sea lice and escaped fish of primary concern. "Offshore" aquaculture has yet to become a focus area of the Norwegian aquaculture industry and the Norwegian authorities. Over the last decade, improved efficiency in farm management has resulted in an increase in fish farm size. Narrow fjords and locked bays, with poor water exchange, are unsuitable for large operations. The negative impacts of sea lice and escapees on wild salmon populations make offshore sites, far away from river mouths, attractive. Furthermore, downscaling of the Oil & Gas sector has reinvigorated an interest, of offshore engineering companies, in aquaculture operations with several new cage concepts for offshore use launched in recent years.

5.2 The GIS analysis

This Norwegian AtlantOS case study followed a framework similar to the one used in the EU project AQUA-USERS (Huber *et al.* 2014, Kaas *et al.* 2015). The different phases/steps of the GIS analysis are illustrated in Figure 3 below.

The initial phases of the process identified requirements, formulated specifications, and an analytical framework was determined. Next, datasets were identified and data connected with salmonid production was extracted; this included data with administrative/spatial constraints, species production requirement data and environmental impact data. Datasets were then organised, analysed, post processed and mapped in GIS. The final step in the analyses combined the GIS-layers to produce a spatial suitability map. Strong end-user involvement is planned to develop the final products in Task 8.5.

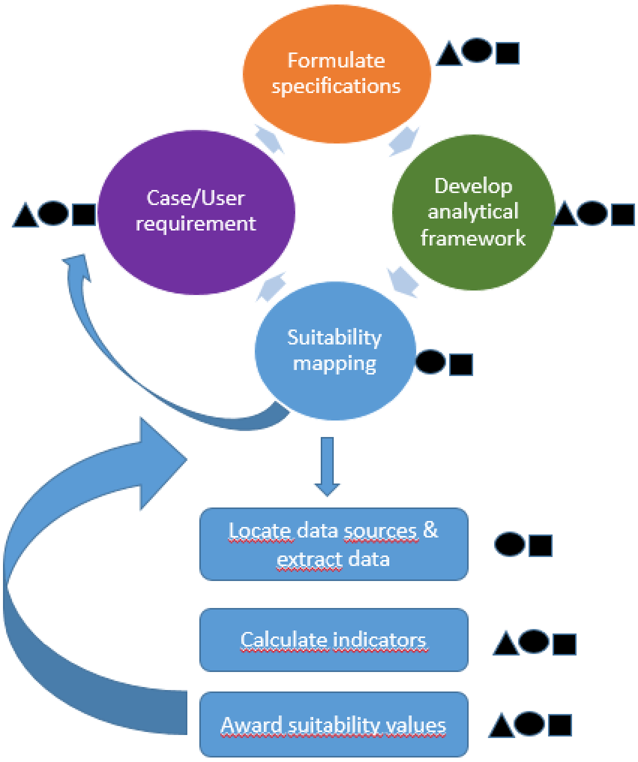

Figure 3. Schematic representation of the GIS framework applied to develop the offshore aquaculture siting products in AtlantOS; modified version of Nath *et al.* (2000). Where ▲ = End User Involvement, ● = Subject Matter Specialist, ■ = GIS Analyst.

5.3 Case requirements, specifications, and analytical framework

In this case, our focus was to identify areas/sites suitable for the offshore production of salmon. “Offshore” aquaculture does not exist in Norwegian waters according to FAO definitions (Lovatelli *et al.* 2013; Table 1). However, the large scale “Off the coast” aquaculture practiced in Norway shares several criteria with “Offshore” aquaculture as defined by Kapetsky *et al.* (2013) and Benetti *et al.* (2010). These criteria, that characterise suitable sites for “off the coast” aquaculture, can be used as a starting point for the analysis in AtlantOS.

The Norwegian legal Acts that regulate aquaculture apply to the entire exclusive economic zone (EEZ) including potential areas for offshore aquaculture. This means that requirements set by legislation such as the biological needs of farmed animals and animal welfare, and the risk based health, safety & environment (HSE) must also be followed in offshore aquaculture operations.

The global assessment of potential short to medium term development of offshore aquaculture by Kapetsky *et al.* (2013) stated that “Offshore” aquaculture will

1. Develop within Exclusive Economic Zones
2. Mainly use culture systems modified from inshore aquaculture
3. Mainly employ marine species with already proven culture technologies and established markets

We followed these assumptions, since it is difficult to foresee future aquaculture operation technological solutions to expand aquaculture development in exposed offshore territories.The Norwegian AtlantOS case study focused on the Contiguous Zone (Figure 4a). The Norwegian coast is divided into production areas for aquaculture; for this study, we selected the marine areas in production zones 7 and 8 (Figure 4b). With regards to distance from the coastline, "offshore" criteria outlined in Table 1 were followed; this included marine areas outside the 3 km coastline buffer.

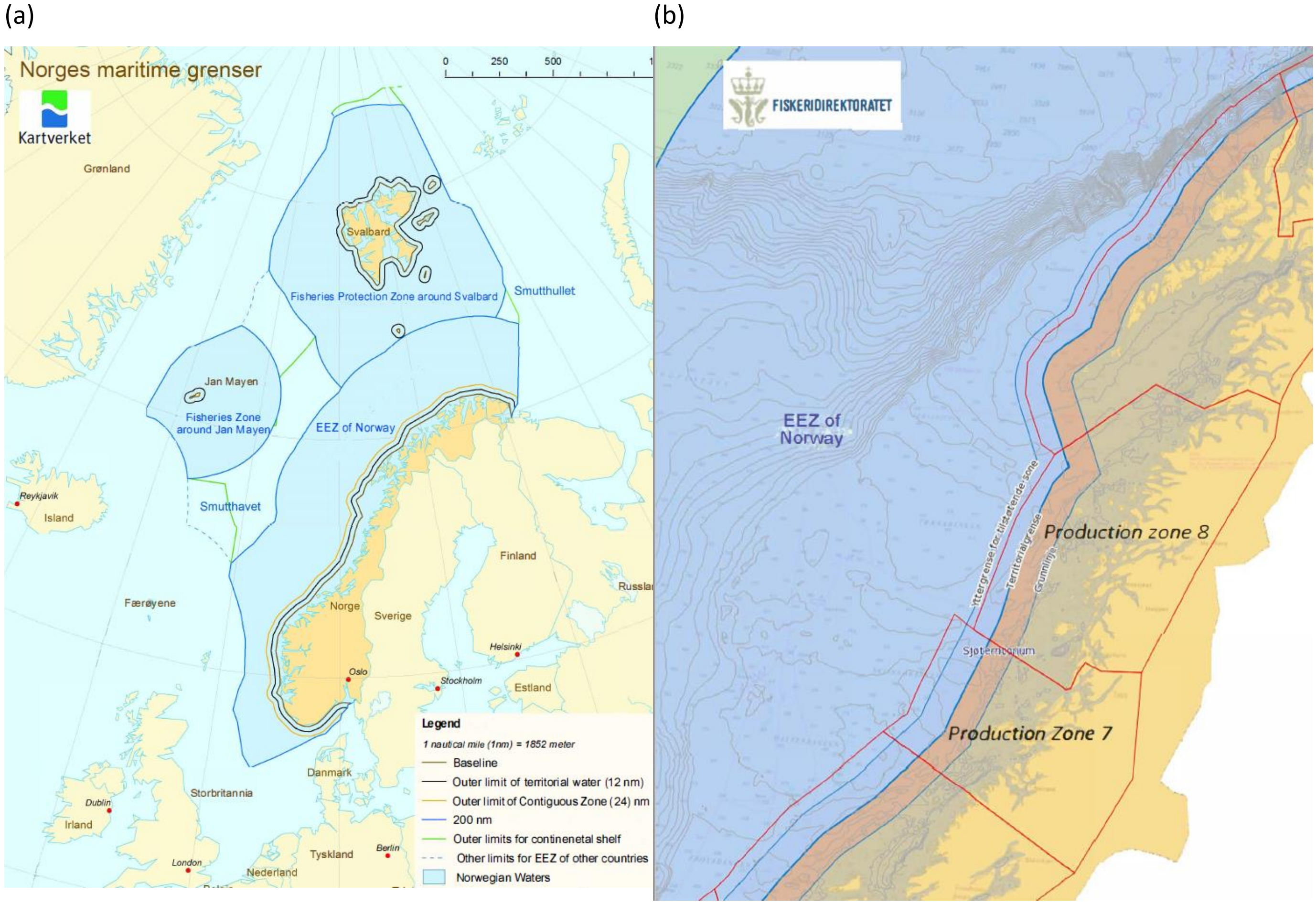

Figure 4. Maps show (a) the Norwegian Maritime Borders and (b) the region of interest, production zones 7 & 8, to investigate suitability for aquaculture. Source: The Norwegian Mapping Authority and Directorate of Fisheries.

"Offshore" aquaculture siting requirements deemed important in the Norwegian case study:

1. Logistics & operations
2. Animal welfare
3. Equipment limitations
4. Health, Safety & Environment
5. Competing, conflicting and complementary use of ocean space

The analytical tools used in the analysis included classification of data combined with a simple overlay of multiple suitability maps.

5.4 Description of Datasets

Two overall topics were defined as follows:

- **Administrative Constraints** to identify spaces already occupied by other marine activities such as Shipping Routes, Wind Parks and, Oil & Gas installations.
- **Suitability for Production** to identify areas with optimal physical and chemical water conditions for salmonids.

Administrative data: Administrative factors include multiple legal restrictions. Potential suitable areas will be excluded if the marine space is already allocated to other human activities in the government plans (Planning and Building Act), if they are protected under the Diversity Act (e.g. national parks and coral reefs) or if they are protected by the Culture Heritage Act (ship wreck etc.). In these areas, (new) aquaculture facilities are prohibited. Areas with a strong interest from other marine sectors might have certain restrictions (e.g. spawning and fishing grounds, kelp beds and recreational areas). Here new aquaculture sites are assessed individually for each case proposed. Administrative data are listed in Table 2.

Table 2. List of administrative data and corresponding data sources used to make the Norwegian product.

Data layer	**Description of data**	**Data source**
Administrative data		
Oil & Gas fields	Areas of offshore Oil & Gas production	Norwegian Petroleum Directorate
Offshore Windfarms	Areas of Offshore Windfarms	Norwegian Water Resources and Energy Directorate
Other Aquaculture Sites	Positions of existing Aquaculture Sites Recommended minimum distance of 5 km from fish slaughterers and processing plants, brood stock facilities, water intakes and land based producing sites, sea based fry production sites, net cleaning sites, and big on-growing fish farms (> 6000 tonnes Maximum Allowed Biomass). Recommended minimum distance of 2.5 km from other on-growing fish farms, land-based on-growing facilities and important salmon rivers.	Directorate of Fisheries
Security Zones around Shipping Routes	Areas restricted due to Security Zones around Major Shipping lanes. Normally 1 km on each side of the shipping route.	Norwegian Coastal Administration
Spawning Grounds	Defined areas with increased density of eggs and/or increased density of sexually mature adults.	Directorate of Fisheries
Feeding/Nursery Grounds	Defined areas where the density of adult individuals is greater than in other areas. A nursery area is a grazing area used by fry / small fish.	Directorate of Fisheries
Fishing Areas	Present and historic Fishing Areas (vocational, leisure and tourism) that with expected continued use in the future. Includes areas for both active (seine, purse seine or shrimp trawls) and passive gear (gillnets and longlines).	Directorate of Fisheries
Marine Protected Areas	Areas protected under the following laws: Diversity Act 2009, biotope protection by the Wildlife Act of 1981, the Nature Conservation Act 1970, the Nature Conservation Act of 1954 Act on Jan Mayen of 1930 and Law on Nature Conservation of 1910. In addition, the areas protected under the following legislation on Svalbard: Svalbard Act of 1925 and the Svalbard Environmental Act of 2002. The data set provides access to the legal requirements applicable to each individual protection decision.	Norwegian Environment Agency

Production data: Physical, chemical, and biological variables important to culture of salmon. These include depth, temperature, current velocity and wave heights (List of data types are presented in more detail in Table 3).

- **Depth:** Norwegian Food Authorities require that fish farm net pens are ≥ 20 m from the seafloor.
- **Temperature:** Important for fish physiology, changes in temperature influence water circulation, feed intake, digestion, growth and oxygen solubility. The Norwegian Food Authorities have set temperature suitability requirements for each salmonid life stage. The temperature tolerance of smolts (young salmon) is between 3 and 18 °C, while adults can tolerate temperatures between 1 and 18 °C. For our study, the temperature requirements for the smolt life stage were used as this would allow potential sites suitable for the entire grow-out phase to be identified.
- **Current velocity:** It is important to determine water exchange in fish cages and the dilution/dispersion of waste products as these can impact fish welfare (e.g. muscle tone, respiration). Negative effects on fish welfare occur at high and low current velocities. Recent studies have shown that salmon become fatigued at water current velocities of 125 cm/s (Hvas *et al.* 2017). Normal circular schooling patterns are disrupted at current velocities of 30 – 35 cm/s. High water current velocities of 45 – 65 cm/s cause the fish to head against the direction of the flow, and become evenly spread out in sea cage (Johannsson *et al.* 2014, Hvas *et al.* 2017). On the other hand, low water current velocities are known to increase agonistic behaviour (Solstorm *et al.* 2015, 2016). The Norwegian Food Authorities requirements for a smolt ready for transfer to marine waters, is a current velocity of < 40 cm/s. Requirements do not exist for larger fish as they can tolerate high current velocities. Some guidelines exist on acceptable minimum water current velocities e.g. 30 minutes with < 1 cm/s when the tide turns. Kapetsky *et al.* (2013) suggested that for fish a range between 10 and 100 cm/s is tolerable; the study did not focus specifically on salmon. In our analysis, we used the recommended minimum current velocities listed in Kapetsky *et al.* (2013), and the maximum current velocities given by the Norwegian Food Authorities for smolts. The approach taken was conservative; if the limits were exceeded one time these areas were excluded.
- **Wave height:** Limits the type of equipment/cages used in open marine waters as it is an important factor to consider for day to day farm operations and maintenance activities. There is very little information published on wave height and salmon welfare. Norwegian authorities do not have a maximum allowable wave height, but require a wave assessment to get site approval. According to the Directorate of Fisheries, the most exposed sites in Norway have a significant wave height (Hs) of 4.5 m, and this is often used as a rule of thumb in the industry.

Table 3. List of production data and corresponding data sources used to develop the Norwegian products.

Production data	Description of data	Data source
Water depth	Water depth in meters. **Suitability criterion used in this study:** depths 80-500 m.	The Norwegian Mapping Authority
Temperature (surface layer)	Modelled water temperature from NorKyst 800. NorKyst 800 is a hydrodynamic model provided by the Norwegian Meteorological institute (MET). The model setup was developed with the cooperation of the MET, the Institute of Marine Research and the Norwegian Institute for Water Research (NIVA) and is described in Albretsen *et al.* (2011). The model domain, with an 800 m spatial resolution, covers the entire Norwegian coastline. The model is based on the ROMS code. The model is validated with observation data from eight permanent coastal stations http://www.imr.no/forskning/forskningsdata/stasjoner/index.html Daily mean temperatures at six depth levels (0, 3, 10, 15, 25 and 50 m depth) were downloaded for two years (2015 and 2016). Minimum and maximum values for each grid cell and depth over all depths were extracted. **Suitability criterion used in this study:** temperature 3-18 °C	Model data from Norkyst 800 Norwegian Meterological Institute
Current velocity	Modelled current velocity from NorKyst 800 NorKyst 800 (details above). Hourly values of current velocity components u,v (for velocity towards the east and north, respectively) were downloaded for the 6 depth levels for approximately 7 months (14th September 2016 to 18th March 2017). Hourly current velocity was calculated and then the mean current speed for 12 hour periods (hours 0-11 and 12-23). Finally, minimum and maximum values of these 12-hour means for each grid cell over all depths were extracted. **Suitability criterion used in this study:** current velocity 10-40 cm/s	Model data from Norkyst 800 Norwegian Meterological Institute
Wave height	Modelled wave height from NorKyst 800 NorKyst 800 (description see above). We used wave model results on an hourly basis. Data was only available for 4 months, i.e. the period 1st November 2016 to 28th February 2017. However, this part of the year has high waves. Total significant wave height for this period was downloaded and the maximum value for each grid cell was extracted. Total significant wave height is the sum of swell height and sea wave height. **Suitability criterion used in this study:** max Hs is < 4.5 m	Model data from Norkyst 800 Norwegian Meterological Institute

5.5 Data selection

An aquaculture expert assessed all datasets before the GIS analyses was carried out. Since Oil & Gas installations do not currently exist in the study area, this layer was omitted. Modelled data showed water temperature > 18 °C did not occur in test period examined. All other data layers were deemed suitable for use.

5.6 Data analyses and selection of suitability criteria

Based on the available and selected data, a set of criteria for creating suitability classes was employed for each parameter. To create spatial suitability maps, all datasets were first transformed into suitability layers. Only Boolean (or Binary) suitability was used, where the data or area is either suitable (1) or unsuitable (0). The layers were then combined to form the suitable map.

Legal/administrative restrictions layers

Data for legal/administrative layers was converted into raster files, creating Boolean (or binary) raster files with values of 0 (not suitable) and 1 (suitable). These layers included existing aquaculture activities, marine protected areas, coastal waterways and offshore windfarms.

Other sector interest restrictions layers

Data on “areas of interest to other sectors” were converted into raster files, creating Boolean (or binary) raster files with values of 0 (not suitable) and 1 (suitable). These layers included spawning (nursery grounds) and fishing areas.

Production layers

Water depth: Suitability for water depth: water depth > 80 m and < 500 m was defined as 1. Water depth deeper than 500 m and shallower than 80 m was defined as 0.

Temperature: Suitability for full grow-out cycle (can use smolt straight from hatchery): Temperature above 18 °C was defined as 0, temperature below 18 °C was defined as 1. Temperature above 3 °C was defined as 1 and temperature below 3 °C was defined as 0.

Current speed: Suitability for full grow-out cycle in the sea (can use smolt transferred directly from hatchery): Current speed above 10 cm/s was defined as 1 and current speed below 10 cm/s was defined as 0. Current speed above 40 cm/s was defined as 0, current speed below 40m/s was defined as 1.

Wave height: Suitability for full grow-out cycle in the sea: Hs < 4.5 m was defined as 1 and Hs > 4.5 m was defined as 0.

5.7 Results

5.7.1 Administrative/legal constraints and constraint related to other sectors

Administrative and legal restrictions exist in the maritime space of interest (Figures 5 and 6). Aquaculture and maritime activities are in operation and several waterways with buffer zones cover substantial areas. The study area is home to marine protected areas and habitats that include kelp beds and corals. One example, the Vega Archipelago was inscribed on the UNESCO List of World Cultural and Natural Heritage[2]. This area is important to wild salmon stocks and several fjords are protected. Finally, there are other sectors, such as fisheries and wind farms, competing for marine space. In these areas, new aquaculture site applications may be approved, however, any new application will be rigorously assessed on a case by case basis.

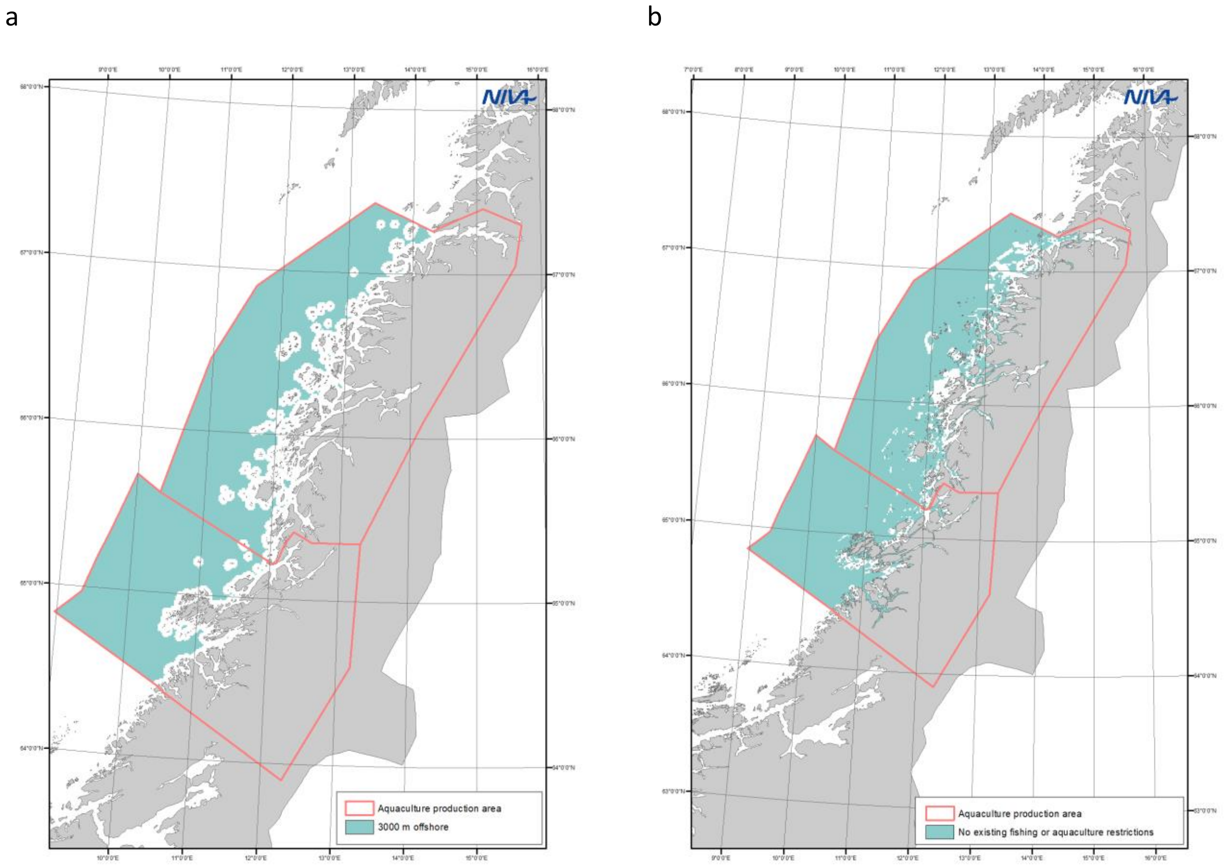

Figure 5. Areas with administrative and legal restrictions. Plots shows (a) Areas defined as “offshore”, and (b) Areas restricted by aquaculture and fisheries activities. This includes existing fish farms, fishing areas, penning in sites, spawning grounds, and nursing grounds. Blue-Green indicate areas have no restrictions.

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[2] http://www.verdensarvvega.no/index.php/en/

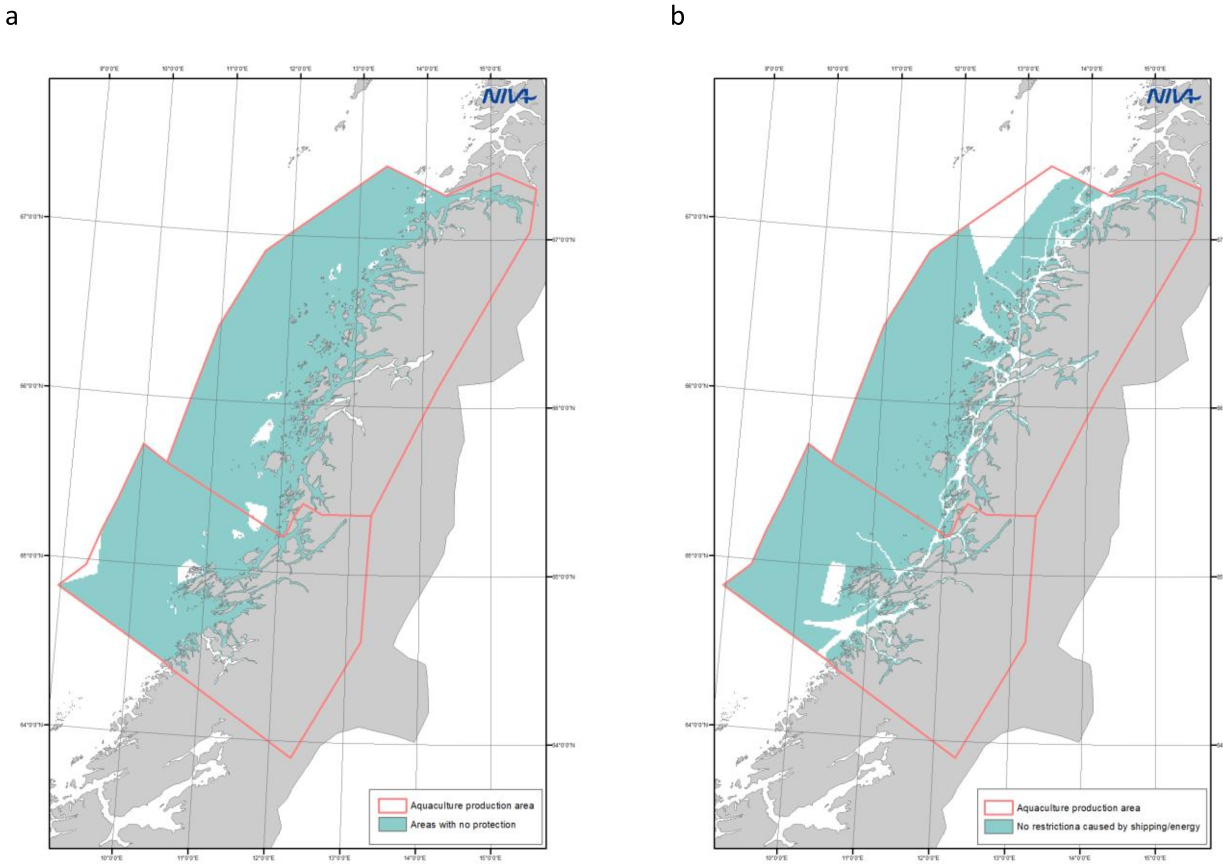

Figure 6. Areas with administrative and legal restrictions. Plots shows (a) Areas with restrictions related to marine protection; wild salmon protection (national salmon fjords), existing and proposed (decision pending) marine protected areas, and protected habitats such as coral reefs and kelp beds, and (b) Areas with restrictions related to waterways and wind farms. Blue-Green denotes areas with no restrictions.

5.7.2 Production data

Shallow waters surround a high number of Islands. Large areas, when the bathymetry was < 80 m, were deemed unsuitable (Figure 7a). Water temperature did not exceed 18 °C in the time period examined (layer not shown). Water temperature was generally > 3 °C; except within and at the mouth of some of the fjords. However, large parts of the study area had suitable temperature ranges according to the suitability criteria followed (Figure 7b). The region is highly dynamic and a considerable marine area did not fulfil the suitability criteria for the maximum and minimum current velocities (Figure 7c). In large areas, time periods with current velocities both below 10 cm/s and above 40 cm/s were encountered. The study area is also highly dynamic regrading waves, and large areas do not satisfy the suitability criteria for Hs max < 4.5 m (Figure 7d).

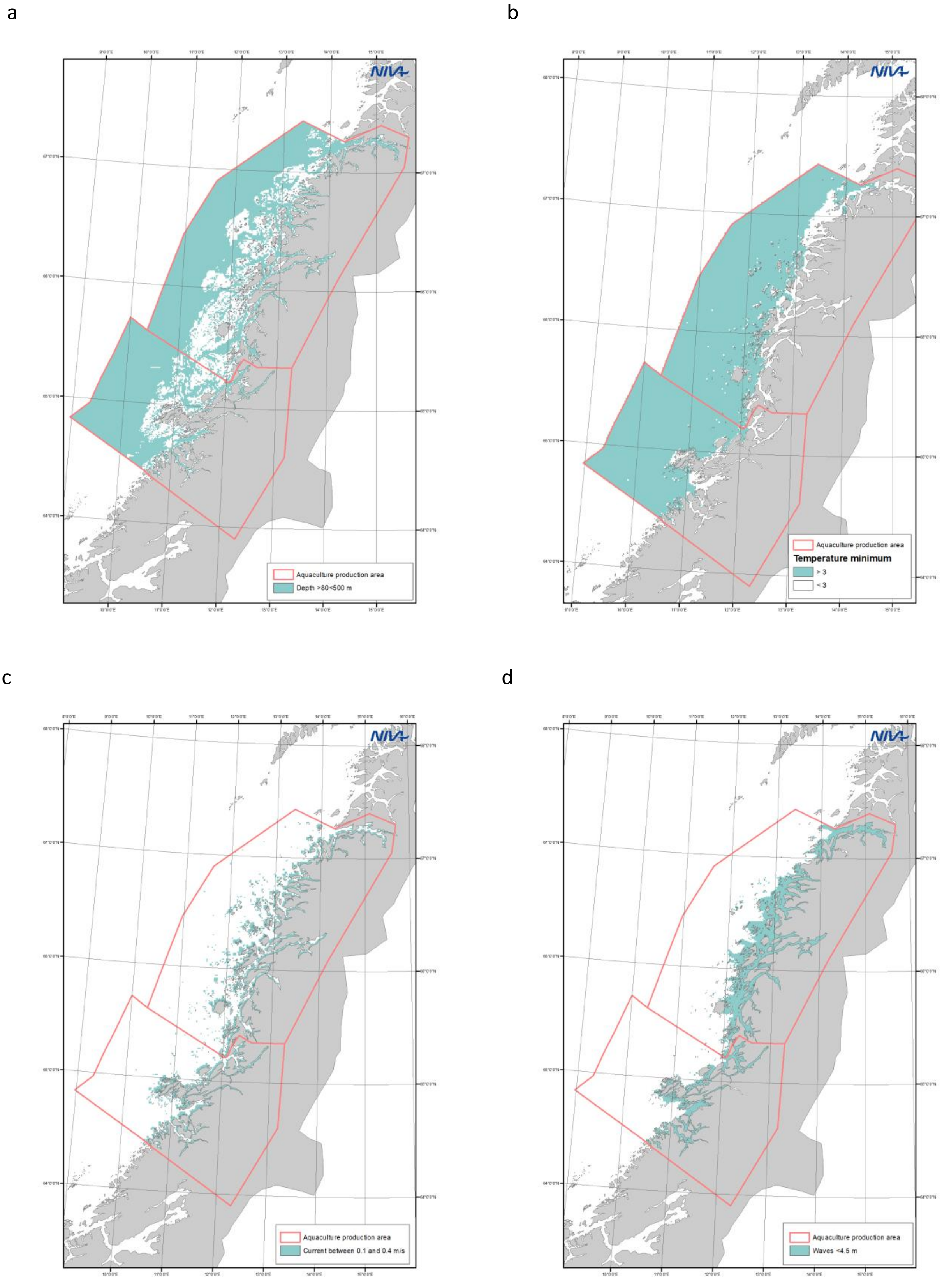

Figure 7. Plot show areas with (a) depths > 80m and < 500 m, (b) minimum water temperatures > 3° C, (c) current velocities between 0.1 and 0.4 m/s and (d) max significant wave height (Hs) < 4.5 m, suitable for potential offshore aquaculture sites. Blue-Green denotes areas that fulfil the suitability criteria.

When all site suitability layers were combined, a low number of potentially suitable offshore aquaculture sites were identified (Figure 8). The analysis was conservative, as the criteria were limited to identify areas where smolts could be transferred directly from the hatchery. Areas with current velocities in the range 40-100 cm/s would be suitable for large salmon; this part of the production cycle at sea could be investigated further. Strict criteria were used for some variables e.g. when one observation exceeded the limit criterion the area was deemed unsuitable e.g. the suitability criteria for Hs max of < 4.5 m. For many of the criteria used the suitability is not likely to be binary, but rather depend on the length of the time period of exceedance. Hence there is scope for refinement of criteria in dialogue with end users.

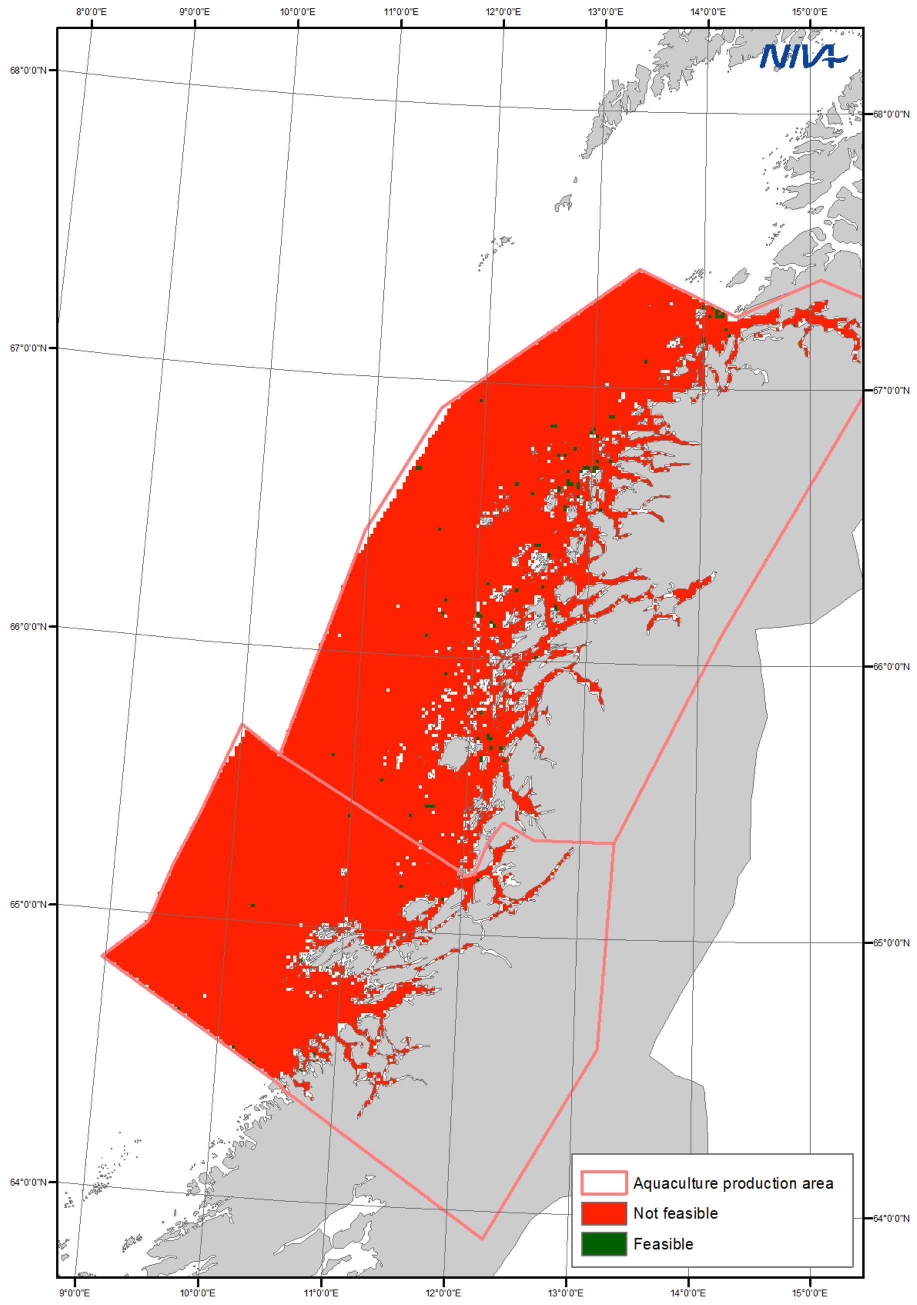

Figure 8. Plot shows areas of potential for offshore aquaculture.

6. Irish Case study

The information product developed in this case study seeks to highlight potential aquaculture sites in Irish Atlantic waters. The aquaculture sector has enormous growth potential with an expected increase of volume production (across all species) of ~ 78 % by 2020 (Harnessing our Ocean Wealth, 2012, a national integrated marine plan). In 2015, the Irish Government approved and published the National Strategic Plan for Sustainable Aquaculture Development to cover the years 2014 – 2020; to develop the Irish aquaculture sector in an environmental, economic and socially sustainable way. The Government support plan aims to sustainably grow the production of the Irish aquaculture industry (across all species) by 45,000 tonnes in the years ahead. Current employment in this sector is 1,841 (full time equivalent jobs). The 2016 annual aquaculture survey (BIM, 2016) indicates that licenced Irish aquaculture production trends are more or less stable with a slight increase in salmon production in recent years. Ireland is one of the largest EU producers of certified organic salmon (~ 80 % of Irish grown salmon is organic). In 2015, Irish aquaculture produce volume (across all species) increased by 27 % to over 40,000 tonnes with a monetary increase of € 33 million (BIM, 2016). In Ireland, proposed aquaculture activities must comply with a number of national and EU regulations (e.g. the Fisheries (Amendment) Act 1997; the Foreshore Act 1933; the EU Habitats Directive 92/43/EEC; the EU Birds Directive 79/409/EEC; the Consolidated Environmental Impact Assessment Directives 2011/92/EU). The Irish aquaculture licence process involves a legal framework from pre-application stage to licence decision; the decision-making process is currently under independent review to examine current challenges and to identify improvements that could be made in line with best International practice.

The AtlantOS aquaculture site selection product described here was derived from a physical model; validated by the *In-situ* ocean data. A number of variables (bathymetry, wind, wave and currents, exposure) were used to develop the product.

6.1 Physical model used to develop the product

West Coast SWAN Wave Model

The Marine Institute runs and developed a wave model to simulate wave conditions for Irish waters and this can be used to estimate conditions with a good degree of confidence. The west coast of Ireland wave model was developed using the open-source SWAN (Simulating Waves Nearshore) code. The model domain encompasses Irish coastal waters from 12.0 to 7.5° W and 50.0 to 56.5° N and this model is nested within the East Atlantic wave model run operationally at the Marine Institute. SWAN is a third-generation wave model that computes random, short-crested wind-generated waves in coastal regions (Booij *et al.*, 1999). The West Coast wave model has a horizontal resolution of 0.004 degrees and it uses wind forcing from NOAA's GFS (Global Forecast System) model. Wave data at the boundaries is provided by the East Atlantic model, which, in turn, is forced from the Wave Watch 3 (WW3) model developed by FNMOC (U.S. Navy Fleet Numerical Meteorology and Oceanography Centre; Tolman, 2009). The model has undergone extensive validation using wave data from a number of databuoys around the coast. Forecasts from the East Atlantic model are produced daily and the data is published on the Marine Institute website.

Data source (URL): Marine Institute ERDAPP Server [http://erddap.marine.ie/erddap/info]

- http://erddap.marine.ie/erddap/griddap/IMI_EATL_WAVE.graph
- http://data.marine.ie/Category/Index/12

Data Policy of the source: open and free

Irish Marine Institute Northeast Atlantic Model: "NEA_ROMS"

The North-East Atlantic ROMs 3-D model is a well-established, validated and operationally run hydrodynamic model. It provides hindcasts, nowcasts and forecasts of sea state in NE Atlantic waters. The model runs every day to produce a 3-day forecast for parameters such as temperature, salinity, current and sea surface height. The results are published on a THREDDS server in Netcdf format. The model encompasses all of Ireland's territorial waters and beyond. It became operational in 2008, and is an implementation of ROMS (the Regional Ocean Modelling System), a free-surface, hydrostatic, primitive equation ocean model (Shchepetkin and McWilliams, 2005). It is an *open-source,* community ocean *model that* uses a horizontal, curvilinear C-grid and a stretched vertical coordinate. The model domain covers a significant portion of the northwest European continental shelf, the Porcupine and Rockall Banks and the Rockall Trough at a variable horizontal resolution, ranging from 1.1-1.6 km in Irish coastal waters to 3.5 km in the southern part of the domain. There are 40 sigma-coordinate levels in the vertical with a concentration of levels at the surface and the bottom. The model bathymetry utilises data from a number of sources including the multibeam dataset produced by the Irish National Seabed Survey and Integrated Mapping for the Sustainable Development of Ireland's Marine Resources (INFOMAR) programmes. Atmospheric forcing uses the ECMWF (European Centre for Medium-Range Weather Forecasts) operational system. The model supports a number of end user needs e.g. harmful algal bloom predictive transport (for AtlantOs Task 8.1). *In-situ* and satellite measurements of the oceanic variables such as sea temperature and water currents from moored and free-floating instruments (e.g. weather buoys, ARGO floats, ADCPs (Acoustic Doppler current profiler)) have been used to validate the model.

Data source (URL): Marine Institute ERDAPP Server [http://erddap.marine.ie/erddap/info]

- http://erddap.marine.ie/erddap/wms/IMI_NEATL/index.html
- http://data.marine.ie/Category/Index/12

Data Policy of the source: open and free

6.2 *In-situ* ocean observing data sources used to validate Irish models:

In-situ data from multiple ocean observing platforms (e.g. Argo profiling floats, tide gauges, *in-situ* moored data buoys) are an essential component of product development. The data sources listed below have helped to validate the Irish 3-D hydrodynamic and wave models.

Data source (URL): Copernicus Marine Environment Monitoring Service (CMEMS) portal [www.marine.copernicus.eu] and/or Marine Institute ERDAPP Server [http://erddap.marine.ie/erddap/info] and/or Coriolis [http://www.coriolis.eu.org/Data-Products/Data-Delivery] and/or JCOMMOPS [http://www.jcommops.org]

- *In-situ* tide gauges (26 tide gauge locations):
  http://erddap.marine.ie/erddap/tabledap/IrishNationalTideGaugeNetwork.html
  http://data.marine.ie/Category/Index/12
- *In-situ* data buoys (wave climate):
  http://erddap.marine.ie/erddap/tabledap
  http://data.marine.ie/Category/Index/12
- ARGO profiling floats:
  http://www.jcommops.org/board?t=Argo
  http://www.argodatamgt.org/Access-to-data/Argo-data-selection
- Satellite SST observation product ODYSSEA L4 CMEMS:
  SST_NWS_SST_L4_NRT_OBSERVATIONS_010_003

Data Policy of the source: open and free

6.3 Product development

A GIS based model approach was used to create the product and used > one year (13 months) of simulated model data. GIS raster files were created and extracted in four different layers to view the results spatially. Spatial maps were created offline.

The study focused on four variables

1. water depth (metres)
2. maximum tidal velocity (based on harmonics derived from a one year run of the NE_Atlantic model), max_Hs (metres)
3. 90 % percentile value of a significant wave height (Hs), Hs_P90 (metres)
4. maximum significant wave height(Hs), max_Hs (metres)

The simple model used the following criteria (rules) to create a layer for each variable

- water depth ≥ 15 m,
- maximum tidal velocity of < 1 m/s,
- maximum significant wave height, *max_Hs*, < 4 m
- Ninetieth percentile value of a significant wave height (*Hs*), *Hs_P90* < 2 m

Simple raster analysis was used to apply rules to the individual layers and isolate areas where the above exposure criteria were met (value of 1) or not met (value of zero). The superposition of the four layers shown in Figure 9 was then used to create a new raster – the final model output. The resulting raster contains binary data: cell values of 1 where all the criteria are met and cell values of 0 where one or more of the criteria failed. The spatial extent of cells with a value of 1 are presented in Figure 10 and Figure 11 below for the west and southwest coasts, respectively. These represent the locations of potential offshore aquaculture sites for this simple model.

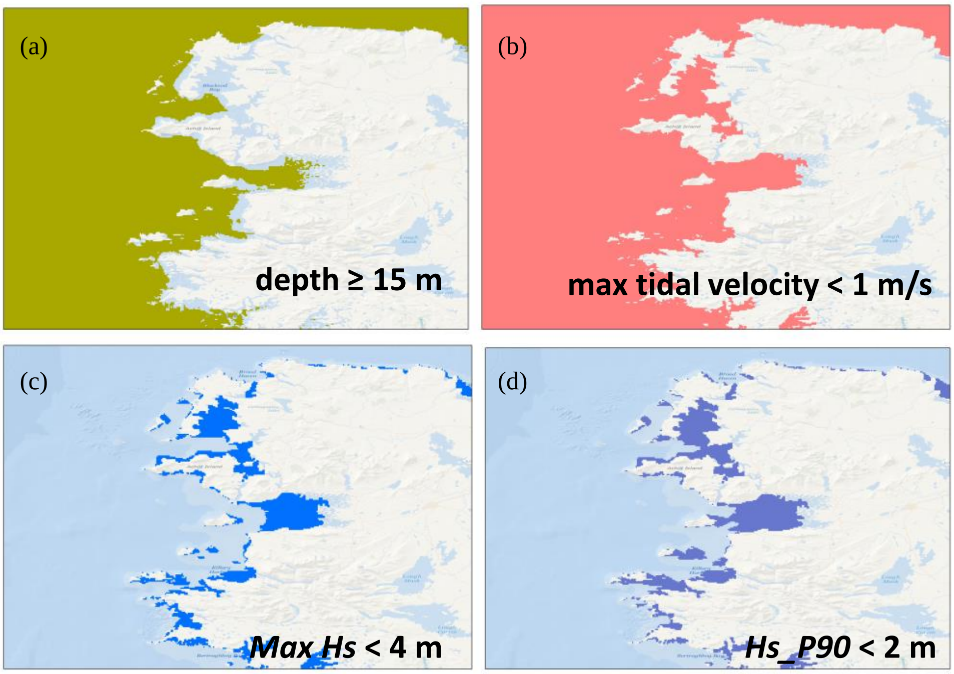

Figure 9. Example of the product subcomponents (i.e. model output layers) based on physical variables redrawn from Dabrowski et al., 2015. Where (a) water depth ≥ 15 m, (b) maximum tidal velocity of < 1 m/s, (c) maximum significant wave height, max_Hs, < 4 m and (d) 90 % percentile value of a significant wave height (Hs), Hs_P90 < 2 m. These layers are then overlaid to form one raster output file that shows locations where offshore aquaculture sites could potentially be situated.

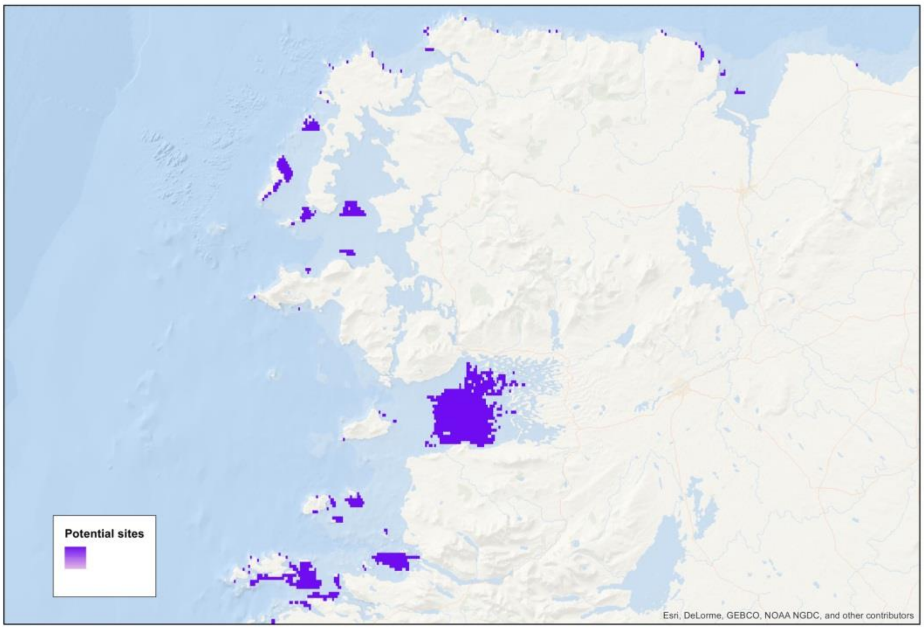

Figure 10. Plot shows locations where offshore aquaculture sites could potentially be situated off the west coast of Ireland based on physical variables. Method used follows Dabrowski et al., 2015.

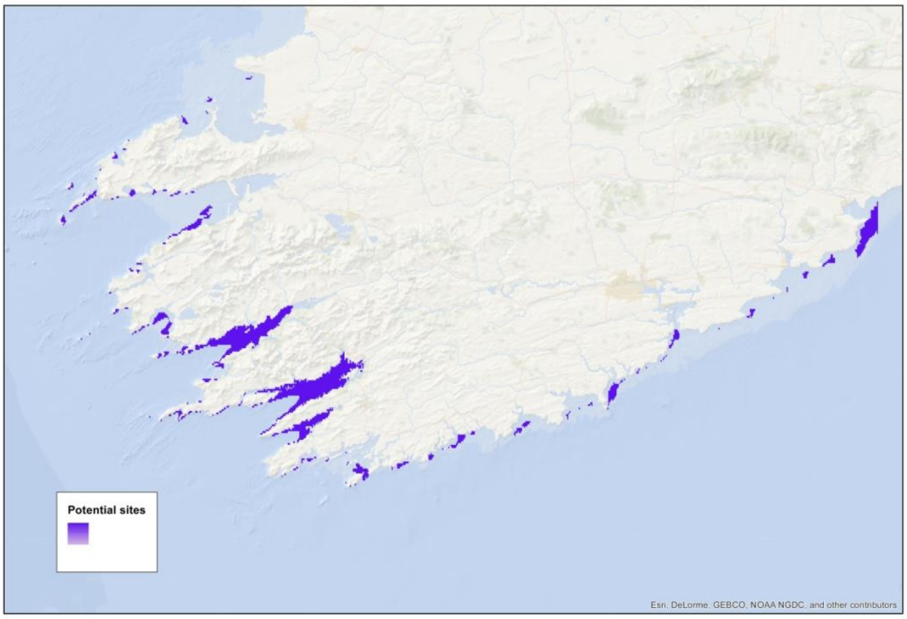

Figure 11. Plot shows locations where offshore aquaculture sites could potentially be situated off the southwest coast of Ireland based on physical variables. Method used follows Dabrowski et al., 2015.

6.4 Legal / Administrative GIS layered products

Since aquaculture licensing decisions must comply with all EU and national legal requirements, this section provides additional information to end-users (e.g. decision makers) on the GIS products that can help in the process. Currently, there is a lack of any available site decision tools that could be coupled with the modelled product developed for Irish waters. Layered product examples, however, can be viewed on the Irish Marine data Atlas (link: http://atlas.marine.ie). Available and restricted GIS layers, at the time of writing this report, are listed in Table 4 below. Please note that some GIS layers have data restrictions and the user must apply directly to the data owner to get access to the datasets. Figures 12-17 below show open source GIS layers overlaid on the modelled product developed in this task.

Table 4. Administrative GIS layer content available on the Irish Marine Atlas (http://atlas.marine.ie). Note: some layers have restricted access. Where SPA = Special Protected Area, SAC = Special Area of Conservation, PHNA =, RAMSAR = location in Iran where the RAMSAR convention international treaty for the conservation of wetlands was signed in 1971, IAA = Irish Aviation Authority and UKHO= United Kingdom Hydrographic Office.

Data Layer (Administrative Layers)	Data Usage
Aquaculture Sites*	Restricted Access - License agreement with owner required.
Sea Cables*	Restricted Access - License agreement with owner required.
Security Zones around Shipping Routes (coastal waterways) IAA Danger Area & Traffic Separation Scheme – (UKHO)	Restricted access - The license agreement allows it to be viewed on the marine atlas: http://atlas.marine.ie
Offshore Wind Farms	No data in the study area at the time this study was conducted.
Oil & Gas Installations	Free & Open Access - Offshore platform, offshore commercial field, Exploration Wells.
Spawning Grounds	Free & Open Access.
Feeding/Nursery Grounds	Free & Open Access.
Fishing Areas	Free & Open Access - Inshore Fishing Activities.
Marine Protected Areas	Free & Open Access - SPAs; SACs; PNHA; NHAs; RAMSAR Wetlands UK; Biological Sensitive Areas; Greencastle Codling Protected Areas.

* Data not publicly available from the provider due to data protection regulations.

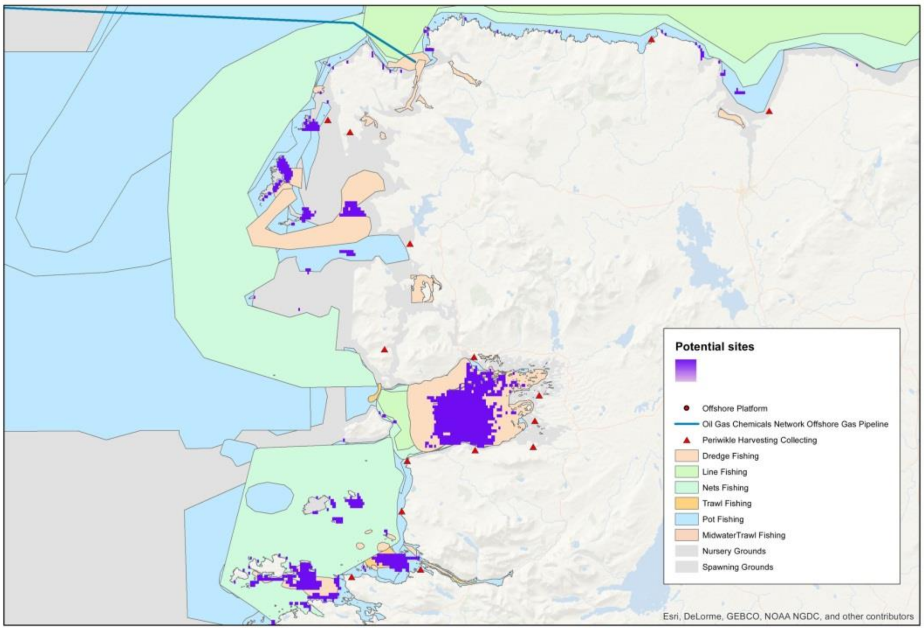

Figure 12. Plot shows locations of Spawning, Nursery, Energy resources and Inshore Fishing in the study region off the west coast of Ireland.

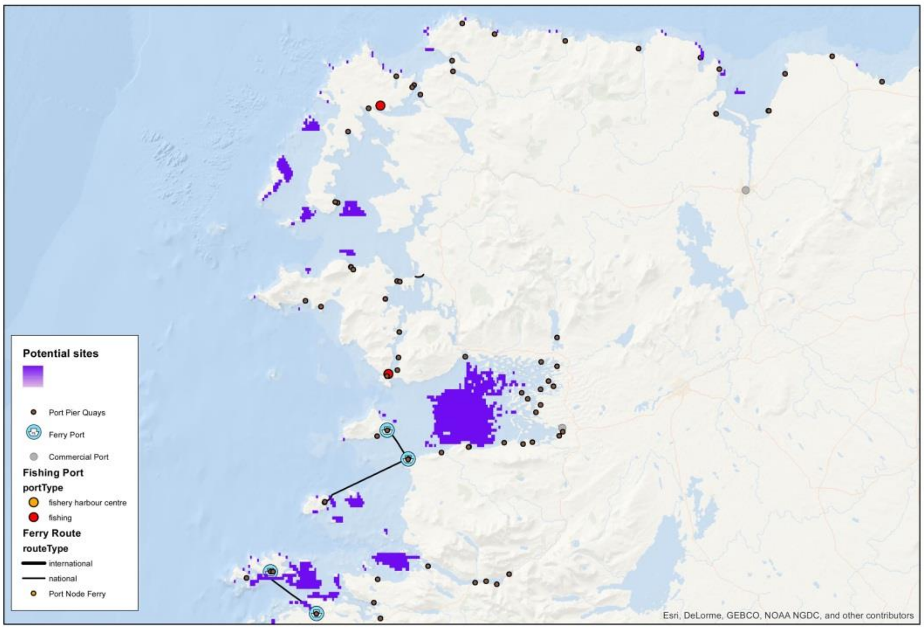

Figure 13. Plot shows the Infrastructure in the study region off the west coast of Ireland.

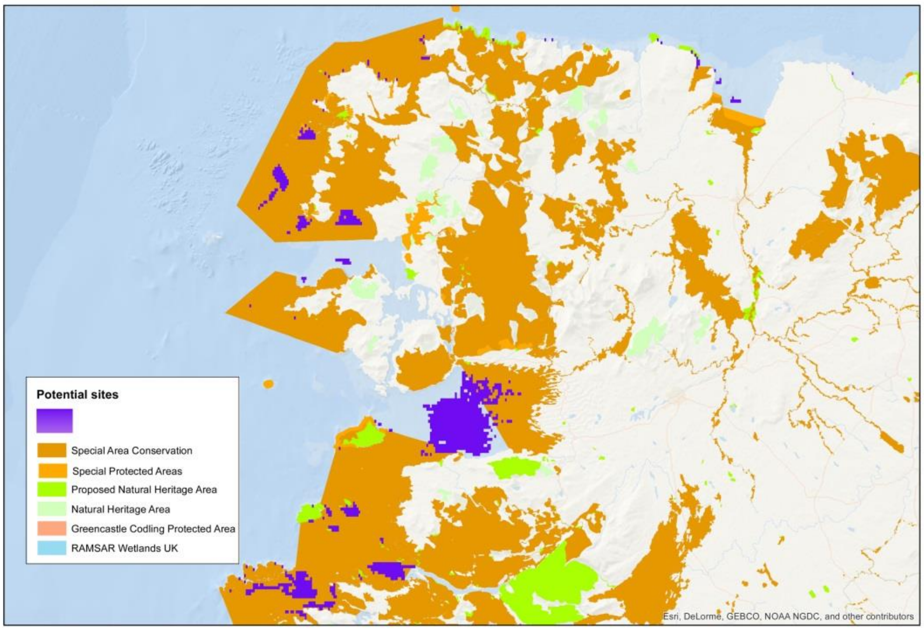

Figure 14. Plot shows the environmental protected and sensitive areas in the study region off the west coast of Ireland.

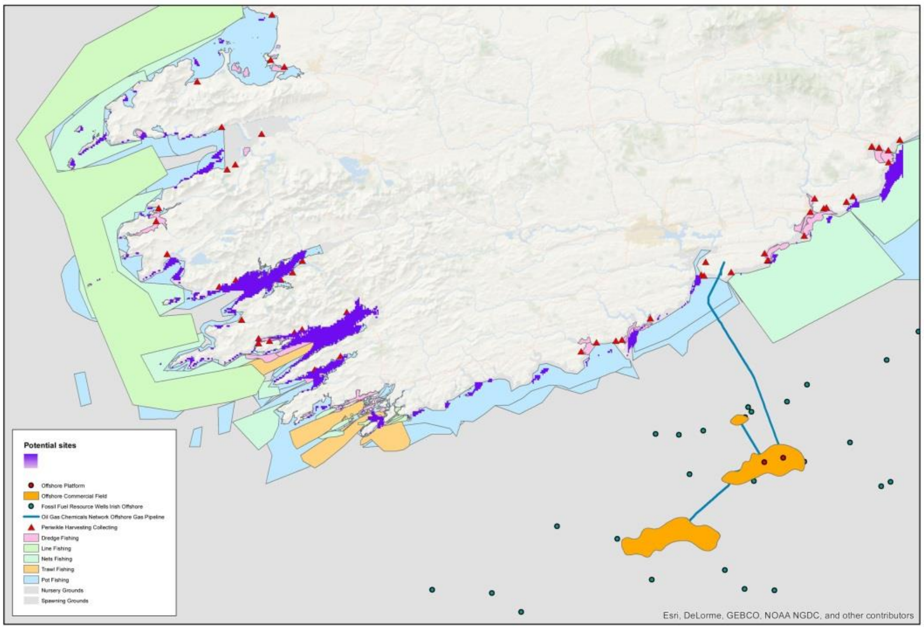

Figure 15. Plot shows locations of Spawning, Nursery, Energy resources and Inshore Fishing in the study region off the west coast of Ireland.

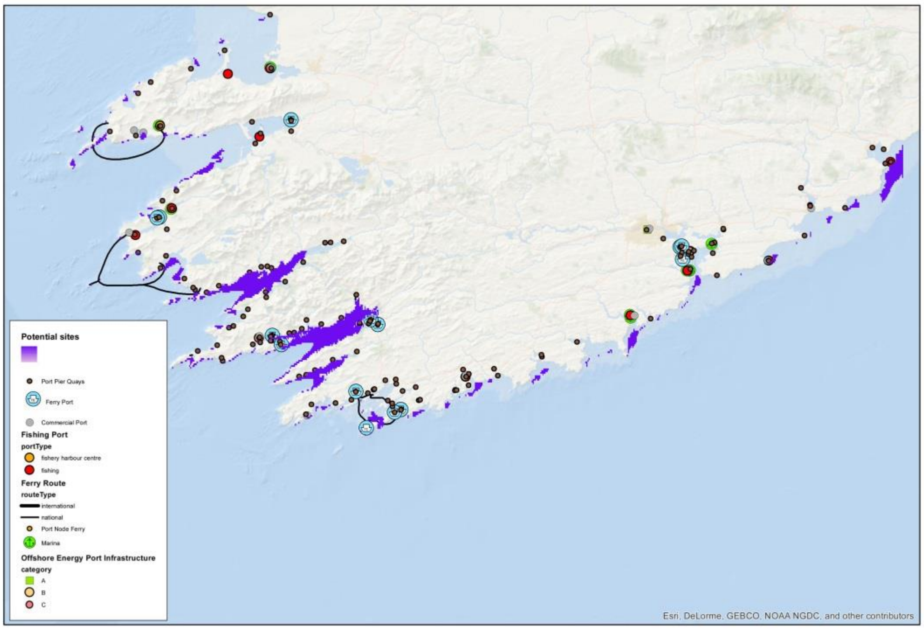

Figure 16. Plot shows the Infrastructure in the study region off the southwest coast of Ireland.

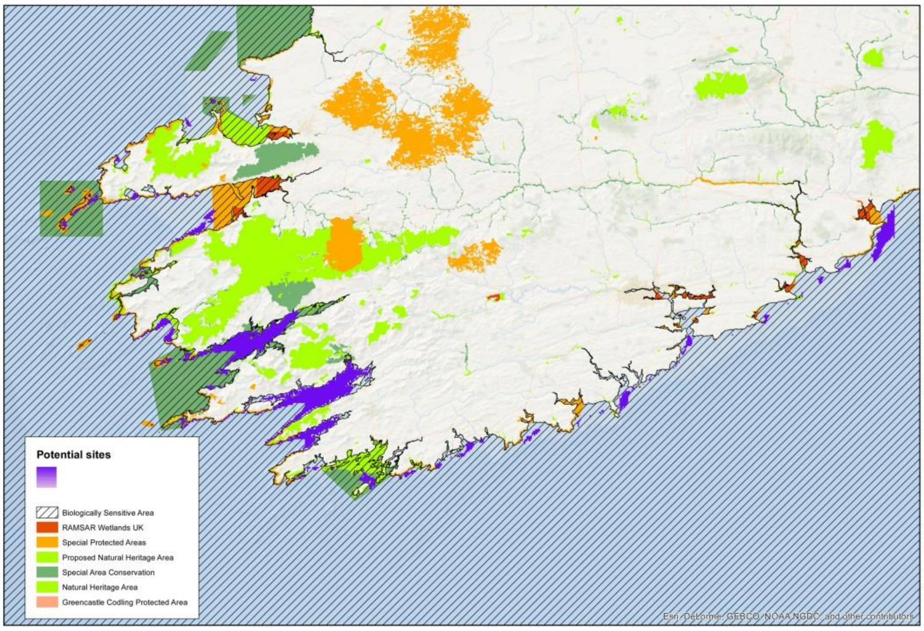

Figure 17. Plot shows the environmental protected and sensitive areas in the study region off the southwest coast of Ireland.

7. Galician Case Study

We have performed an exercise on aquaculture siting in Spanish Atlantic waters following the recommendation COM/2013/229 Strategic Guidelines for the sustainable development of EU aquaculture that stated "having spatial plans in place can help reducing uncertainty, facilitating investment and speeding up the development of sectors such as aquaculture or offshore renewable energy. The lack of space often cited as a hindering factor for the expansion of EU marine aquaculture can be overcome by identifying the most suitable sites amenable for aquaculture".

We have performed a brief review of experiences of offshore aquaculture in the Spanish Atlantic area: in the Canary Islands (cages for seabass and seabream, Popescu 2013) and in the Gulf of Cadiz. The location of finfish and shellfish aquaculture production sites can be obtained from EMODnet Human Activities, where Spanish data have been provided by MAGRAMA ministry. However, data are incomplete and existing aquaculture sites are missing.

The main aquaculture producer in Spain is Galicia, which is one of the largest seafood producers in Europe and in the world, with over 200,000 tonnes of mussel production, generating over 8,000 jobs and incorporating 1,000 aquaculture support vessels. Mussel production is done mainly in rafts in Galician rías (Vigo, Pontevedra, Arousa, Muros and Ares). In Galicia, there is great interest in diversifying aquaculture with new species (including multitrophic approach) and new sites.

Among the main obstacles to the development of offshore aquaculture in Spain are:

- Complex regulation: national government and regional autonomous government competencies. Some offshore sites in national waters, coastal and some off the coast sites subject to regional autonomous legislations.
- Technical issues on the type of platforms and about siting (high waves, storms and strong currents in offshore areas).
- Concerns on the compatibility of offshore aquaculture with current uses. This has led to conflicts in Galicia, where the regional government had to stop, in February 2016, the negotiation of an advanced draft of an aquaculture act due to the pressure of fishermen and shellfish harvester associations. These producers opposed the development of offshore aquaculture on the worry of potential detrimental effects of new aquaculture exploitations on the environment and therefore on the existing aquaculture sites. These stakeholders, especially mussel raft producers and fishermen guilds, consider their current activities more sustainable and environment-friendly when compared to the "industrial" offshore aquaculture activities. Some of the companies interested in offshore aquaculture development are currently looking for sites in nearby waters in the Cantabrian Sea (Asturias), where there is also raising opposition to the establishment of new aquaculture sites.

7.1 Galician product development

A GIS based model approach has been used to perform the siting exercise in Galicia based on the following raster layers:

Water depth was obtained from the GEBCO30 gridded dataset made available in GeoTIFF format by the British Oceanographic Data Center (BODC). The resolution is ca. 30 arc-seconds (ca. 1.5 km at our latitude).

Wave climatology: There is a wave climatology for the Galician region elaborated by the regional agency Meteogalicia during an Atlantic Area project (EnergyMare). Results are available through WMS and WFS services:

http://www.meteogalicia.gal/modelos/atlas/atlasOndas.action?request_locale=gl

The numerical grid has a high resolution grid, reaching a spatial resolution of 75 m inside the Galician Rias and even higher in shallow areas. Meteogalicia supplied a high resolution geotiff file for our siting study.

The criteria chosen in the GIS model were:

- Depth below 15 meters (option a) or below 50 m (option b)
- Maximum significant wave height, *max_Hs*, < 4 m. Obtained from the extreme values with a return period of 10 years (layer RE_TR10_Hs)
- Ninetieth percentile value of a significant wave height (Hs), Hs_P90 < 2 m (layer RM_DLN_H90)

On the basis of these criteria, “suitable” areas for offshore aquaculture were obtained (Figure 18).

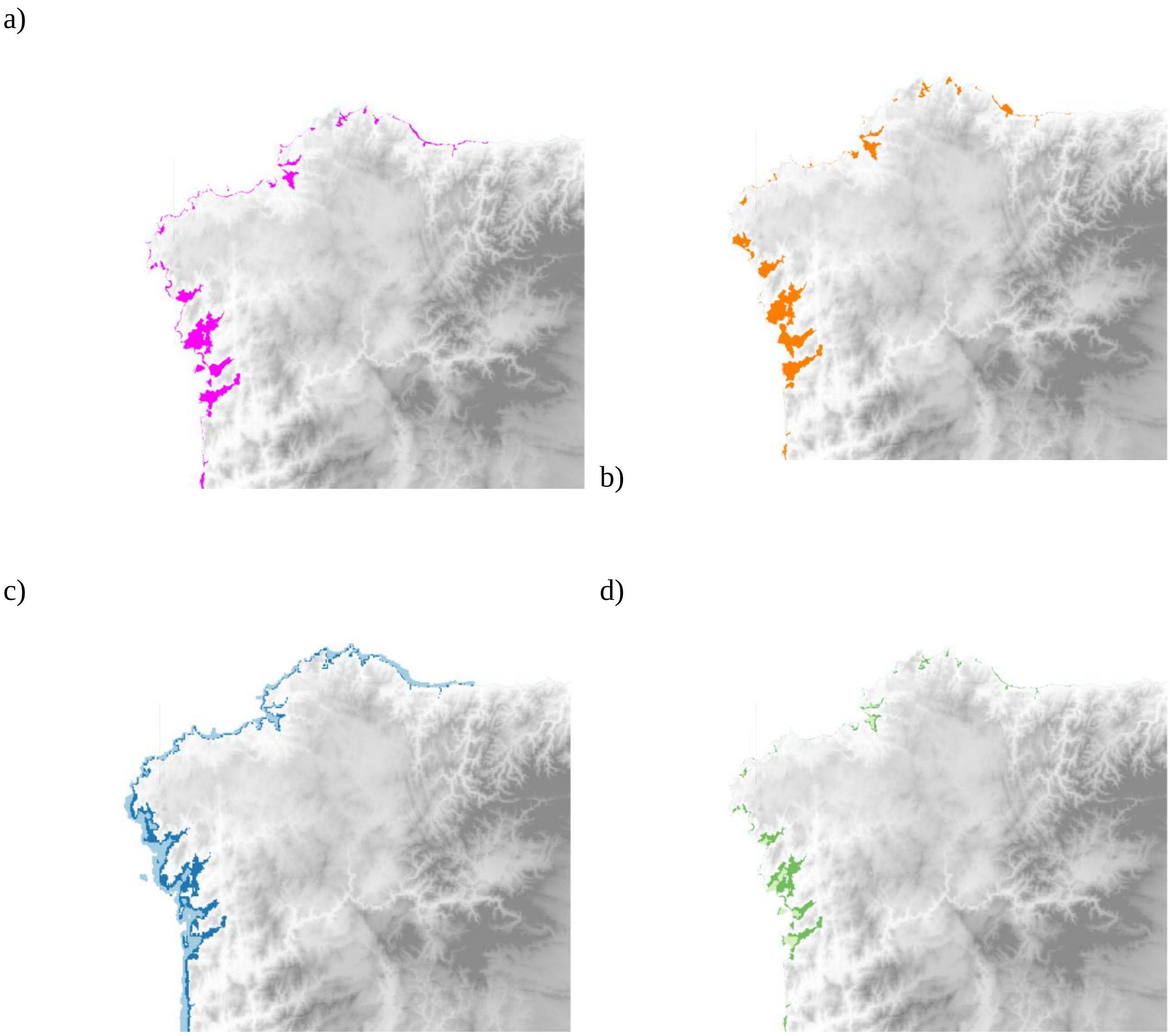

Figure 18. GIS layers a) max_Hs, < 4 m (purple) b) Hs_P90 < 2 m (orange) c) depth < 50 m (light blue), depth < 15 m (dark blue) d) Suitable areas with depth < 50 m (light green), depth < 15 (dark green).

We did not use maximum tidal velocity since velocities above 1 m/s are only observed in very specific places, like the entrance of Ria de Ferrol or the Miño estuary, which as we will see in the following section lie in a harbour entrance (Ria de Ferrol) or in a Nature 2000 protected area (Miño estuary).

7.2 Administrative layers

Several administrative layers (Table 5) have been used to further determine the suitability of the obtained areas and we plot them in Figure 19 together with the “suitable” areas layers.

Table 5. List of administrative data of interest and corresponding data sources.

Data Layer (Administrative Layers)	Data Source
Marine Protected Areas: Atlantic Islands national park	National government. MAPAMA http://www.mapama.gob.es/es/red-parques-nacionales/nuestros-parques/islas-atlanticas/ficha-tecnica/default.aspx
Nature 2000 Sites of Community Importance	National government. MAPAMA http://www.mapama.gob.es/es/biodiversidad/servicios/banco-datos-naturaleza/informacion-disponible/rednatura_2000_lic_descargas.aspx
Fisheries reserve (Galician autonomous government protection)	Galician government http://visorgis.cmati.xunta.es/geoserver/dhgc/wfs (Layer dhgc:CP_reservamarinainterespesquero)
Location of mussel rafts	Galician government http://visorgis.cmati.xunta.es/geoserver/dhgc/wfs (Layer dhgc:ZP_NE_ZonaPoligonoBateas)
Fishing grounds	Instituto Español de Oceanografía http://www.ieo.es/web/ieo/geoportal
Harbour areas	Galician government http://visorgis.cmati.xunta.es/geoserver/dhgc/wfs Layer: dhgc:masasaguapuertos_gc

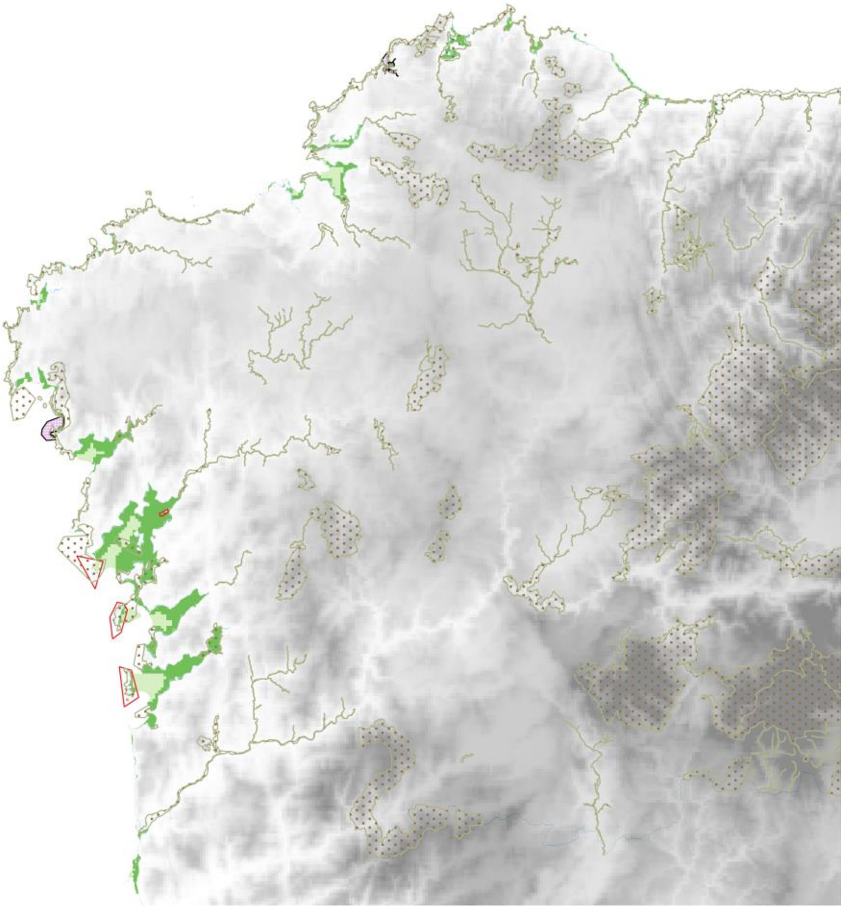

Figure 19. “Suitable” layers for offshore aquaculture with administrative layers overlaid.

The Galician coast is wave exposed and deep. Therefore, suitable areas are located nearshore and in the Galician rias. Some suitable areas lie in protected areas: Atlantic Island national park (red polygon), Natura 2000 sites of community interest (red dotted filled polygons) or fisheries reserves (purple squared filled polygons). Some other areas are affected by the location of a harbour nearby like in the Ria de Ferrol. Finally, we have overlaid a layer showing the location of existing mussel rafts in Galicia (Figure 20). Mussel rafts in Galicia are located in the suitable areas obtained in our analysis. In the Galician Rias Baixas, the quantity of mussel rafts hinders further aquaculture activities. However, there are a few areas where, according to our criteria, potential offshore aquaculture activities could be explored further, although further interaction with stakeholders is required.

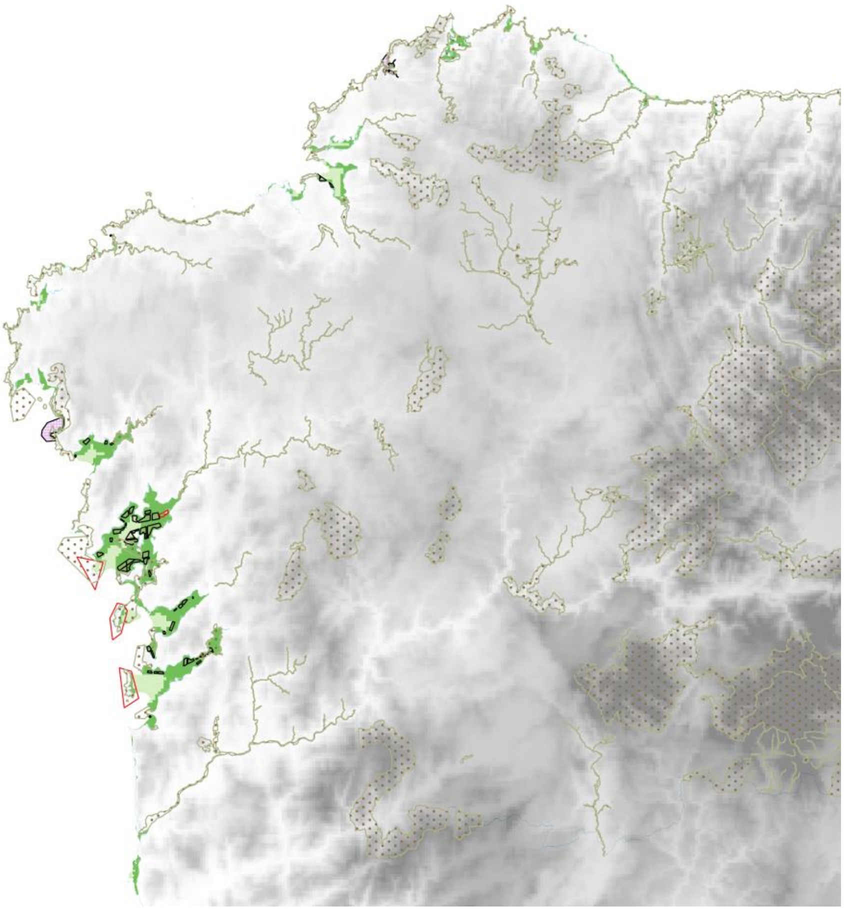

Figure 20. “Suitable” layers for offshore aquaculture with protected areas and existing mussel rafts (black lined polygons) overlaid.

8. Future work and recommendations

8.1 User involvement

According to Nath *et al.* (2000), GIS is by nature an iterative approach and stakeholder involvement is crucial to ensure that relevant data is included and that products developed are “fit for purpose”. Offshore aquaculture site selection has several potential user groups (e.g. decision makers and farm operators). At a global level, analyses such as that carried out by the FAO (Kapetsky *et al.* 2013) can identify countries and regions with untapped potential. Aquaculture regulators and marine spatial planners support the management of environmental protection in a complex setting where multiple marine based activities compete for space. At a local level aquaculture developers and operators are motivated by the suitability of sites and environmental monitoring requirements. While requirements of potential user groups can overlap, data needs in terms of spatial and temporal resolution may differ. Data sharing can also be inhibited due to “choke points” when data request forms need to be submitted prior to data release or restricted access.

Stronger end user involvement will ensure products that are “fit for purpose”. We will work with WP 10 (Task 10.2 “Best Practices in Stakeholder Engagement, Data Dissemination and Exploitation”) to further investigate requirements from aquaculture site selection end-users and to identify potential gaps in availability of suitable data. In particular, data layers related to waves, current velocity and water column structure and to operational and HSE aspects will be investigated further. For example, in Norway an upper limit for Hs has yet to be determined by the authorities. However, the aquaculture industry operates at a max Hs of 4.5 m because operations are difficult above this threshold. A data layer product that presents the number of days per year / season when critical aquaculture operations can be carried out increases the usefulness of the product and the likelihood that the product developed is “fit- for purpose”. End user involvement will help to highlight key species that could potentially be cultured in the future and the limits of associated farming practices. The GIS analysis in this report is simple. Increased end user involvement is needed to gather information on the weight of importance that should be given to each criterion used; such as the Weighted Linear Combination method discussed in Perez *et al.* (2005).

The current tools developed focused mainly on sea state suitability for aquaculture operations. Future tools should mature to include environmental monitoring and the regulation aspects of marine spatial planning (2014 EU Marine Spatial Planning Directive). Hence, more EOVs than the ones used in the analyses here may be relevant for offshore aquaculture siting.

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