Horizon 2020

AQUASPACE

Ecosystem Approach to making Space for Aquaculture
EU Horizon 2020 project grant no. 633476

Deliverable 3.3
AquaSpace tool to support MSP

Revised manual (2nd edition) for AquaSpace tool (version 2)

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Deliverable version	**1.0**

Type of deliverable	**GIS AddIn & Manual**
Dissemination level	**Public**
Delivery date in DoW	**2017/31/08**
Actual delivery date	**2018/30/04**

Reviewed by	**Paul Tett (Coordinator)**

The research leading to these results has been undertaken as part of the AquaSpace project (Ecosystem Approach to making Space for Aquaculture, http://aquaspace-h2020.eu) and has received funding from the European Union's Horizon 2020 Framework Programme for Research and Innovation under grant agreement n° 633476.

Change log

Version	Date	Author	Reason for change
0.1	02/02/2017	AG	Initial draft
0.2	08/31/2017	AG	Revised based on input from co-authors
1.0	10/20/2017	AG	Incorporates coordinator's comments
1.0	04/30/2018	AG	Revised based on project reviewer's comments

CONTENTS

EXECUTIVE SUMMARY

AquaSpace aims to deliver the science base to identify the potential for aquaculture to expand in Europe and to support the corresponding licensing process in the context of Integrated Coastal Zone Management (ICZM) or Marine Spatial Planning (MSP).

The AquaSpace tool is designed to allow for a spatial representation of opportunities and risks of a proposed aquaculture activity at a specific marine location in a multi-use context. Specifically, opportunities relate to socio-economic assessments of the added value of an activity, food security or expected revenues; while risks relate to an evaluation of combined environmental effects of the planned activity and the additional pressure contributions of a new aquaculture activity to the overall human pressures in a management area.

The AquaSpace tool is one of the first Geographic Information System (GIS)-based spatial planning tools that allows for a spatial explicit and integrated assessment of indicators reflecting the economic, environmental, inter-sectorial and socio-cultural risk and opportunities for proposed aquaculture systems, based on a bottom-up approach. Tool outputs (i.e. AquaSpace tool Assessment Report) comprise detailed reports and graphical outputs which can facilitate planning trade-off discussions hence allowing key stakeholders (e.g. industry, marine planners, licensing authorities) to proactively communicate effects of alternative scenarios and take more informed, evidence-based decisions on proposed aquaculture.

Such a transparent visualisation technique facilitates i) an effective implementation of MSP for aquaculture, enabled by using spatially explicit methods and tools, ii) the implementation of a spatially explicit (GIS-based) multi-use context, addressing the functionality for cumulative risk assessments and conflict analysis, and iii) the implementation of an Ecosystem Approach to Aquaculture (EAA), explicitly considering economic and market issues. This integrated approach will support the licensing process and facilitate investments.

This report provides a guide for users of the AquaSpace tool. Introductory sections 2-3 explain the rationale for the tool and provide the background knowledge needed to use it. Section 4 describes the tool outputs. Section 5 is a user manual. Annex I gives sources for information needed to use the tool. Annex III summarises experiences of using the tool in 6 case studies.

SOFTWARE AVAILABILITY AND SYSTEM REQUIREMENTS

Name of software: AquaSpace tool - a GIS AddIn
Developers: Antje Gimpel, Sandra Töpsch, Vanessa Stelzenmüller
Email: antje.gimpel@thuenen.de
Year first available: 2017
Operating System: Microsoft Windows 7, Windows 8/8.1 (32 or 64 bit) or Windows 10
Processor/CPU: 2.7 GHz Intel Core i5 processor or equivalent (4 cores) (hardware below/above will increase/decrease tool run times)
System RAM: 4 GB total minimum, 16 GB recommended
Windows Feature .NET Framework: .NET 4.6 Framework
ESRI ArcGIS: ArcGIS Desktop Basic, Standard or Advanced + Extension Spatial Analyst
Python Environment: Standard Python library 32bit of ArcGIS installation 10.3 and higher
Program size: 1.7 MB; GDB 400 MB
Availability: https://gdi.thuenen.de/geoserver/sf/www/aqspce.html
Cost: nil

CITATION AND COPYRIGHT

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Gimpel, A., Stelzenmüller, V., Töpsch, S., Brigolin, D., Galparsoro, I., Gubbins, M., Marba, N., Miller, D., Moraitis, M., Murillas, A., Murray, A.G., Papageorgiou, N., Pastres, R., Pinarbasi, K., Porporato, E., Roca, G., and Watret, R. 2017. AquaSpace tool to support MSP. Thünen Institute, Hamburg and AquaSpace project (H2020 no. 633476), Oban. Deliverable 3.3. Pdf obtainable from http://www.aquaspace-h2020.eu

Gimpel, A., Stelzenmüller, V., Töpsch, S., Galparsoro, I., Gubbins, M., Miller, D., Murillas, A., Murray, A.G., Pinarbasi, K., Roca, G., and Watret, R. (2018). A GIS-based tool for an integrated assessment of spatial planning trade-offs with aquaculture. Science of the Total Environment, 627: 1644-1655. DOI: 10.1016/j.scitotenv.2018.01.133

This tool is a result of AquaSpace (Ecosystem Approach to making Space for Sustainable Aquaculture) project, funded by the European Union under the H2020 Programme (grant agreement no. 633476).

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1. MANUAL USER GUIDE

It is the purpose of this manual to guide the user through the application of the AquaSpace tool. This document compliments the online support at https://free-redmine.saas-secure.com/projects/aqua and should therefore be used in conjunction with the website. Whereas the online support provides access to all AquaSpace tool files, technical documents and manuals / video instructions facilitating the installation and testing of the AquaSpace tool, this manual provides further information, explanation and key references to the tool functions included. Furthermore, it describes the preparatory work, sequence of steps and related tasks the user should undertake to apply the tool.

This manual aims to provide clear and user-friendly instructions about the terminology used, the concept of the AquaSpace tool, and the tool's functions and indicators for a holistic ecosystem-based Opportunity and Risk Assessment that applies the EAA to MSP. Moreover, it includes suggestions for successful completion of such an assessment.

It is highly recommended to read through the AquaSpace tool description and background information BEFORE starting with the setup of the tool. Below is some guidance for using the manual:

1. The rationale for the development of the AquaSpace tool is given in THE AQUASPACE TOOL: RATIONALE AND BACKGROUND.
2. The concept, tool indicators and terminology used throughout the manual is described in THE AQUASPACE TOOL: CONCEPT, INDICATORS AND TERMINOLOGY.
3. Potential AquaSpace tool outcomes and their interpretation are described in AQUASPACE TOOL OUTPUTS.
4. Technical guidelines, installation and update procedures, first test runs and scenario building are explained in USER MANUAL.
5. Detailed information about the data underlying the AquaSpace tool, their origin and key references are given in ANNEX I AQUASPACE TOOL METADATA.
6. The broader applicability of the AquaSpace tool (including first experiences) is demonstrated in ANNEX III CASE STUDY EXPERIENCES.
7. Where limited data may make it difficult to complete actions described in the manual, it may be helpful to complement desktop data collation with expert and/or stakeholder workshops. These can be used to obtain information that may not be readily available, pool knowledge and expertise and discuss elements of risk and uncertainty associated with an assessment based on limited data.
8. The tool can be used iteratively to compare a set of spatial management scenarios with aquaculture (e.g. varying farm locations, species or production quantities).

2. THE AQUASPACE TOOL: RATIONALE AND BACKGROUND

The central goal of the EU Horizon 2020 project AquaSpace is to provide increased space of high water quality for aquaculture by adopting an Ecosystem Approach to Aquaculture (EAA) to support Marine Spatial Planning (MSP) and to deliver food security and increased employment opportunities through economic growth with a long-term view.

An effective implementation of MSP for aquaculture is enabled by using spatially explicit methods and tools. Studies within the AquaSpace project revealed a need for tools allowing:

- The implementation of an ecosystem approach incorporating the functionality required to support an EAA implementation and explicitly considering economic and market issues.
- The implementation of a spatially explicit Geographic Information System (GIS)-based multi-use context, addressing the functionality for cumulative risk assessments and conflict analysis.
- The intuitive design of the interface, which is meant to be end-user driven, allowing industry and policy-makers to make more informed, evidence-based, decisions.

One promising solution identified during a comprehensive gap analysis in Gimpel et al. (2016) was to develop a tool that could be used to support an Opportunity and Risk Assessment. Such a tool would allow for a spatial representation of all risks and opportunities of a proposed aquaculture site in a multi-use context (Fig. 1). The AquaSpace tool was developed as a GIS Addin under Arc GIS to allow users to compare risks and opportunities over a number of potential sites. It includes functions that enable the user to assess the spatially explicit performance (under different aquaculture planning scenarios) of inter-sectorial, environmental, economic and socio-cultural indicators.

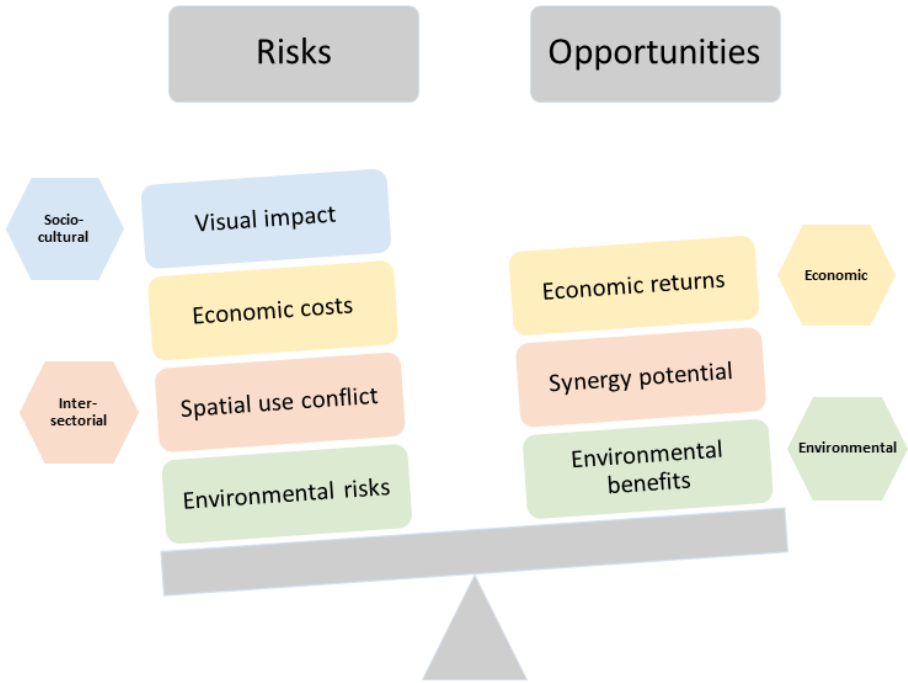


Figure 1: 1st vision of the AquaSpace tool, visualising opportunity and risk categories which should be included when assessing spatial management options for aquaculture.

Thus, risk indicators reflect for instance the spatial conflict potential between human uses, habitat vulnerabilities or combined environmental effects of proposed aquaculture activities, direct and

indirect economic costs or visual impacts. In contrast, indicators reflecting opportunities of a planned aquaculture site comprise total expected revenues or synergy potential with other sectors (Gimpel et al., 2016).

To promote tool exchange and its general applicability, the AquaSpace tool comes with a GIS Geodatabase (GDB) which already integrates several data sets at a European scale. Reflecting the need for spatial explicit assessment approaches to be easy to access, the AquaSpace tool aims further to facilitate the integration of spatial layers generated by other models and tools. In other words, it can be also regarded as an ArcGIS based platform that brings together spatial outputs from models, which can produce a data format that can be imported into ArcGIS.

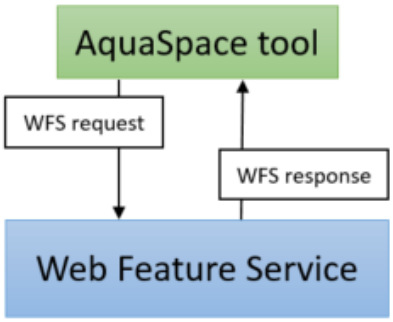


Figure 2: Open Geospatial Consortium Web Feature Service Interface Standard (WFS) provide an interface allowing requests for geographical features across the web using platform-independent calls. In the future, the AquaSpace tool will directly be linked to WFS to request required geodata.

In order to hold down maintenance costs of geodata, the AquaSpace tool has been developed in the GIS environment to be linked with open Geospatial Consortium Web Feature Service Interface Standard (WFS) that provides an interface allowing requests for geographical features across the web using platform-independent calls. Nevertheless, WFS request or rather response still needs a high amount of time loading the data, which slows down tool performance. In future, data exchange might speed up. Previously, the integrated AquaSpace tool GDB fill those gaps. Its content is explained from a scientific view in AquaSpace tool indicators and from a technical perspective in ANNEX: AQUASPACE TOOL METADATA.

The AquaSpace tool is equipped with an end-user driven interface and an interactive menu. It allows the visualization of areas of constraint (e.g. priority shipping lanes) and of potential synergy (i.e. co-location), defined by an interaction matrix which can be modified according to user needs. Further, the tool enables the user to explore a range of options to identify potential sites and assess the opportunities and risks of several scenarios at once. Tool outputs comprise detailed reports and graphical outputs which should facilitate planning trade-off discussions hence allowing key stakeholders (e.g. industry, marine planners, licensing authorities) to take more informed, evidence-based decisions on proposed aquaculture developments and the associated risks and opportunities.

The tool's socio-economic dimension will increase the acceptance of these new developments by local communities and society-at-large (Ramos et al., 2014; Stelzenmüller et al., 2017). Environmental assessments will contribute to the implementation of the Integrated Maritime Strategy and its environmental pillar, the EU Marine Strategy Framework Directive (Gimpel et al., 2013; Stelzenmüller et al., 2014; Gimpel et al., 2016). Integrating indicators, supporting the assessment of inter-sectorial

effects, enables authorities to account for the principles of good MSP practice as required by the EU Maritime Spatial Planning Directive (Gimpel et al., 2016). Ultimately, this integrated assessment approach could support the licensing process and facilitate investments (Stelzenmüller et al., 2017).

3. THE AQUASPACE TOOL: CONCEPT, INDICATORS AND TERMINOLOGY

3.1. AquaSpace tool concept

The AquaSpace tool can be thought of as a spatially explicit Cost-Benefit Analysis. Given a set of planning alternatives, such as different farm locations, it will allow the assessment of the strengths and weaknesses of each alternative. The tool is used to determine options that are informed by the Ecosystem Approach to Aquaculture, and which allow achievement of opportunities (sustainable development) whilst preventing risks (to the environment). The tool is also defined as a systematic process for calculating and comparing opportunities and risks of a decision, policy (with particular regard to government policy) or (in general) project (David et al., 2013).

Broadly, an economic Cost Benefit Analysis (CBA) has two main purposes:

- To determine if a proposed development is a sound investment (justification/feasibility).
- To see how a particular development option (or scenario) compares with alternate projects (ranking/priority assignment) (CA.GOV, 2017).

In the AquaSpace context, the AquaSpace tool CBA also:

- Allows for a spatial representation of opportunities and risks (incl. environmental) of a proposed aquaculture site in a multi-use context (supporting an EAA).

The AquaSpace tool is a GIS AddIn that was implemented under Arc GIS 10.3 and was developed by combining the GIS model builder and python scripts. It runs with Arc GIS 10.3 and newer versions. It comprises functions that enable the user to assess the spatial explicit performance of inter-sectorial, environmental, economic and socio-cultural indicators for different aquaculture planning scenarios. Therefore, the *user's input* defines the study area (country), the port from which aquaculture business should be transacted, the culture species, the corresponding culture system, the compilation of constraining, conflicting or synergistic human uses and the aquaculture locations to be tested. While doing so, the user is directed to act in a sustainable way, being aware of e.g. the ecological footprint of a specific aquaculture or its interaction with other human activities. Consequently, the AquaSpace tool estimates all opportunities and risks based on inter-sectorial, environmental, economic and socio-cultural indicators (Fig. 3). Tool outputs (i.e. AquaSpace tool Assessment Report) are provided in pdf-format. They offer a transparent summary of all tool runs (i.e. scenarios) and the respective indicator values. They give general site information (e.g. species, water depth, water quality), inter-sectorial effects (e.g. spatial conflict potential, disease spread), environmental effects (e.g. degree of exposure, cumulative pressures, distance to waste disposal sites) and economic and market issues (economic performance, effectiveness and efficiency). Further, the report includes mappings and graphics, enabling the user to proactively communicate opportunities and risks. Such a transparent information policy can build stakeholders support, which is critical to the successful establishment of aquaculture and ongoing operations.

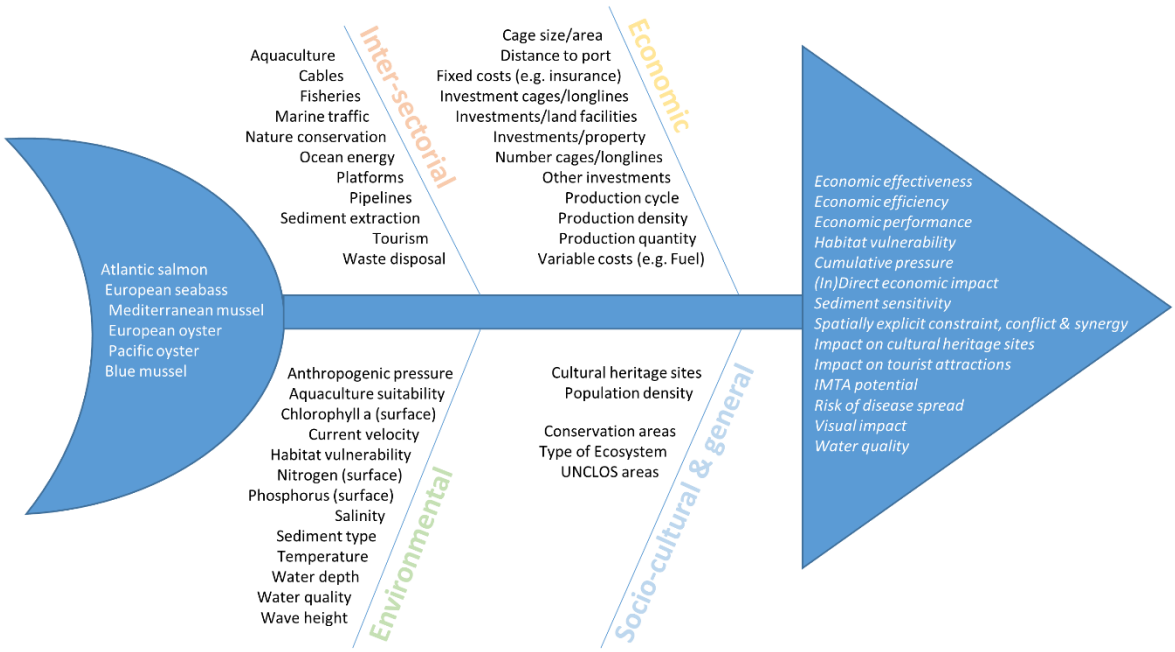


Figure 3: A brief insight in the AquaSpace tool, (from left to right) giving an overview about i) all species considered, ii) data and information AquaSpace tool assessments are built on and iii) (additional) site-specific information received by applying the AquaSpace tool functions (Economic performance = Revenue, Added Value (AV); Economic effectiveness = Return on Fixed Tangible Assets, Opportunity costs; Economic efficiency = Net Present Value; Economic impact = (In)Direct impact on the AV, (In)Direct impact on employment; IMTA = Integrated Multi-Trophic Aquaculture, UNCLOS = United Nations Convention of the Law Of the Sea).

3.2. AquaSpace tool indicators

This section provides further information about the AquaSpace tool indicators (i.e. counted or measured variables). More precisely, it describes how the parameters, underlying the tool functions and defining the ultimate indicator values, were determined (incl. scientific background information related to this). Detailed information about the source of the data (in raw, uninterpreted form), credits and how the data have been processed are given in ANNEX I AQUASPACE TOOL METADATA. Most of the data sets are already implemented in the tool (e.g. environmental data), others are depending on the user input (e.g. production in kg, Annex I).

This section (3.2) is structured around the *AquaSpace Assessment Report* (described in section 4, AQUASPACE TOOL OUTPUTS), which guides the user through the results of using the tool. This section also explains how the results were computed.

3.2.1. General site information

The first information given in the report are the user ID and the date of assessment. The site tested is provided with a site number, which is ascending throughout the tool application. All information is listed in three columns: i) indicator name, ii) indicator value and iii) indicator description.

The first part of the report includes general site information, which is crucial to get an initial overview of the site to be tested, the species to be tested, the culture system and aquaculture related information about the surrounded area/the test site's surrounding such as water depth and quality. Indicators included read as followed:

- Site specific information
  - Ecosystem (country; marine or freshwater)
  - Water depth (m)
  - Water quality (level of background pollution)
- Management information
  - UNCLOS area
  - Conservation area
- Aquaculture specific information
  - Aquaculture (finfish, shellfish or algae)
  - Species to be cultivated (species name)
  - Culture system (cage, longline, bottom, trestles; culture system size in m^3/ha)
  - Stocking density (per m^3/ha)
  - Production cycle (years)
  - Production (tons)

Based on the *user input* a (case study) area is chosen, data sets are clipped (to improve the performance of the tool) and a specific aquaculture site is zoomed in on. Further, the user input polygon is buffered by a species-specific environmental footprint. Assuming a precautionary approach, the environmental footprint of shellfish (longline) is determined to be 50m (Chamberlain et al., 2001) while that for finfish aquaculture is set at 800m (Hall-Spencer et al., 2006; Marbà et al., 2006; Holmer et al., 2008; Sanz-Lázaro et al., 2011).

Site specific information provided in the report include the ecosystem to be assessed (currently, tool application is restricted to the marine environment), the water depth (1*1km raster layer) and the water quality, which is based on distance of the aquaculture site to waste disposal sites (e.g. coastal discharge). The water quality indicator is parameterized by expert opinion, assuming that a distance > 1.8km indicates a low risk of pollution and therefore a high water quality (3 = high), a distance of < 1.8km indicates medium water quality and a distance of < 100m indicates a low level of water quality (1 = low) (Maritime Safety Queensland, 2017).

Management information provided in the report includes information about various areas in which use is limited by the United Nations Convention on the Law of the Sea (**UNCLOS area**). Specified for this legal indicator are an abbreviation of the country name and the area to be assessed. Those include i) 'internal waters', which covers all water and waterways on the landward side of the baseline. The coastal state is free to set laws, regulate use, and use any resource. Foreign vessels have no right of passage within internal waters; ii) 'territorial waters', which are out to 12 nautical miles from the baseline, the coastal state is free to set laws, regulate use, and use any resource; or iii) 'exclusive economic zones' (EEZs), which extend from the edge of the territorial sea out to 200 nautical miles from the baseline. Within this area, the coastal nation has sole exploitation rights over all natural resources (UN, 2017)). Information about **conservation areas** indicate, if the user input overlaps with a i) National Park, ii) Natura 2000 sites; or iii) OSPAR MPAs (OSPAR, 2017).

Aquaculture specific information provided in the report include the option the user has chosen regarding the aquaculture type to be assessed (finfish, shellfish or algae), the species to be cultivated and the culture system (cage, longline, bottom, trestles). Here, further particulars can be made according to the cage size in m³, the stocking density per m³, the production cycle the user want to assess in years and the amount of production in kg/tons. A detailed example for the German case study is given in the subsequent sub-section dealing with indicators (Economic Effects).

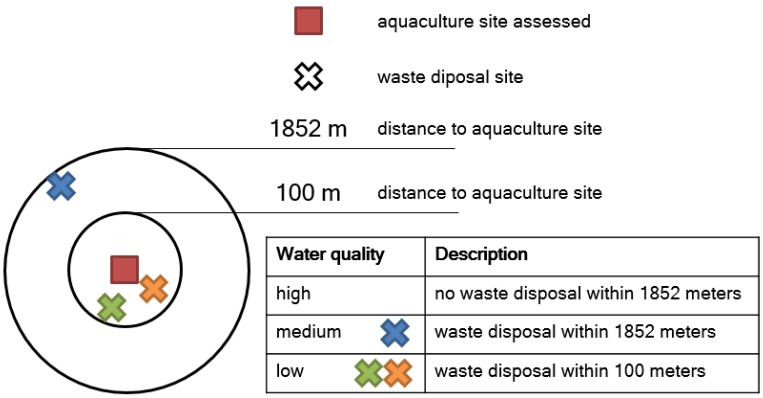


Figure 4: Exemplified assessment and determination of local water quality close to aquaculture site, which is defined based on background pollution. This information is derived using a distance calculation in the GIS layer "waste disposal".

3.2.2. Indicators

The second part of the report includes information about the intersectorial, environmental, economic and socio-cultural indicators implemented, which are crucial to evaluate the trade-off of sites tested and to interpret the results. Indicators included read as followed:

- Inter-sectorial effects
  - Spatial interaction matrix*
  - Spatial conflict potential (highest conflict score with other human uses)*
  - Spatial synergy potential (highest synergy score with other human uses)*
  - Integrated Multi-Trophic Aquaculture potential (IMTA; Yes or No, recommended IMTA species)
  - Risk of disease spread (based on minimum distance between aquaculture sites)
- Environmental effects
  - Aquaculture suitability (low to high)
  - Wave height specific exposure of the site (m)
  - Current velocity (m/s)
  - Sediment type
  - Chlorophyll a (mg/m³; surface)
  - Temperature (°C)
  - Salinity (PSU)
  - Nitrogen (mol/L NO3; surface)
  - Phosphorus (mol/L PO4; surface)
  - Cumulative pressure (1 - 8; 8 = high magnitude)

    - Habitat vulnerability (1- 3, 3 = highly vulnerable)
- Economic effects
    - Economic performance (revenue, added value)
    - Economic effectiveness (benefits, return on fixed tangible assets, opportunity cost)
    - Economic efficiency (net present value)
    - Economic impact (induced impact, indirect impact)
- Socio-cultural effects
    - Visual Impact (landscape, seascape, distance to populated areas)
    - Cultural heritage (shipwrecks, archaeological sites, distance calculation)
    - Tourism

*in combination with Fisheries, Ocean energy, Platforms, Cables, Pipelines, Sediment extraction, Marine traffic, Waste disposal, Marine Protected Areas (MPA).

3.2.2.1 Inter-sectorial effects

The calculation of **spatial conflict potentia**l and **spatial synergy potential** depends on user specifications. The user has completed an interaction matrix to define spatial constraints (score 6), conflicts (score 2-5) and opportunities (i.e. spatial synergy potential due to co-location; score 1) before testing scenarios for aquaculture in a wider MSP context (Lee and Stelzenmüller, 2010; Gimpel et al., 2013). In order to incorporate the high variability of MSP implementation processes in different regions, the input is kept flexible. Whereas sites designated for marine conservation (Boyd and Service, 2014) or waste disposal might constitute a constraint, in contrast, wind energy development can offer a possibility for spatial synergies with aquaculture (Gimpel et al., 2015). Also, the planning for new aquaculture sites might be constrained by important fishing grounds (Stelzenmüller et al., 2013). Those areas should be highlighted as a conflict, where management measures need to be based on trade-off assessments (e.g. opportunity costs). The AquaSpace tool offers the opportunity to distinguish between high intensity fishing effort ('Fisheries q3') and medium to low fishing effort ('Fisheries') per country when completing the interaction matrix. Conflict scores can be defined based on expert knowledge, or extracted from the literature (Lee and Stelzenmüller, 2010; Gimpel et al., 2013).

Table 1: Interaction matrix based on *user input* to define constraints, conflicts and opportunities (i.e. synergies). Example for the German case study aquaculture with *Dicentrarchus labrax*.

	Aquaculture
Fisheries (q3)	5
Fisheries	2
Ocean energy	1
Platforms	6
Cables	5
Pipelines	5
Sediment extraction	5
Marine traffic	6
Waste disposal	6
Marine Protected Areas (MPAs)	6
Tourism	3

Table 2: Matrix of potential conflicts developed by Lee and Stelzenmüller (2010). No conflict = 0; mutually exclusive = 5. Redrawn from Gimpel et al. (2013).

	Aquaculture	***Fisheries***	***Offshore wind farm***	***Platforms (oil, gas)***	***Cables***	***Pipelines***	***Sediment extraction***	***Marine traffic***	***MPAs***	***Waste disposal***
Aquaculture	-									
Fisheries	5	-								
Offshore Wind farm	2	2	-							
Platforms (oil, gas)	4	5	5	-						
Cables	0	2	2	1	-					
Pipelines	0	2	3	2	4	-				
Sediment extraction	5	1	5	5	5	5	-			
Marine traffic	5	2	5	5	0	0	2	-		
MPAs	4	5	5	5	3	3	5	4	-	
Waste disposal	5	3	5	5	2	2	5	1	5	-

Further, the highest conflict score of aquaculture with other human activities is indicated in the report under spatial conflict potential. Conflict scores can be defined based on expert knowledge, or extracted from the literature (Lee and Stelzenmüller, 2010; Gimpel et al., 2013) as presented in table 2. In contrast, the spatial synergy potential can be displayed. Spatial co-locations of marine areas might become increasingly important in the future, in the light of sustainable development in the already heavily used offshore marine realm. In applications of the AquaSpace tool, different spatial co-location scenarios for the coupling of offshore aquacultures with e.g. wind farms can be evaluated in order to support efficient and sustainable marine spatial management strategies. Both, spatial conflicts and synergies are defined with the aid of the interaction matrix, which is explained in the User Manual subsection: Create interaction matrix.

Independent of this interaction matrix, species-specific areas suitable for an **Integrated Multi-Trophic Aquaculture (IMTA) potential** are indicated. IMTA systems combine aquaculture species to recycle effluent dissolved and particulate nutrients from a higher trophic-level species (fish) to nourish extractive, lower trophic-level species, such as filter feeders (mussels, oysters), polychaetes, sea cucumbers and/or seaweed (Neori et al., 2007; Gimpel et al., 2015; Troell et al., in review). These systems aim at balanced nutrient budgets and minimize the waste production originating from fed aquaculture species through the filtering capacity of other extractive species clearing the water (Troell et al., 2009). Moreover, by using nutrient losses of higher trophic-level species as feeding products, IMTA could provide additional economic benefits (Neori et al., 2007; Gimpel et al., 2015). According to Brigolin et al. (2009), for each ton of farmed mussel harvested per year 0.008t nitrogen (N; excreted in dissolved inorganic form) is immediately available for phytoplankton uptake: this amount more than compensates the N exported as harvested mussel (Tab. 3). Such benefits can be used by co-locating finfish and shellfish farms. Therefore, the AquaSpace tool buffers polygons of existing aquaculture sites by 200m, indicating areas attractive for such an approach.

Table 3: Estimated nutrient fluxes through an offshore mussel (*Mytilus galloprovincialis*) farm. Assumed are 600t farmed mussels harvested per year.

	Nitrogen	*Phosphorus*
introduced (at seeding)	0.8	0.07
ingested	16	2
removed (by harvesting)	**3.36**	**0.3**
released (as excretion, faeces and pseudo-faeces)	12	1.5
in particulate form		**1.5**
in dissolved inorganic form	**4.8**	

Being part of inter-sectorial effects, the **risk of disease spread** should be assessed. Risk of infection decreases with distance from source, and modelled kernels of infection risk are widely used in modelling spread of both terrestrial (Keeling et al., 2001) and aquatic animal diseases (Kristoffersen et al., 2009). Patterns of decline risk have been assessed for Infectious Salmon Anaemia Virus (ISAV), Cardiomyopathy Syndrome (CMS) and Pancreas Disease (PD) (Kristoffersen et al., 2009; Aldrin et al., 2010). Sea lice infestation pressure has been shown to decline with distance as well (Salama and Murray, 2011; Middlemas et al., 2013; Shephard et al., 2016). Based on this, average distances have been extracted for the AquaSpace tool. Precautionary assumptions capture the basic nature of the risk interaction, averaged over different sites and seasons, and so can be used for strategic planning. The factors behind risk are i) the amount of pathogen produced, ii) the rate of decay of pathogens and iii) the distance they are transported at a given concentration given this decay rate (Murray et al., 2005):

A concentration C_x of exponentially decaying pathogen (at rate k) after a specific time t can be calculated as:

$$C_x = B^{-kt} \ (1),$$

where B is the size of the pathogen source normalised to a standard source.

Table 4: Decay rate examples from Spanish and German case studies. Decay rates are here considered as fast (f), moderate (m) or simply unknown (?). Where decay is fast it may be approximated by k = 0.1, for medium k = 0.05. Uncertainty (confidence) is high for all cases here, but ranks from 1 = high to 3 = very high.

	Host	Pathogen	Decay	Confidence
Germany	Sea Bass	Nodavirus	f or m	2
	Dicentrarchus labrax	Vibrio	f	1
		Pasturella	f	1
	Mussels	*Marteilia maurini*	m	2
	Mytilus sp.	Picarnolikevirus	f or m	2
		Vibrio	f	1
Spain	Oyster	Bonamia Osterae, B. exitiosa	m	2
	Ostrea spp.	*Marteilia refringens*	m	2
	Crassostrea spp.	*Perkinsus marinus*	?	3
		Microcytos mackiini	?	3
		Oyster Herpesvirus	f	1

A specific time t' for a particular proportion to be reached (say 10% of an index concentration where B = 1) can be calculated as:

$$t' = ln(\frac{C_x}{B})/(-k) \ (2),$$

Assuming a tidal current displacement is $a12/\pi$ (Anon 2000) and the residual current velocity is b, the distance can be calculated as:

$$\mathrm{D}' = \frac{\mathrm{t_x}}{\pi + \mathrm{bt}'} \ (3),$$

where t_x is the minimum of t' or 12 hours.

So for a tidal amplitude a, a residual current b, and a pathogen decay rate k we can calculate the time required for pathogens to decay to a given proportion of their initial concentration that is considered to represent a level of risk of relevance to planning (Tab. 5). A Cx of 0.1 indicates for instance farms that are highly interacting, a Cx of 0.01 indicates a distance which should be kept at fire break separation for notifiable disease spread. A k of 0.1 indicates a rapid decay, while a rate of k = 0.01 indicated a slow decay (Tab. 5). A current velocity a indicates short term currents of 50 and 25 cm s^{-1} and the long term advection b values of 1 or even 2.

A final factor is the relative size of the source of infection B, the farm biomass (Salama and Murray, 2011). In Scotland for instance median consented biomass of farms is about 900 tonnes so for simplicity $B = F/900$, where F is the consented farm biomass in tonnes. Shedding will also be altered by prevalence of infection and shedding of pathogens (Urquhart et al., 2008; Gregory et al., 2009),

which can be included as variation in *B* if greater knowledge of specific pathogens dynamics is available.

Table 5: Pathogen specific distances at which concentration of exponentially decaying pathogen C_x (at rate *k*) exists with a tidal current displacement *a* and residual current velocity displacement *b*. *F* for consented farm biomass in tonnes; *F* = 0.5, 1 or 2.

C_x	k	a	b	F 0.5	F1	F2	
0.05	0.1	50	1	7.71	7.96	8.21	ISAV
0.05	0.1	25	1	4.27	4.52	4.77	ISAV
0.01	0.1	50	2	9.70	10.19	10.69	precautionary ISAV
0.1	0.01	50	1	12.67	15.17	17.66	sea lice
0.1	0.01	25	1	9.23	11.73	14.22	sea lice
0.05	0.01	50	2	23.46	28.45	33.44	precautionary lice
0.01	0.01	50	2	35.05	40.04	45.03	ultra precautionary

Allowing for these uncertainties a worked example is provided for German sea bass farms (expected to be over 2000 tonnes biomass). Assuming a 5% decay per hour for nodavirus (instead of the 10% for ISAV), then distances of interaction could range from 4.1km (*a* = 25, *b* = 0.5 if both residual and tidal currents are weak and with a *Cx* = 0.05) to 14.5km (*a* = 25, *b* = 2 and *Cx* = 0.01) for a precautionary limit under strong tidal and advection currents. The main driver of uncertainty is the appropriate current regime for the southern North Sea.

3.2.2.2 Environmental effects

Information about environmental effects provided in the report is mostly depending on data already incorporated in the AquaSpace tool. Data giving information about the **aquaculture suitability** of a site were extracted from the WATER tool (Where Can Aquaculture Thrive in Europe), which specifies the performance of key species, such as Mediterranean mussel or Atlantic salmon, as a function of environmental data (i.e. sea surface temperature, dissolved oxygen, current speed, chlorophyll a concentration, depth) (Boogert et al., 2017).

In order to show the degree of exposure at a tested site, the significant **wave height** (in m) is output. Further indicators include **current velocity** in meters per second (m/s) and the **sediment sensitivity**, classified on the base of the sediment type, i.e. rocks (5), mixed sediment (4), coarse & gravel (3), sand (2) and mud (1). Minimum, mean and maximum values are given per grid cell for indicators useful to assess the growth performance of a species, i.e. **chlorophyll a** concentration at surface (mg/m³), **temperature** (°C) and **salinity** (PSU), and for indicators useful to assess the impact from/on the environment, i.e. **nitrogen** (mol/L) at surface, and **phosphorus** (mol/L) at surface. Unfortunately, adequate data about plastic marine debris or Particulate Organic Carbon (POC) were not available at European scale.

For the outcome of an ecosystem-based MSP process to be sustainable, all current and future human activities together with their associated pressures on key ecosystem components have to be included. The assessment of **cumulative pressures** requires a sound knowledge base of the complex spatial and temporal relationships between human activities and the sensitivity of the environment (Stelzenmüller, 2008; Stelzenmüller et al., 2010; Stelzenmüller et al., 2018). In order to account for a potential future shift in such pressures (introducing aquaculture sites on top of other pressures from other human activities) the AquaSpace tool accounts for cumulative pressures affecting the integrity of the marine habitat. Following the approach described in Elliot (2002); UNEP/GRID-Arendal (2002); Gimpel et al. (2013) all human activities occurring on a large scale in European waters were

categorised into generic pressure categories comprising abrasion (fisheries, aggregate mining), alteration (marine transport, aggregate mining, aquaculture finfish, aquaculture shellfish, tourism, waste disposal), contamination (pipelines, marine transport, platforms, tourism, waste disposal), enrichment (aquaculture finfish, waste disposal), extraction (fisheries, aggregate mining), obstruction (pipelines, platforms, windfarms), siltation (aggregate mining, tourism, waste disposal), and smothering (pipelines, cables, platforms, windfarms). Assigning a score of 1 to each pressure category, the cumulative pressure indicator reflects a sum of pressure categories found at each culture site tested (1 – 8; 8 = high magnitude of pressure). In addition, we used a DPSI (Driver-Pressure-State-Impact) conceptual model and definitions (Fig. 5) to illustrate the pathways of effects showing the links between drivers of human activities (Driver) and their respective normalized pressures (Pressure) occurring in the European waters (Elliot, 2002; UNEP/GRID-Arendal, 2002).

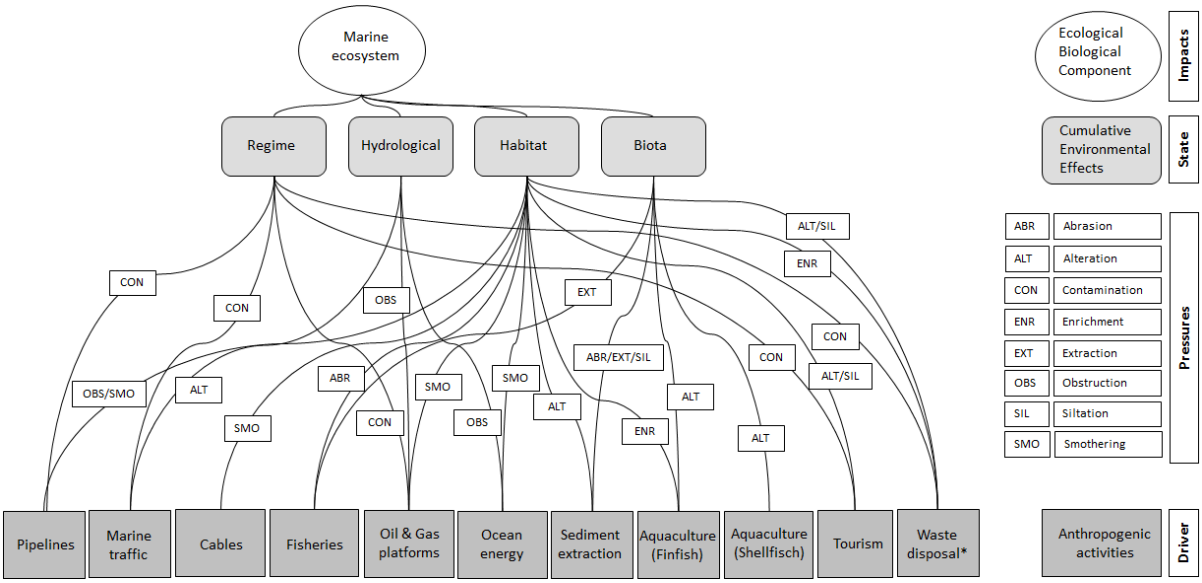


Figure 5: Driver Pressure State Impact (DPSI) model visualising the allocation of human activities (Drivers) to pressure categories (Pressure) having an effect on the state of the state of the marine habitats (State) and therefore an impact on the ecosystem assessed (Impact). Redrawn from Gimpel et al. (2013). *Waste disposal includes coastal discharge, dredge dumping and munitions dumping sites.

In order to account for cumulative environmental effects and the risk of impact on ecosystem components, essential but highly sensitive benthic habitats were scored for their vulnerability to aquaculture (**habitat vulnerability**). Those scores (1- 3, 3 = highly vulnerable), combined with the respective EUNIS code of these habitats, were modified from Alkiza et al. (2016) and incorporated in the AquaSpace tool assessment (Tab. 6). All of those habitats have been rated by expert knowledge as being incompatible with aquaculture. As mentioned before, each planning site is buffered by a species specific environmental footprint. Thus the AquaSpace tool helps prevent the destruction of highly vulnerable habitats.

Table 6: Habitat vulnerability to aquaculture activity. The habitats are already linked to EUNIS coding. Vulnerability scores range from 1-3, with 3= highly vulnerable. Table modified from Alkiza et al. (2016).

Habitat	EUNIS code	Vulnerability to aquaculture
Infralittoral rock and other hard substrata	A3	2
Atlantic and Mediterranean high energy infralittoral rock	A3.1	1
High energy infralittoral seabed		1
High energy infralittoral mixed hard sediments		1
Atlantic and Mediterranean moderate energy infralittoral rock	A3.2	2
Moderate energy infralittoral seabed		2
Moderate energy infralittoral mixed hard sediments		2
Atlantic and Mediterranean low energy infralittoral rock	A3.3	3
Low energy infralittoral seabed		3
Low energy infralittoral mixed hard sediments		3
Silted kelp on low energy infralittoral rock with full salinity	A3.31	3
Circalittoral rock and other hard substrata	A4	2
Atlantic and Mediterranean high energy circalittoral rock	A4.1	2
High energy circalittoral seabed		2
High energy circalittoral mixed hard sediments		2
Very tide-swept faunal communities on circalittoral rock or mixed faunal turf communities on circalittoral rock	A4.11 or A4.13	3
Sponge communities on deep circalittoral rock	A4.12	2
Atlantic and Mediterranean moderate energy circalittoral rock	A4.2	2
Moderate energy circalittoral seabed		2
Moderate energy circalittoral mixed hard sediments		2
Faunal communities on deep moderate energy circalittoral rock	A4.27	2
Atlantic and Mediterranean low energy circalittoral rock	A4.3	2
Low energy circalittoral seabed		2
Low energy circalittoral mixed hard sediments		2
Brachiopod and ascidian communities on circalittoral rock	A4.31	2
Faunal communities on deep low energy circalittoral rock	A4.33	2
Infralittoral coarse sediment	A5.13	2
Circalittoral coarse sediment	A5.14	2
Deep circalittoral coarse sediment	A5.15	2
Deep circalittoral Seabed		2
Infralittoral fine sand or infralittoral muddy sand	A5.23 or A5.24	2
Infralittoral fine sand	A5.23	2
Infralittoral muddy sand	A5.24	2
Circalittoral fine sand or circalittoral muddy sand	A5.25 or A5.26	2
Circalittoral fine sand	A5.25	2
Circalittoral muddy sand	A5.26	2
Deep circalittoral sand	A5.27	2
Infralittoral sandy mud or infralittoral fine mud	A5.33 or A5.34	2
Infralittoral sandy mud	A5.33	2
Infralittoral fine mud	A5.34	2

Habitat	EUNIS code	Vulnerability to aquaculture
Circalittoral sandy mud or circalittoral fine mud	A5.35 or A5.36	2
Circalittoral sandy mud	A5.35	2
Circalittoral fine mud	A5.36	2
Deep circalittoral mud	A5.37	2
Infralittoral mixed sediments	A5.43	2
Circalittoral mixed sediments	A5.44	2
Deep circalittoral mixed sediments	A5.45	2
Deep circalittoral mixed hard sediments		2
Seagrass beds	A5.53	3
Posidonia beds	A5.535	3
Seagrass beds on litoral sediments	A2.61	3
Maerl beds	A5.51	3

3.2.2.3 Economic effects

The AquaSpace tool provides a general economic view of the aquaculture activity according to the future productivity and market expectations. Economic analyses are conducted in different steps providing both direct assessment and economic impact assessment. The assessment procedure is explained and exemplified below. Direct assessment comprises a quantitative assessment to evaluate the direct economic performance of an aquaculture activity, and a qualitative (i.e. rating) assessment of its effectiveness and its efficiency. This rating stage is very relevant when trying to compare between two or more aquaculture activities. Indirect or induced assessment comprises an estimation of the impact (i.e. economy-wide effects) on other sectors (related to aquaculture) after introducing a production change, i.e. a new production attached to the aquaculture sites.

Based on AquaSpace tool functions, the potential **economic performance** of the aquaculture activity (i.e. the contribution of the planned aquaculture site to the local economy) is assessed in terms of the economic viability. The economic indicators are:

$$Revenue \ = production * market\ price \ (4),$$

$$AV \ = Revenue - intermediate\ and\ operating\ expenses \ (5),$$

where AV is the Added Value and intermediate or operating costs are e.g. fuel and feeding costs.

The **economic effectiveness** (i.e. the extent to which the specific economic objectives settled for this activity are achieved) is measured (based on AquaSpace tool functions) through the following indicators:

$$RoFTA \ = \frac{Profit}{Investment} \ (6),$$

where ROFTA is the Return on Fixed Tangible Assets (aquaculture attractiveness or return of the investment in aquaculture) and Profit is expressed as:

$$Profit = AV - remaining\ costs \ (7),$$

with remaining costs as e.g. salaries and wages.

$$Opportunity\ cost \ = AER - RoFTA \ (8),$$

where AER is the Annual Equivalent Rate of a potential investment (potential revenue that is forfeited by not developing an alternative to the aquaculture activity).

Further the **economic efficiency** is represented by the Net Present Value (NPV) and accounts for the resources employed and results achieved with a time horizon of 5 and 10 years (assessed based on an AquaSpace tool functions):

$$NPV = \sum_{t=1}^{t=T} AV \ (9),$$

where T is the number of years to consider when calculating the NPV. If NPV >0, the aquaculture is considered as profitable activity.

Finally, the **socio-economic induced (direct and indirect) impact** on the production and the AV is assessed using regional input-output multipliers which account for the commodities produced by each industry and the use of these by other industries and users (based on AquaSpace tool functions). While the calculation of Input – Output Tables using the Leontief model is described in Annex II, the indicators are listed below:

$$Induced\ direct\ impact\ on\ production = A * DI \ (10),$$

$$Induced\ indirect\ impact\ on\ production = A[(I - A)^{-1} - I] * DI \ (11),$$

$$Induced\ direct\ impact\ on\ the\ AV = (Diagonal\ Matrix\ with\ ratio\ AV/Production) * A * DI \ (12),$$

$$Induced\ indirect\ impact\ on\ the\ AV = (Diagonal\ Matrix\ with\ ratio\ AV/Production)A[(I - A)^{-1} - I] * DI \ (13),$$

where A is the technical coefficients matrix, DI the direct impact (e.g. revenues), and $(I - A)^{-1}$ the Leontief inverse matrix.

Table 7: Input for a production increase per region, based on regional input-output models and exemplified for Germany, Greece, Italy, Spain and Uk. Input parameters will be offered by request.

	INTEREST RATES	INDUCED DIRECT IMPACT ON PRODUCTION	INDUCED INDIRECT IMPACT ON PRODUCTION	TOTAL IMPACT	INDUCED DIRECT IMPACT ON ADDED VALUE	INDUCED INDIRECT IMPACT ON ADDED VALUE
GERMANY	0.07	0.26	0.45	1.45	0.16	0.27
GREECE	-0.02	0.24	0.35	1.35	0.15	0.22
ITALY	1.71	0.35	0.67	1.67	0.19	0.36
SPAIN	0.00	0.49	0.9	1.94	0.21	0.39
UK	0.32	0.56	0.98	1.98	0.12	0.21

Table 8: Economic (Impact) Analysis exemplified by a planned aquaculture with European Seabass in Germany. Details specified as followed: [1] Investment on equipment (per cage/trestle/longline); [2] Other investments (excl. Equipment, land facilities and properties); [3] Investment on land facilities; [4] Investment on properties; [5] Market value culture species per ton; [6] Average no. of days at sea/culture site; [7] Average fuel costs Euro/km; [8] Annual expenditure on wages/salaries; [9] Intermediate costs variable (e.g. juveniles/seeds/food); [10] Other costs (variable); [11] Annual rate on capital resources (%); [12] Intermediate costs fixed (e.g. insurance/maintenance and repair ship); [13] Other costs (fixed). Aquaculture-specific information modified from Ebeling (2016). Interest rates for Germany taken from IMF (2017).

Description	***Unit***	***Quantity***	***Price/Unit***	***Total value***
Production cycle	years	1		
Production density	tons/m³ or ha	0.01255		
Cage size/area	m³/ha	8960		
Production quantity	tons	4000		
Distance (example)	km	31.48		
Number cages/longlines	quantity	36		
Investment cages/longlines[1]	Euro		1173000	42,228,000.00 €
Other investments[2]	Euro		19000000	19,000,000.00 €
Costs/land facilities[3]	Euro		1500000	1,500,000.00 €
Costs/property[4]	Euro		1272452.5	1,272,452.50 €
Revenues				
Gross revenue[5]	tons	4000	5500	22,000,000.00 €
Variable costs				
Fuel (0.55 Euro/litre; 4.58 Euro/km)[6,7]	days at sea/y	53	15284.85232	15,284.85 €
	fuel costs Euro/km	4.58		
Wages[8]	Euro		399960	399,960.00 €
Intermediate costs (e.g. juveniles/seeds/food)[9]	Euro/ton		2070.00	8,280,000.00 €
Other costs (variable)[10]	Euro		481428.75	481,428.75 €
Interest on operating capital (in %)[11]	%	9176673.60	0.07	642,367.15 €
Total variable costs				**9,819,040.75 €**

Description	Unit	Quantity	Price/Unit	Total value
Fixed costs				
Intermediate costs (e.g. insurance/maintenance and repair ship)[12]	Euro		48125	48,125.00 €
Other costs (fixed)[13]	Euro		3482352.5	3,482,352.50 €
Interest on property		1272452.5	0.07	89,071.68 €
Interest on fixed capital (without property)		3530477.50	0.07	247,133.43 €
Total fixed costs				**3,866,682.60 €**
Total costs				**13,685,723.35 €**
Net return				**8,314,276.65 €**
ECONOMIC ASSESSMENT				
Revenue	Euro			**22,000,000.00 €**
Profit	Euro			**8,314,276.65 €**
Added value	Euro			**13,671,875.00 €**
RoFTA (Return on Fixed Tangible Assets)	%			**0.13**
Opportunity cost	%			**0.05**
NPV (Net Present Value)	Euro			**-9,643,842.66 €**
ECONOMIC IMPACT				
Induced direct impact on production	Euro			**5,829,059.83 €**
Induced indirect impact on production	Euro			**2,631,102.56 €**
Total impact	Euro			**31,930,800.00 €**
Induced direct impact on added value	Euro			**3,470,864.68 €**
Induced indirect impact on added value	Euro			**5,912,907.91 €**

3.2.2.4 Socio-cultural effects

To account for spatial expressions of some socio-cultural effects and impacts of aquaculture, the AquaSpace tool enables inputs relating to **visual impacts**. In particular, the effects considered are those relating to the visibility of aquaculture sites and infrastructure, and its contribution to the characteristics of the landscapes / seascapes.

The analysis of visibility of aquaculture sites is a requirement in best practice for assessing potential visual impacts on landscapes and seascapes in several countries (e.g. UK; Scottish Natural Heritage (2011)). The output from the analysis enables the determination of the extent of surface features visible to one, or a set of observers. Such features can be individual fish cages, infrastructure (e.g. feeder systems), individual aquaculture sites, or the cumulative effects of multiple aquaculture sites.

The outputs are reported as:

i. maps of visibility of features, and estimates of the number of features visible from any given point in a pre-selected viewing distance (e.g. number of fish cages or aquaculture sites visible from any specified location);
ii. estimates of the extent of the area from which such features are visible.

The input data for the AquaSpace tool can be used to take account of:

i. the geographic extent of views of individual or multiple fish cages, at the level of the individual cages or aquaculture site as a whole;
ii. the proportions of views occupied by individual aquaculture sites, from specific sites of importance (e.g. designated viewpoints, visitor attractions, sites of significant cultural heritage).

These data enable consideration of the potential significance on the landscape of expanding, or reducing, the extent of aquaculture, and with respect to other spatially represented data, such as: designated areas, existing land uses, landscape character, and visual receptors (i.e. from what and where are people exposed to features in a view), such as viewpoints, transport routes, settlements, and prominent topographic features.

It is important to distinguish between: (i) The visibility of particular sites from specified locations (e.g. properties, settlements, transport routes, viewpoints), including offshore routes if appropriate. (ii) The relative visibility of seascapes from 'all' locations (in reality a subset) both onshore and offshore which provides a means of considering where there are 'hot spots' and gaps from where features may be visible.

The variables in the visibility analysis can be set to represent the details of the dimensions and types of aquaculture infrastructure which would be appropriate to developments consistent with the use of the AquaSpace Tool. Such variables are the viewing distance and the height of the structures, guides for which are provided in table 9.

Outputs from data layer can also be imported into the AquaSpace Virtual Reality toolset. This enables policy, industry and public stakeholders to interpret aquaculture developments with respect to visual indicators of landscapes, or site landscape and seascape features (e.g. aquaculture, renewable energy, leisure, transport) (See AquaSpace factsheet on Virtual Seascapes).

Table 9: Examples of visible distance to the horizon for different heights of object or observer (Miller and Morrice, 2002). In the three last rows, the observer is supposed to be in Wales.

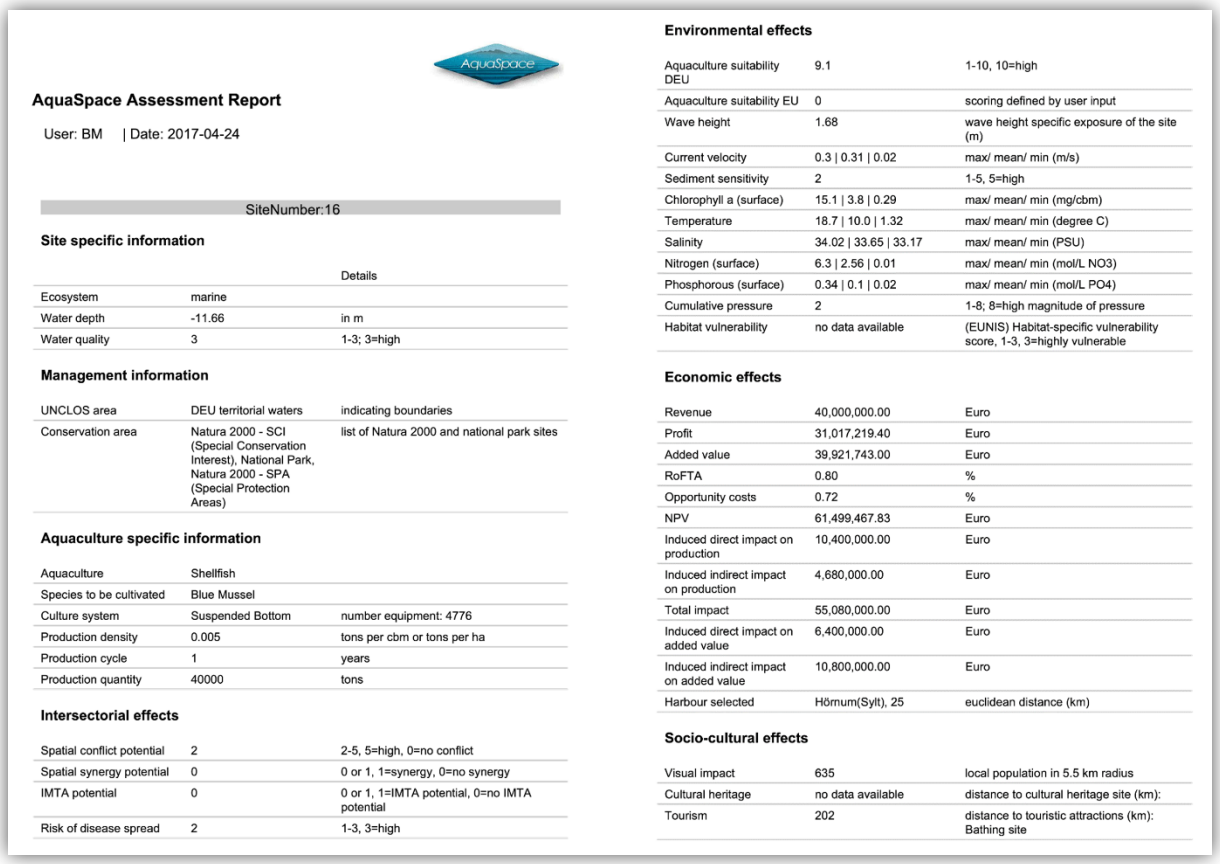
Height of observer (m)	*Height of object (m)*	*Distance (nm)*	*Distance (km)*	*Example*
1.8	100	25.1	46.4	Man-made structure
1.8	50	18.6	34.4	Man-made structure
1.8	1.8	5.9	10.9	Two observers of equal height and elevation
1.8	0	3	5.5	Observer on beach
1085	0	72.8	134.9	Top of Mt. Snowdon
892	0	66	122.3	Top of Cadair Idris
311	0	39	72.2	Top of Mynydd Caregog

Information is also provided on sites of interest for their significance or contribution to **cultural heritage.** These sites, such as shipwrecks, are analysed using a distance-based functions implemented in the AquaSpace tool.

Another indicator which reflects socio-cultural impacts is based on spatially explicit information about areas used for recreational activities. The '**tourism**' indicator is parameterised using the distance to all features related to recreation (i.e. short distance = high impact, long distance = low impact). The AquaSpace tool is pre-populated with data about bathing sites, with flexibility to include other data which are of importance at a case study level can be incorporated (see User Manual section on Customization options). Such data is not available for many areas (e.g. the German case study), but is extensive in others (e.g. for Scotland available data include dive sites, historic MPAs, sailing areas for cruising, racing, and sailing, and anchorage sites).

4. AQUASPACE TOOL OUTPUTS

The visualisation of tool outputs is provided by a pdf-formatted report, generated for each tool run (Fig. 6), which contains charts facilitating the comparison of different scenarios assessed (Fig. 7) at specific sites (Fig. 8).



AquaSpace Assessment Report

User: BM | Date: 2017-04-24

SiteNumber:16

Site specific information

		Details
Ecosystem	marine	
Water depth	-11.66	in m
Water quality	3	1-3; 3=high

Management information

UNCLOS area	DEU territorial waters	indicating boundaries
Conservation area	Natura 2000 - SCI (Special Conservation Interest), National Park, Natura 2000 - SPA (Special Protection Areas)	list of Natura 2000 and national park sites

Aquaculture specific information

Aquaculture	Shellfish	
Species to be cultivated	Blue Mussel	
Culture system	Suspended Bottom	number equipment: 4776
Production density	0.005	tons per cbm or tons per ha
Production cycle	1	years
Production quantity	40000	tons

Intersectorial effects

Spatial conflict potential	2	2-5, 5=high, 0=no conflict
Spatial synergy potential	0	0 or 1, 1=synergy, 0=no synergy
IMTA potential	0	0 or 1, 1=IMTA potential, 0=no IMTA potential
Risk of disease spread	2	1-3, 3=high

Environmental effects

Aquaculture suitability DEU	9.1	1-10, 10=high
Aquaculture suitability EU	0	scoring defined by user input
Wave height	1.68	wave height specific exposure of the site (m)
Current velocity	0.3 | 0.31 | 0.02	max/ mean/ min (m/s)
Sediment sensitivity	2	1-5, 5=high
Chlorophyll a (surface)	15.1 | 3.8 | 0.29	max/ mean/ min (mg/cbm)
Temperature	18.7 | 10.0 | 1.32	max/ mean/ min (degree C)
Salinity	34.02 | 33.65 | 33.17	max/ mean/ min (PSU)
Nitrogen (surface)	6.3 | 2.56 | 0.01	max/ mean/ min (mol/L NO3)
Phosphorous (surface)	0.34 | 0.1 | 0.02	max/ mean/ min (mol/L PO4)
Cumulative pressure	2	1-8; 8=high magnitude of pressure
Habitat vulnerability	no data available	(EUNIS) Habitat-specific vulnerability score, 1-3, 3=highly vulnerable

Economic effects

Revenue	40,000,000.00	Euro
Profit	31,017,219.40	Euro
Added value	39,921,743.00	Euro
RoFTA	0.80	%
Opportunity costs	0.72	%
NPV	61,499,467.83	Euro
Induced direct impact on production	10,400,000.00	Euro
Induced indirect impact on production	4,680,000.00	Euro
Total impact	55,080,000.00	Euro
Induced direct impact on added value	6,400,000.00	Euro
Induced indirect impact on added value	10,800,000.00	Euro
Harbour selected	Hörnum(Sylt), 25	euclidean distance (km)

Socio-cultural effects

Visual impact	635	local population in 5.5 km radius
Cultural heritage	no data available	distance to cultural heritage site (km):
Tourism	202	distance to touristic attractions (km): Bathing site

Figure 6: Extract of the *AquaSpace Assessment Report* (Blue mussel, scenario 16). The visualisation of tool outputs is ensured on the basis of a pdf-formatted report, generated for each tool run, provided with charts (Fig. 7) and a map (Fig. 8).

In order to describe selected tool outcomes, figure 7 visualises graphs showing the environmental indicators *Aquaculture Suitability, Water Depth, and Wave Height specific Exposure of the site*, which might get relevant for stakeholders requiring spatial explicit information in search of suitable sites for their culturing species as well as for their aquaculture type-specific equipment. While aquaculture suitability was highest in the 2nd scenario assessed, a shallow water depth might be preferred as given in the 5th scenario assessed. Moreover, the slightest wave height specific exposure of the site was given in the 3rd and 5th scenario assessed.

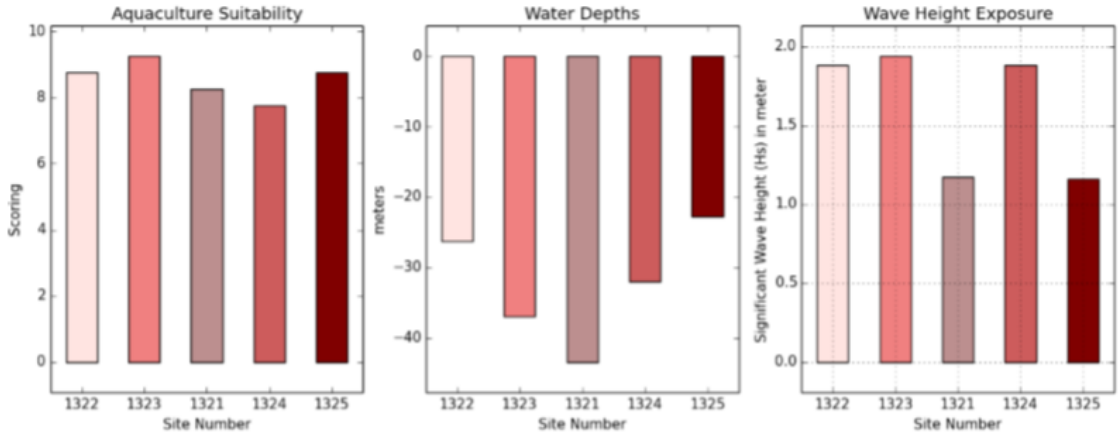


Figure 7: Visualisation of selected environmental indicators *Aquaculture Suitability, Water Depth, and Wave Height Exposure* for each of 5 sites, which could help stakeholders assessing equipment needed for aquaculture at each sites.

The report map can be designed individually. In order to define the background layer, the user can choose from all map layers available. Figure 8 presents an example, where a cumulative pressure layer was selected. The number of scenarios which can be assessed is not limited. Nevertheless, in case of calculating more than five scenarios simultaneously, the tool outputs a csv file (Tab. 10). As shown below, 10 scenarios were calculated for demonstration purpose in application of the AquaSpace tool. All indicators which can vary in between those scenarios will be listed.

Such a transparent visualisation technique facilitates i) an effective implementation of MSP for aquaculture, enabled by using spatially explicit methods and tools, ii) the implementation of a spatially explicit (GIS-based) multi-use context, addressing the functionality for cumulative risk assessments and conflict analysis, and iii) the implementation of an ecosystem approach, explicitly considering economic and market issues. The latter allows for more informed, evidence-based decisions, which gains on significance, especially for industry:

Aquaculture companies face considerable challenges and take on considerable risk in establishing and operating an aquaculture site. Gaining and maintaining stakeholder support by demonstrating economic benefits on a proactive and periodic basis can help limit overall project risks (Plumstead, 2012). Outputs of an economic impact analysis are typically used to demonstrate the economic importance of aquaculture operations to:

- Decision makers that generally approve aquaculture operations.
- Community stakeholders that can control and approve the issuance of permits.
- Other stakeholders such as NGOs (and other non-profit organizations) that want to ensure that aquaculture operations benefit local communities.

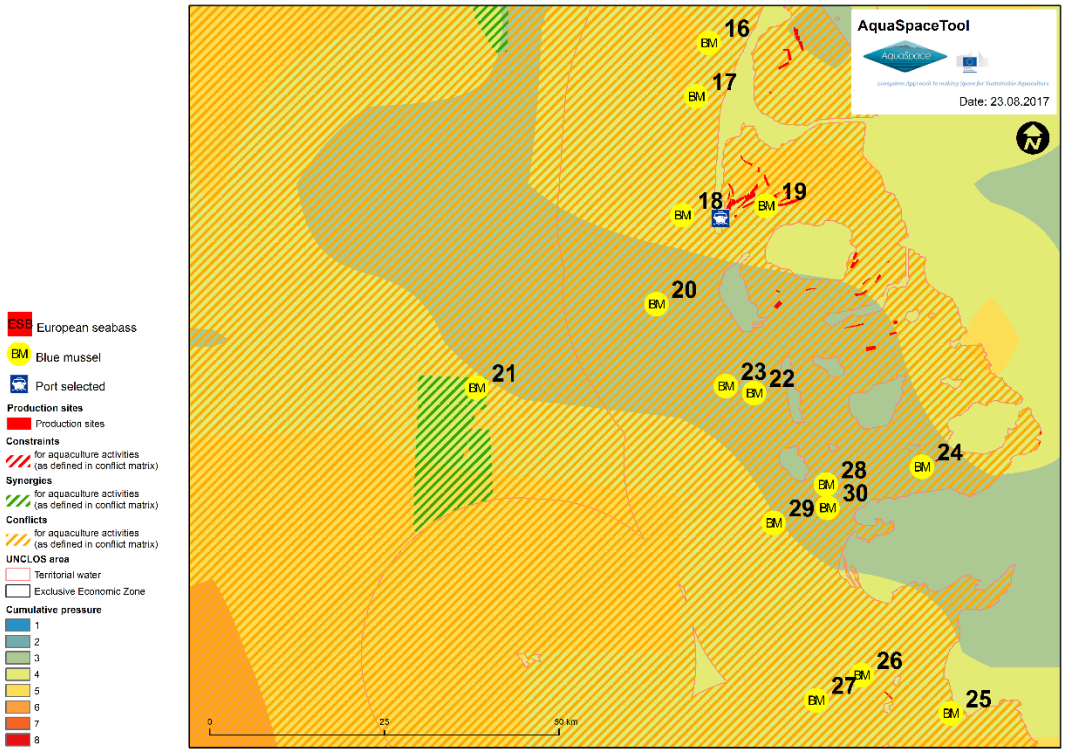


Figure 8: AquaSpace tool output map for blue mussel (scenarios 15 – 30), the case-specific port selected (Hörnum/Sylt), areas of constraint, synergy and conflict, management boundaries, areas of aquaculture production and a cumulative pressure map, selected manually as background map for the AquaSpace tool map output. The AquaSpace tool can be applied for an unlimited amount of scenarios.

Table 10a: Exemplified output file in CSV format giving an overview about indicators assessed during AquaSpace tool application (part 1). Indicators useful to assess the growth performance of a species (i.e. chlorophyll a concentration at surface, temperature and salinity) are not included (AV = Added Value, IMTA = Integrated Multi-Trophic Aquaculture, NPV = Net Present Value, RoFTA = Return on Fixed Tangible Assets).

Scenario (site number)	*IMTA potential*	*Risk of disease spread*	*Spatial conflict*	*Spatial synergy*	*Aquaculture suitability*	*Cumulative pressure*	*Current velocity*	*Habitat vulnerability*	*Nitrogen*	*Phosphorus*	*Sediment sensitivity*	*Water depth*	*Water quality*	*Wave height exposure*
1	0	1	5	0	5	2	0.19		2.08	0.1	2	-23.11	3	1.17
2	0	1	2	1	5	4	0.25		1.71	0.1	2	-21.83	3	1.95
3	0	1	2	1	5	4	0.16		0.43	0.1	2	-22.22	3	2.01
4	0	1	5	1	5	4	0.15		0.32	0.1	2	-29.53	3	2.01
5	0	1	5	1	5	4	0.18		0.15	0.08	2	-42.2	3	1.98
6	0	1	5	1	5	4	0.16		0.2	0.07	2	-45.38	3	1.87
7	0	1	5	1	4	4	0.6		0.2	0.07	1	-41.71	3	1.84
8	0	1	5	1	4	4	0.21		0.18	0.18	1	-41.39	3	1.8
9	0	1	5	1	5	4	0.19		0.16	0.31	2	-42.33	3	1.81
10	0	1	5	1	5	4	0.6		0.17	0.05	2	-39.65	3	1.91
11	0	2	5	1	5	4	0.37		0.1	0.05	1	-41.41	3	1.85
12	0	1	2	1	5	4	0.24		0.1	0.05	2	-39.26	3	1.78
13	0	3	2	1	5	4	0.17		0.32	0.1	2	-38.83	3	1.82
14	0	1	2	1	5	4	0.17		0.69	0.1	2	-30.48	3	1.86
15	0	1	2	1	5	4	0.15		1.17	0.1	2	-33.08	3	1.88

Table 10b: Exemplified CSV file giving an overview about indicators assessed during AquaSpace tool application (part 2). Indicators useful to assess the growth performance of a species (i.e. chlorophyll a concentration at surface, temperature and salinity) are not included (AV = Added Value, IMTA = Integrated Multi-Trophic Aquaculture, NPV = Net Present Value, RoFTA = Return on Fixed Tangible Assets).

Scenario (site number)	*AV (in mio)*	*Induced direct impact on production (in mio)*	*Induced indirect impact on production (in mio)*	*Induced direct impact on AV (in mio)*	*Induced indirect impact on AV (in mio)*	*NPV*	*Opportunity costs*	*Profit (in mio)*	*Revenue (in mio)*	*RoFTA*	*Cultural heritage*	*Tourism*	*Visual impact*
1	13.67	5.72	2.57	3.52	5.94	-29.62	0.0545	8.32	22.00	0.1299		132	0
2	13.67	5.72	2.57	3.52	5.94	-29.62	0.0544	8.31	22.00	0.1298		139	0
3	13.67	5.72	2.57	3.52	5.94	-29.62	0.0537	8.27	22.00	0.1292		210	0
4	13.67	5.72	2.57	3.52	5.94	-29.62	0.0537	8.26	22.00	0.1291		208	0
5	13.67	5.72	2.57	3.52	5.94	-29.62	0.0536	8.26	22.00	0.1290		204	0
6	13.67	5.72	2.57	3.52	5.94	-29.62	0.0533	8.24	22.00	0.1287		226	0
7	13.67	5.72	2.57	3.52	5.94	-29.62	0.0531	8.23	22.00	0.1286		234	0
8	13.67	5.72	2.57	3.52	5.94	-29.62	0.0530	8.22	22.00	0.1284		245	0
9	13.67	5.72	2.57	3.52	5.94	-29.62	0.0532	8.24	22.00	0.1287		204	0
10	13.67	5.72	2.57	3.52	5.94	-29.62	0.0538	8.27	22.00	0.1292		162	0
11	13.67	5.72	2.57	3.52	5.94	-29.62	0.0536	8.26	22.00	0.1291		158	0
12	13.67	5.72	2.57	3.52	5.94	-29.62	0.0536	8.26	22.00	0.1291		134	0
13	13.67	5.72	2.57	3.52	5.94	-29.62	0.0538	8.27	22.00	0.1293		120	0
14	13.67	5.72	2.57	3.52	5.94	-29.62	0.0540	8.28	22.00	0.1294		89	0
15	13.67	5.72	2.57	3.52	5.94	-29.62	0.0542	8.30	22.00	0.1297		81	0

5. USER MANUAL

This user manual describes the preparatory work, sequence of steps and related tasks that the user should undertake to apply the AquaSpace tool. It assumes a knowledge of the tool concept, functionality and outputs described in preceding sections. The manual describes how to install the tool and how to use it.

5.1. The AquaSpace tool: a brief insight

The AquaSpace tool enables the user to assess individual marine site locations planned for aquaculture in terms of essential biological, ecological, economic, physical and social aspects. It is implemented as an AddIn for ArcGIS Desktop (from 10.3.1 and ArcGIS Basic with Spatial Analyst). The initial installation of the AquaSpace tool is a manual process of copying/pasting of file packages provided. All steps are precisely described under => Install the AquaSpace tool files.

Important to mention is that the AquaSpace tool comes initially with an EU-wide data package, provided as file GDB 10.3. Implemented are basic settings for test runs at German case study level, allowing the check if the installation procedure was performed properly. Ensuing from that, the user can customise the tool settings individually and even replace datasets. Those procedures are explained under => Customization options but require a minimum of ArcGIS usage skills. Register via https://gdi.thuenen.de/geoserver/sf/www/aqspce.html) to get access to comprehensive video instructions for installation process and usage of the tool - provided online (https://free-redmine.saas-secure.com/projects/aqua).

5.1.1. AquaSpace tool components

The user receives via => https://gdi.thuenen.de/geoserver/sf/www/aqspce.html access to the AquaSpace Redmine website, where all AquaSpace tool files, technical documents as well as video instructions are provided, facilitating the installation and testing of the AquaSpace tool. The current status of technical documentation can be found under => Documents. In addition, user requests (in particular regarding tool bugs, data hints or support requests) can be placed under => New Issue.

The tool is composed of:

- The mxd (ArcGIS format) project
- The tool bar
- The Geodatabase (GDB)

The Arc GIS mxd file visualises the spatial extent of the tool in terms of a background map (esri bg map), all data sets required to run the tool and the respective symbology (Fig. 9). Therefore, it ensures the correct symbolisation and paths' availability when using the tool.

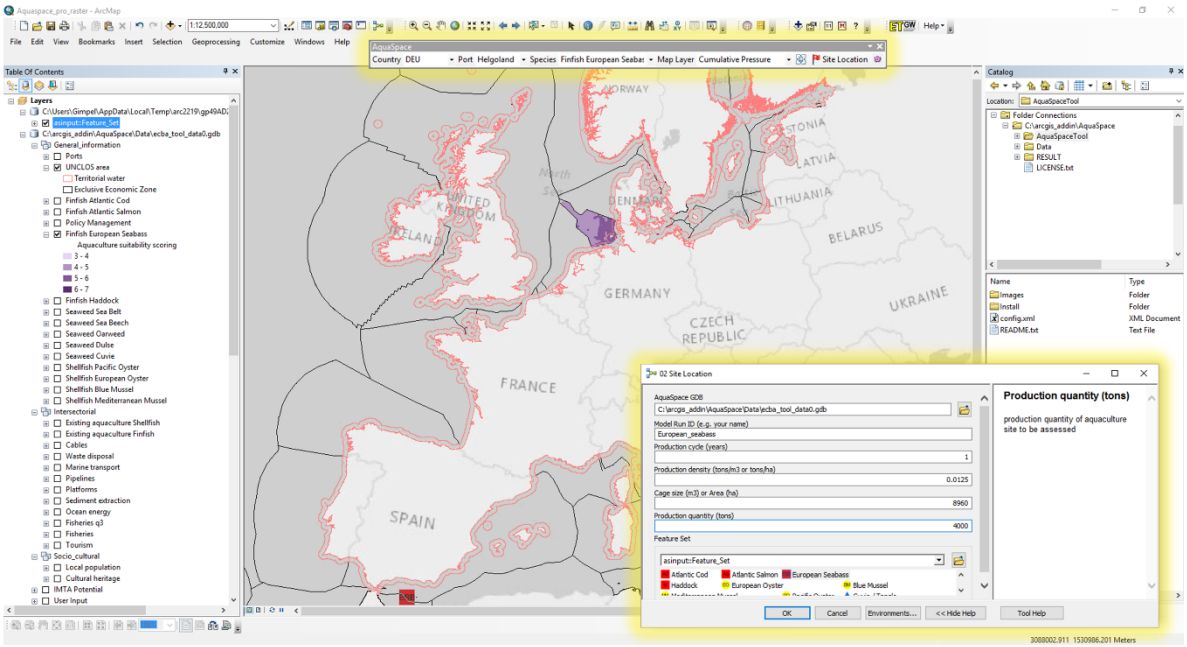


Figure 9: The AquaSpace mxd, including the table of contents (left), the AquaSpace toolbar (top, highlighted in yellow) and the Arc GIS catalog window (right), showing the AquaSpace Geodatabase (GDB). The AquaSpace siting tool (highlighted in yellow at the bottom right) is available from the AquaSpace toolbar and facilitates the site selection.

The Arc GIS toolbar allows the user to select the country to be studied, which limits the spatial extent of the data processed and speeds up the assessment process. If the user favours another extent than the one on country level, he can define it manually (by zooming in or out) using the blue 'Transfer extent' button when the desired extent is adjusted. Next, the user has to define a port from which location the aquaculture site should be managed and supplied. The port is used as a baseline for economic, distance-based calculations. The species can be chosen subsequently and forms the baseline in terms of suitable area to be assessed. In order to define that layer, which should be visible in the final result map as background layer, the user can choose one of all map layers available. Finally, the user can start selecting the particular locations that will be considered in the calculations for the aquaculture species he wants to assess. If different interactions combinations shall be evaluated per model run, the user can define varying scorings by using the purple button opening up the interaction matrix tool (Fig. 10).

Figure 10: The AquaSpace toolbar, simplifying the selection of the extent (Country), the harbour from which the aquaculture site will be supplied (Port), the aquaculture species to be assessed (Species), the background layer which shall be highlighted in the result map (Map Layer), the manually defined extent (blue button), the siting tool (Site Location) and the Interaction matrix tool (purple button) (from left to right).

The GDB template contains all the required feature classes with table schemes as implemented and applied by the AquaSpace tool. For each GDB item metadata have been acquired that describe the item itself (feature class or GDB table) as well as the content of each field of table scheme. In

ArcGIS the metadata can be viewed via the user interface by selecting => Item description from a layer's => properties menu. It can also be accessed from ArcMap, Catalog Window => right click desired feature class => Item description (Fig. 11).

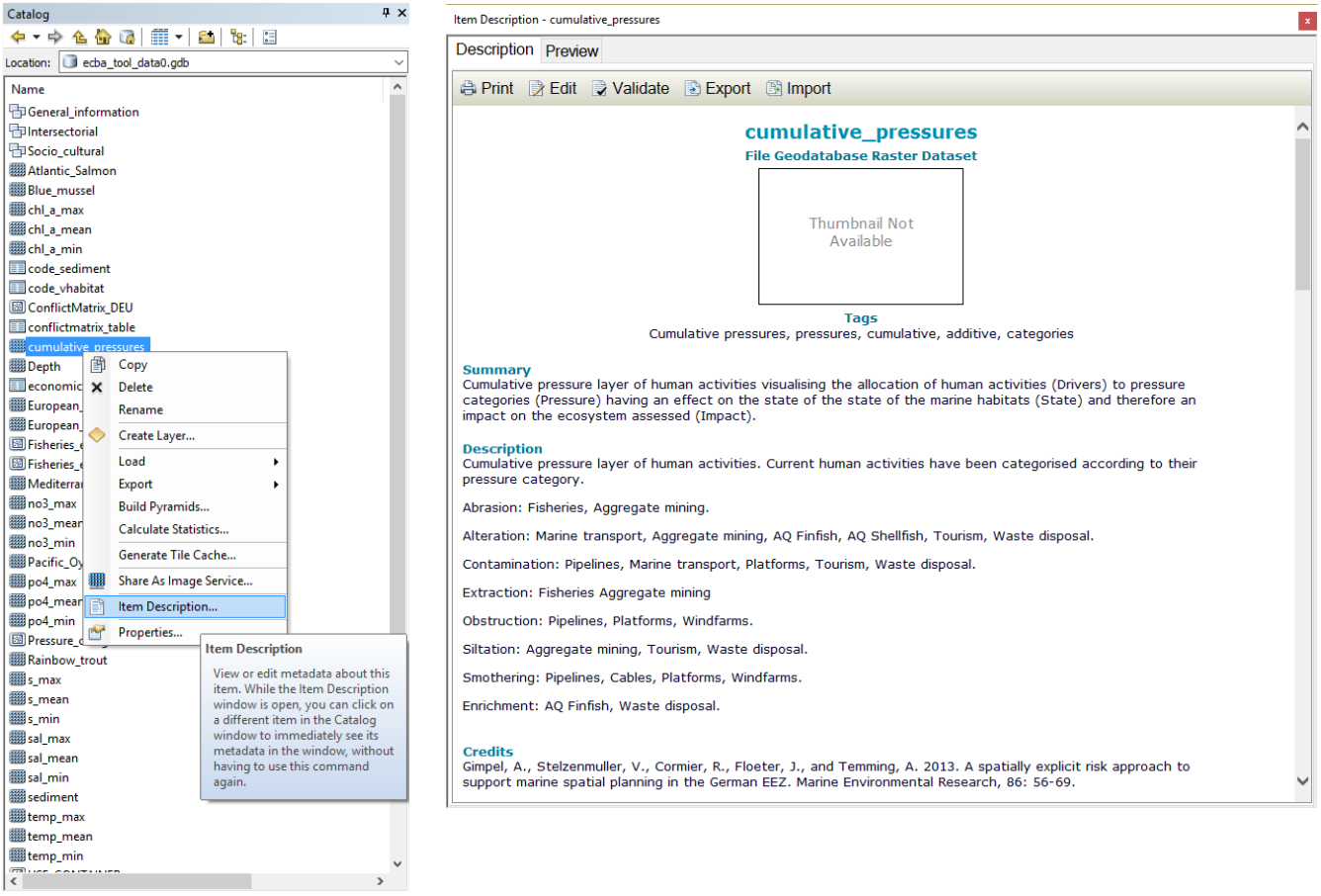


Figure 11: Arc Map catalog window with the AquaSpace Geodatabase (left). Metadata can be examined via the item description, here exemplified by the cumulative pressures layer (right).

5.1.2. Process view

Each tool section (e.g. User Input) addresses one specific process step as shown in figure 12. The users input defines the study area (country), the port from which aquaculture business should be transacted, the culture species, the corresponding culture system, the compilation of constraining, conflicting or synergistic human uses and the aquaculture locations to be tested. While doing so, the user is directed to act in a sustainable way, being aware of e.g. the ecological footprint of a specific aquaculture or its interaction with other human activities. Consequently, the AquaSpace tool estimates all opportunities and risks based on inter-sectorial, environmental, economic and socio-cultural indicators. Tool outputs (i.e. AquaSpace tool Assessment Report) are provided in pdf-format, whose design offer a transparent summary of all tool runs (i.e. scenarios) and the respective indicator values. Given are general site information (e.g. species, water depth, water quality), inter-sectorial effects (e.g. spatial conflict potential, disease spread), environmental effects (e.g. degree of exposure, cumulative pressures, distance to waste disposal sites) and economic and market issues (economic performance, effectiveness and efficiency). Further, the report is equipped with visualisation techniques like mapping and graphics, enabling the user to proactively communicate opportunities and risks. A transparent information policy builds stakeholders support, which is critical to the successful establishment of aquaculture and ongoing operations.

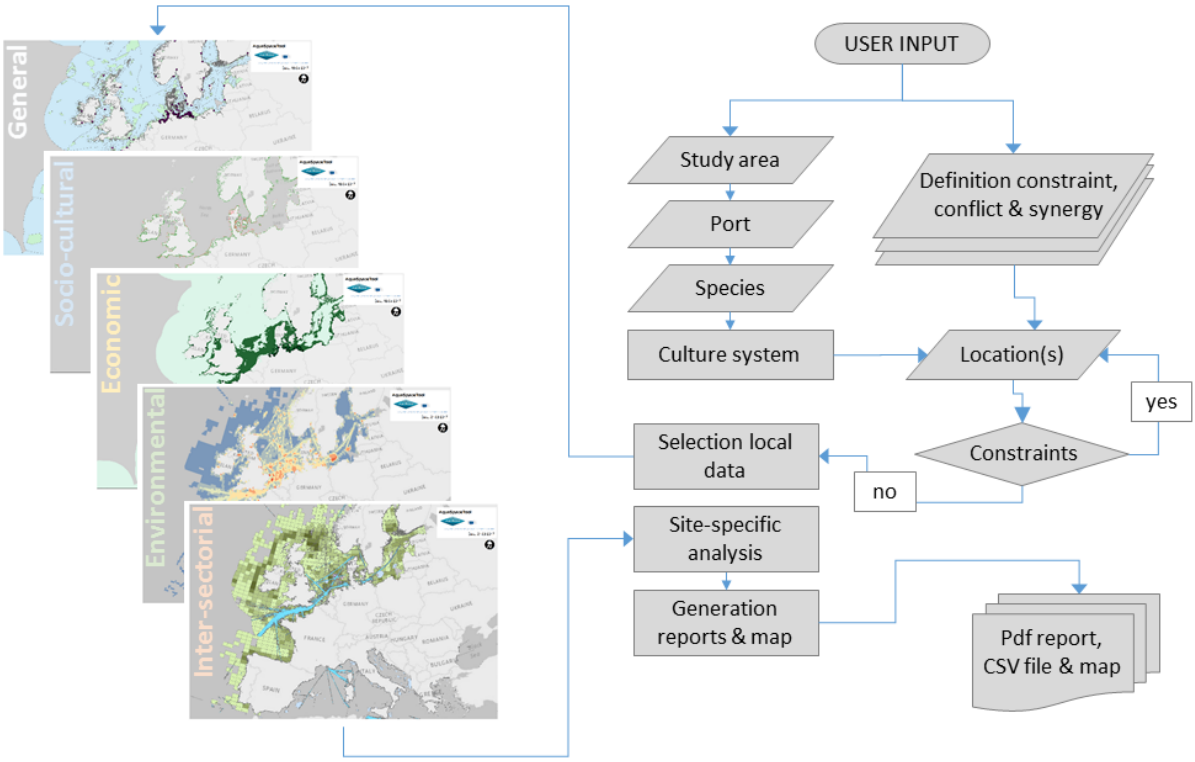


Figure 12: AquaSpace tool conceptual overview. The *users input* defines the study area (e.g. country), the port from which aquaculture business should be transacted, the culture species, the corresponding culture system, the compilation of constraining, conflicting or synergistic human uses and the aquaculture locations to be tested. Next to general input data (e.g. management area or culture system to be assessed), inter-sectorial, environmental, economic and socio-cultural data are processed.

5.2. Installation guide

A quick start guide to install the scripts, add the GDB and connect all the required processing and storage paths for the AquaSpace tool to work correctly is given under Quick start. Subsequently, a detailed workflow is given with support to install all files needed to run the tool (Install the AquaSpace tool files), clipping case study data sets (Clip your data set) customisation procedures (Customization options), create an interaction matrix (Create interaction matrix), add your economic input data (Add your economic input) and how to perform the site assessment (Perform site assessment) with different scenario evaluations (Scenario building) (Fig. 13).

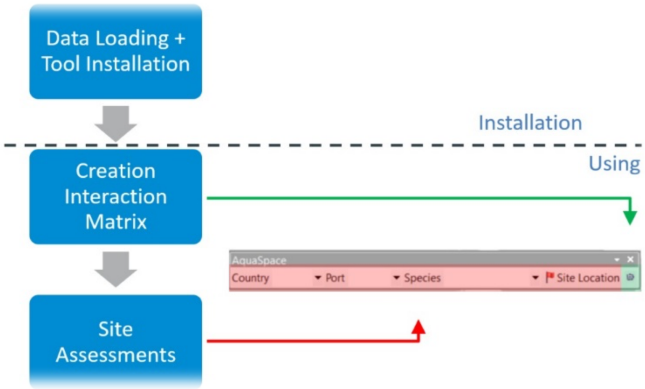


Figure 13: Visualisation of the AquaSpace tool installation and application process.

5.2.1. Quick start guide

1. Part of AquaSpace tool Installation

- Check the AquaSpace tool system requirements carefully, see [[http://free-redmine.saas-secure.com/documents/83]]
- Watch the video of installation process, see [[http://free-redmine.saas-secure.com/documents/85]]
- Get the latest version under => **News**, consider your ArcGIS version and follow the installation/update instructions carefully, in case you have questions please do not hesitate to place your support request under => **New issue**
- Watch the video for AquaSpace tool usage, see [[https://free-redmine.saas-secure.com/documents/91]]
- Test your local installation by a test run using the default GDB (German case study) simply by starting the **Aquaspace_pro.mxd** file under => C:\arcgis_addin\AquaSpace\Data, if you get an error or warning, please check the track list under issues [[https://free-redmine.saas-secure.com/projects/aqua/issues]] and place a new issue here in case you could not find the support you need

2. Part of GDB Data Adjustments for your AquaSpace case study area

- **Clip your country data set / case study area:** this step is recommended in case there is no case study area listed under prepared country datasets, see: [[https://free-redmine.saas-secure.com/news/46]]. In this context, by offering an EU-wide data package we aim to minimize the user effort of data harmonization and data adding. But for ArcGIS performance issues it is highly recommended to clip your country/ case study data set, see video instructions [[http://free-redmine.saas-secure.com/documents/82]]. This step is completed as soon as your clip result is stored under => C:\arcgis_addin\AquaSpace\Data and is renamed by the standard **ecba_tool_data0.gdb**
- Add your own data to the AquaSpace GDB, see [[https://free-redmine.saas-secure.com/documents/92]]
- Create your individual interaction conflict matrix, see Tool use case: create interaction matrix
- Now you are ready for using the AquaSpace Tool for your case study, please go to Tool application

5.2.2. Install the AquaSpace tool files

1. Store the downloaded files on your PC

- AquaSpace Tool expects the following storage path => **C:\arcgis_addin\AquaSpace**. Different storage paths would require more adjusting configuration work at the tool installation.
- Go to => C:\arcgis_addin\AquaSpace\AquaSpaceTool and double-click the "AquaSpaceTool Esri Addin file"

2. Adjust the PC Python Library

- Backup the current Python Installation => C:\Python27\ArcGIS10.3 – copy folder (this avoids losing the original scripts that come with ArcGIS) and name it ArcGIS10.3_ESRI
- In C:\Python27 overwrite the ArcGIS10.3 folder with the new folder "ArcGIS10.3" PLEASE NOTE both installation procedures for python library transfer – one for ArcGIS 10.3 and another for ArcGIS 10.4 - depending on your local ArcGIS version

3. Adjust ArcGIS Map Style

- Transfer the Legend Item "IMTA" from the source file => ArcGISMapStyleToCopy_IMTA.style ("Style Manager": „Styles" / "Add Style to list") to your personalized ArcMap Style => C:\Users\<USER_NAME>\AppData\Roaming\ESRI\Desktop10.3\ArcMap with copy&paste by using the ArcMap Style Manager (menu "Customize"=>"Style Manager") (Fig. 14)

4. Add the AquaSpace toolbar to your mxd

- Open "Aquaspace_pro_raster.mxd". The layer data sources will be invalid for Constraints, Conflicts and Synergies (Fig. 15; those will re-connected under Create interaction matrix)
- Choose the toolbar via => Customize => Toolbars => "AquaSpace"
- Drag and drop the toolbar on the top of your mxd

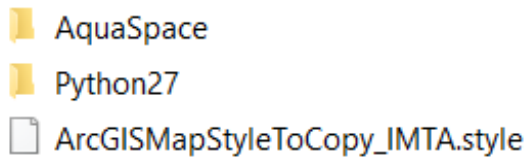


Figure 14: Visualisation of the AquaSpace tool installation folders.

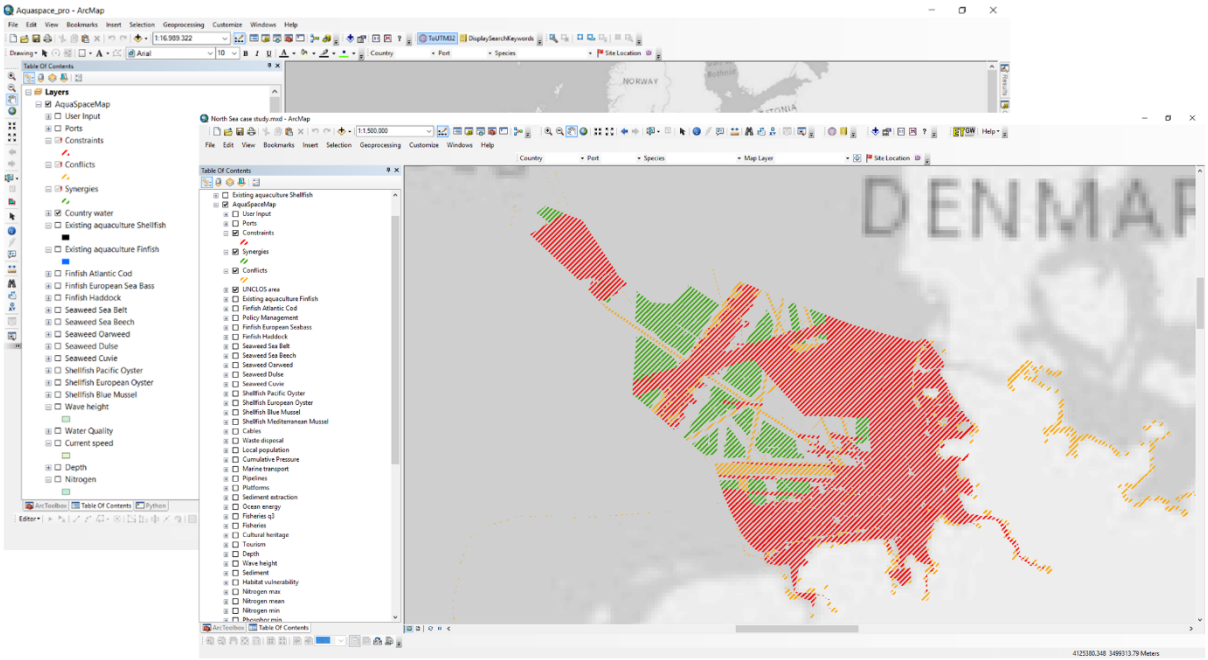


Figure 15: The AquaSpace mxd with invalid Constraints, Conflicts and Synergies-layers (back), mxd with valid layers defined manually at case study level (front).

5.2.3. Clip your data set

It is highly recommended to clip your individual country's data set (if it is not provided online yet) in order to maximise the tool's processing efficiency of the relevant outcomes and guarantee the tool run is complete.

1. Go to C:\arcgis_addin\AquaSpace\Data

- Open the mxd file, pick a country listed by the AquaSpace Tool, close mxd (the chosen spatial extent is written to the GDB). In order for this process to work and no error messages to appear the user must make sure that all ESRI products that could possibly access file content of the AquaSpace GDB are closed in order to avoid data locks.

2. Go to C:\arcgis_addin\AquaSpace\AquaSpaceTool\Install

- Double-click the „clip.py" python script, after a few seconds you will be prompted to input a name for the GDB copy you will be creating by applying the python script. The script run takes some time to run fully. The processing duration depends on the size of the EEZ area, for example GDB or Spain takes more than 30 minutes to get clipped.

3. Go back to C:\arcgis_addin\AquaSpace\Data

- Save a copy of C:\arcgis_addin\AquaSpace\Data\ecba_tool_data0.gdb into to the „backup" folder C:\arcgis_addin\AquaSpace\Data\backup (the copy remains there as your recovery data set; also, use this folder for future GDB updates by WP3)
- Delete C:\arcgis_addin\AquaSpace\Data\ecba_tool_data0.gdb
- Rename your GDB in ArcCatalog (copy created by clip.py) into „ecba_tool_data0.gdb" (the mxd file and the tool functions expect this GDB name)

5.2.4. Customization options

WP3 deployed the AquaSpace tool with an EU wide vector data set in ESRI File GDB 10.3 format. The aquaculture suitability layer already implemented are coming from two different sources: i) suitability vector layer for the test runs at German case study scale and ii) suitability raster layer at European scale (identified in WP2 in application of the WATER tool) for individual case study runs (Boogert et al., 2017). If both data sets available are considered to be insufficient, it is possible to add iii) your own suitability layers.

The following table provides the overview where and to what extent the tool can be customised. Data delivered can be exchanged, but please be aware that a re-projection of raster, data renaming and GDB-import needs to be done according to the instructions listed subsequently and the preconditions defined in table 12.

Table 11: Overview where and to what extent the tool can be customised.

Dos	***Don'ts***
	GDB
	Rename data sets or feature classes
mxd	**mxd**
Add individual fishery classifications	Rename a layer as provided with the AquaSpace tool
Add individual tourism polygons	Change the position of a layer beyond the layer group
Add individual suitability raster layers	
Add further layers (not visible in the report)	
Change the position of a layer (but stay within the layer group)	
Change the symbology of a layer (will influence the proper output of the report map/legend)	
Customize displayed default values of economic input parameters (use of model builder required)	

1. Add individual fishery classifications

- Open "Aquaspace_pro_raster.mxd". The layer data sources will be invalid for Constraints, Conflicts and Synergies (Fig. 15; those will re-connected under Create interaction matrix)
- In the Table of Contents (Layer Group "Intersectorial"), double click the layer => "Fisheries" in order to open the Layer Properties. Choose the tab "Symbology"
- Select Show: "Quantities" and choose the Value: "EU_landing" under Fields
- Select "Classify" and choose Method: "Quantile" and Classes: "4" (Fig. 16)
- Please take down the value of the 3rd quantil (highlighted in blue in Fig. 16), close the Classification with "Ok" and close the Layer Properties with "Ok"

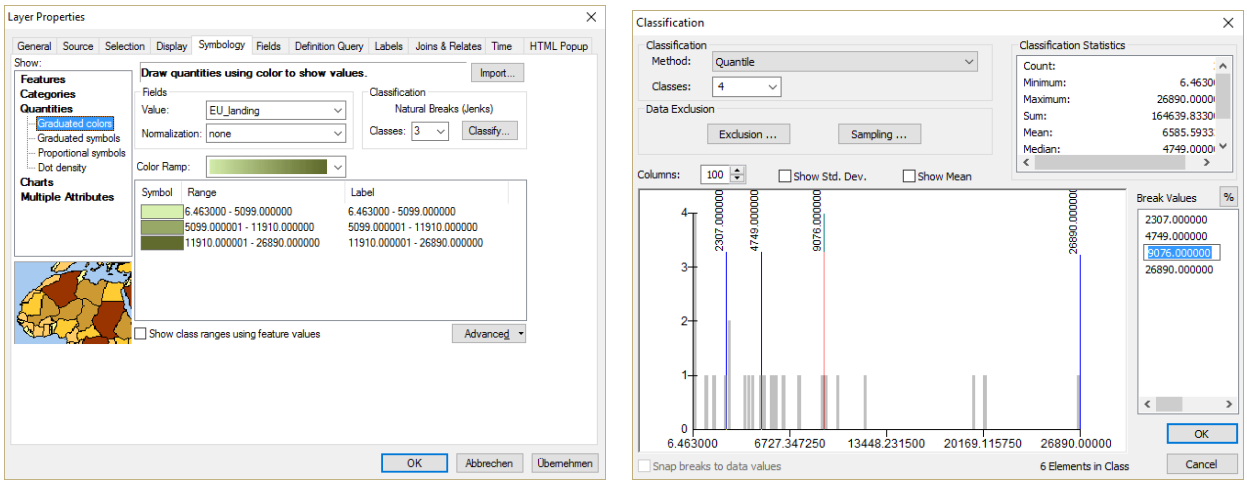


Figure 16: Visualisation of the Layer Properties tab "Symbology" and the Classification scheme to be selected for "Fisheries".

- In the Table of Contents (Layer Group "Intersectorial"), double click the layer => "Fisheries q3" in order to open the Layer Properties. Choose the tab "Definition query"
- Please type in Definition Query: "EU_landing >= *your q3 value*" (example highlighted in blue in Fig. 16) and close the Layer Properties with "Ok"
- Now two layers have been created for fisheries: a high intensity fisheries layer (fisheries q3) and a layer integrating the remaining fishing intensity. Those can be individually scored in the interaction matrix.

- Please note, that provided fisheries data can be replaced with individual fisheries data (if available)

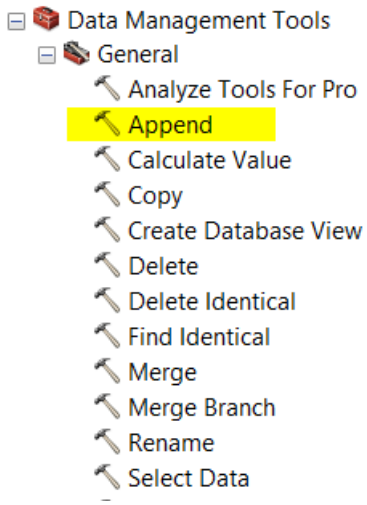
    - Consult the data scope und GDB Scheme for whether/ how your data cover the AquaSpace data model requirements
    - Match your data to AquaSpace tool data entities, plan & prepare the data import to the AquaSpace GDB regarding necessary fields, field values, Geographic Coordinate System (GCS)
    - Integrate your individual fisheries polygon in the tool application step [Create interaction matrix]

2. Add your own layers to (e.g. to the Tourism-layer) of the AquaSpace tool

- Consult the data scope und GDB Scheme for whether/ how your data cover the AquaSpace data model requirements
- Match your data to AquaSpace tool data entities, plan & prepare the data import regarding necessary fields, field values, GCS

    - The Tourism layer requires for instance the GCS: "WGS84", the Fields: "T_name" and "T_description" and the Field values: <text>

- Use the ArcGIS toolbox tool "Append" (Fig. 17) to load the data and fill the Geodatabase (GDB) template. For more information on this tool read the online documentation resource: http://help.arcgis.com/EN/arcgisdesktop/10.0/help/index.html#//001700000050000000



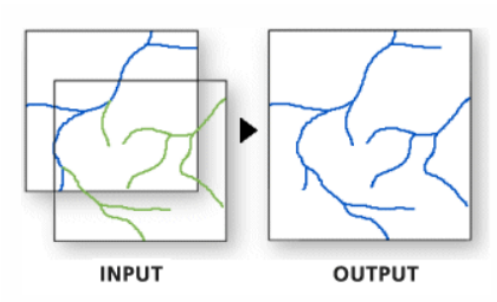


Figure 17: The Arc GIS tool "Append" (under => Toolbox, Data Management Tools, General) applied to include case study-specific tourism data.

3. Add your own suitability raster layers to the AquaSpace tool

- Check the AquaSpace tool data requirements carefully, see table 12
- Backup your latest GDB if necessary (no need to back up the tool)
- Delete the current suitability map rasters in the GDB
- Open "Aquaspace_pro_raster.mxd"
- Add the GCS "ETRS_1989_LAEA" to ArcMap's favourites list
    - Table of contents: open the data frame properties by context-menu (mouse right-click) on "Layers" (upmost item)
    - Register tab Coordinate System
    - Via the listed folder "Layers" expanded, click on "ETRS_1989_LAEA" and use button "Add to Favorites" (Fig. 18)

Table 12: Overview of data aspects required and adjusted as precondition.

Raster data	Tool expectation
Geographic Coordinate System (GCS)	ETRS_1989_LAEA, WKID: 3035
Naming of rasters in the GDB	Import the raster data into GDB with: • spec_blue_mussel • spec_european_oyster • spec_atlantic_salmon • spec_european_seabass • spec_mediterranean_mussel • spec_pacific_oyster

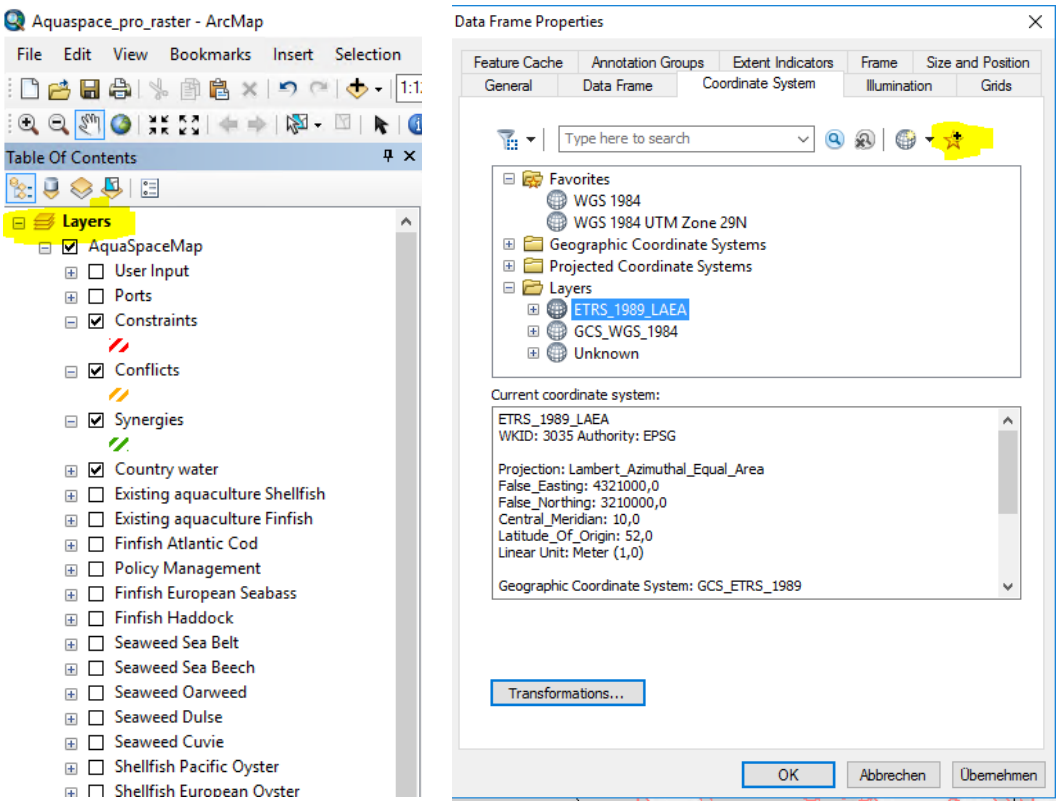


Figure 18: Visualisation of the re-projection of the AquaSpace mxd project.

- Switch over to ArcToolbox and open Tool “Project Raster” (location: Data Management Tools: Projections and Transformation: Raster; this tool enables re-projection, renaming and data loading at once; Fig. 19)
- Fill the tool according to the picture, for the “Output Coordinate System” needed you have now access to your GCS favorites: “ETRS_1989_LAEA”; the suitable transformation algorithm from source projection to target projection will be chosen automatically by ArcMap
- Close ArcMap without saving

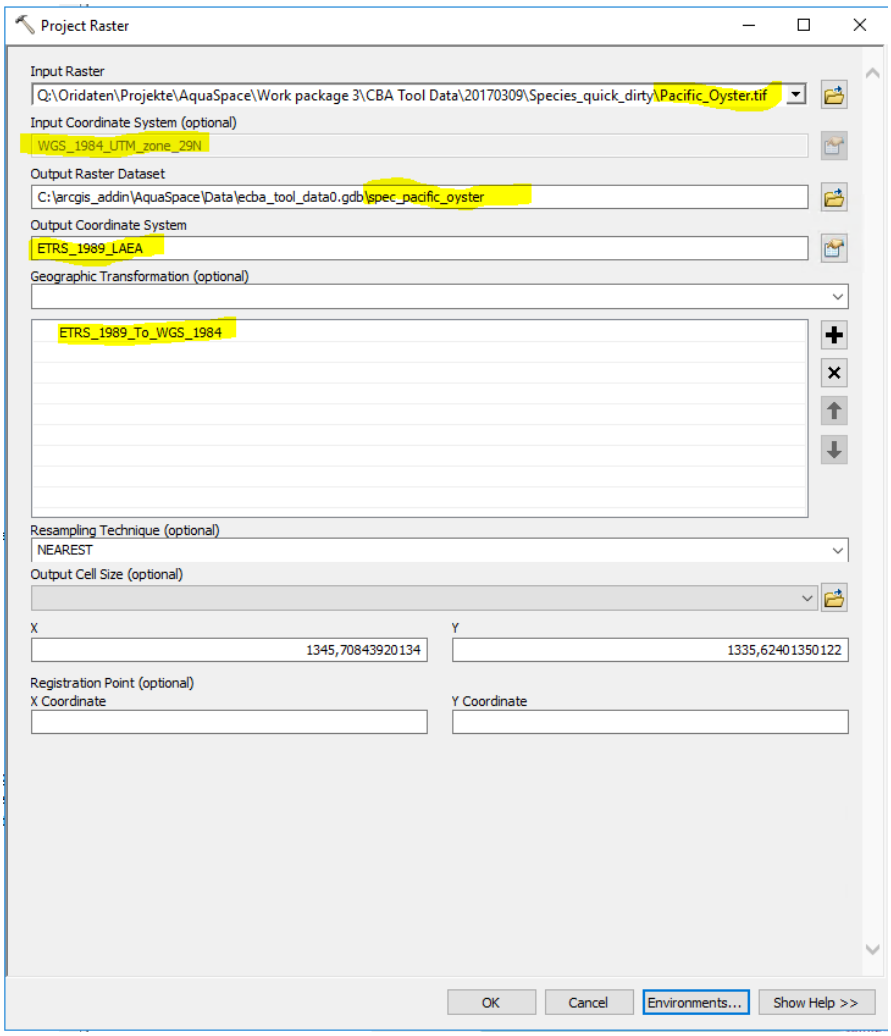
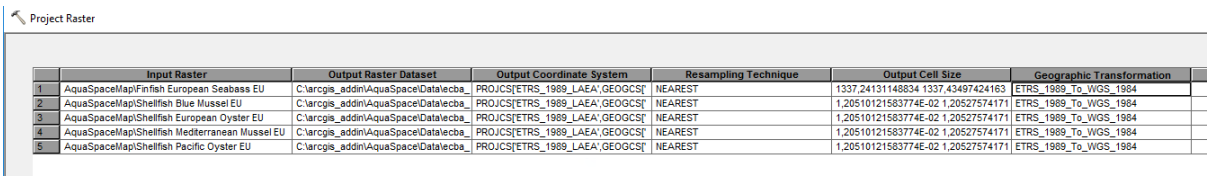


Figure 19: Visualisation of the tool "Project raster", applied to re-project a raster.

- Alternatively, the batch modus is offered, see ArcGIS documentation for the 'Project raster' tool (Fig. 20)
- Re-open "Aquaspace_pro_raster.mxd" in order to check/replace/repair broken raster data sources



Project Raster

	Input Raster	Output Raster Dataset	Output Coordinate System	Resampling Technique	Output Cell Size	Geographic Transformation
1	AquaSpaceMap\Finfish European Seabass EU	C:\arcgis_addin\AquaSpace\Data\ecba_	PROJCS['ETRS_1989_LAEA',GEOGCS[''	NEAREST	1337,24131148834 1337,43497424163	ETRS_1989_To_WGS_1984
2	AquaSpaceMap\Shellfish Blue Mussel EU	C:\arcgis_addin\AquaSpace\Data\ecba_	PROJCS['ETRS_1989_LAEA',GEOGCS[''	NEAREST	1,20510121583774E-02 1,20527574171	ETRS_1989_To_WGS_1984
3	AquaSpaceMap\Shellfish European Oyster EU	C:\arcgis_addin\AquaSpace\Data\ecba_	PROJCS['ETRS_1989_LAEA',GEOGCS[''	NEAREST	1,20510121583774E-02 1,20527574171	ETRS_1989_To_WGS_1984
4	AquaSpaceMap\Shellfish Mediterranean Mussel EU	C:\arcgis_addin\AquaSpace\Data\ecba_	PROJCS['ETRS_1989_LAEA',GEOGCS[''	NEAREST	1,20510121583774E-02 1,20527574171	ETRS_1989_To_WGS_1984
5	AquaSpaceMap\Shellfish Pacific Oyster EU	C:\arcgis_addin\AquaSpace\Data\ecba_	PROJCS['ETRS_1989_LAEA',GEOGCS[''	NEAREST	1,20510121583774E-02 1,20527574171	ETRS_1989_To_WGS_1984

Figure 20: Preconditions defined for the re-projection of a raster using the batch modus of the 'Project Raster' tool.

5.3. Tool application

5.3.1. Create interaction matrix

- Open the mxd: The layer data sources will be invalid for Constraints, Conflicts and Synergies (Fig. 15; we will re-connect these now)
- Change the view of the table of contents to "list by source", right click on the "conflictmatrix_table" and choose => Edit features => Start Editing
- Choose your individual interaction scoring in column => CONFLICT_SCORE
    - An example from the literature is given in Indicators => Inter-sectorial effects => Table 1
    - Two layers are provided for interactions with fisheries: high intensity fisheries "Fisheries q3", and the remaining fishing intensity "Fisheries"
    - If you provide individual fisheries data to define spatial constraints for high intensity fisheries, set the table column for "Fisheries q3" on value <Null>
    - If you provide individual fisheries data to define spatial conflicts for fisheries in general, set the table column for "Fisheries" on value <Null>
- Stop editing => Stop Editing, save your changes made to the interaction matrix and close the editor
- Use the purple button (figured as toothed wheel) in the AquaSpace toolbar (Fig. 10) to open the Interaction matrix model (Fig. 21). Choose a => Model Run ID (e.g. your name) and load the => conflict matrix table as edited

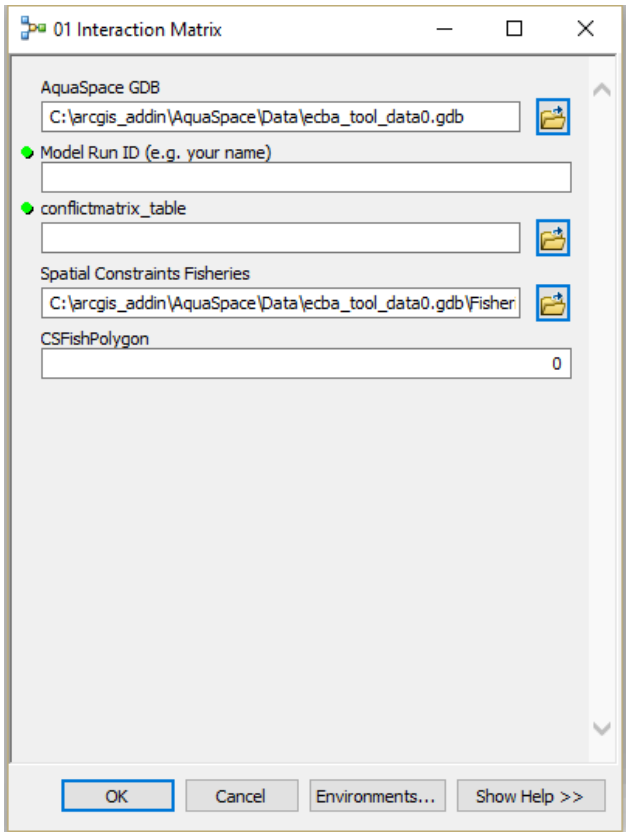


Figure 21: AquaSpace "Create Interaction Matrix" model.

- If individual fisheries data are available (see => Customization options), the polygon can be selected under => Spatial Constraints Fisheries
- Please insert a conflict score for your individual fishery layer under => CSFishPolygon (Remember: spatial constraints/mutually exclusive = score 6, low to very high likelihood of conflict = score 2 - 5 and synergy potential = score 1). IF NOT, please leave this row as it is (C:\arcgis_addin\AquaSpace\Data\ecba_tool_data0.gdb\Fisheries_empty)
- Push "Ok" to create your personal Interaction matrix (Fig. 22

Table

conflictmatrix_table

OBJECTID *	USE_A	USE_B	CONFLICT_SCORE	Combination Code	GEOMETRY
1	Aquaculture	Aquaculture finfish	very high likelihood of conflict	01	PG
2	Aquaculture	Aquaculture shellfish	synergy, no conflict	02	PG
3	Aquaculture	Platform	constraint, mutually exclusive	03	PT
4	Aquaculture	Cable	low likelihood of conflict	04	PL
5	Aquaculture	Pipeline	low likelihood of conflict	05	PL
6	Aquaculture	Sediment extraction	constraint, mutually exclusive	06	PG
7	Aquaculture	Shipping	constraint, mutually exclusive	07	PG
8	Aquaculture	Waste disposal	constraint, mutually exclusive	08	PT
9	Aquaculture	Policy Management	constraint, mutually exclusive	09	PG
10	Aquaculture	Ocean energy	synergy, no conflict	10	PG
11	Aquaculture	Fisheries q3	very high likelihood of conflict	11	PG
12	Aquaculture	Fisheries	low likelihood of conflict	12	PG
13	Aquaculture	Tourism	constraint, mutually exclusive	13	PG

0 (0 out of 13 Selected)

economic_input_figures conflictmatrix_table

Figure 22: Personal Interaction Matrix successfully installed.

- Repair broken links (invalid for Constraints, Conflicts and Synergies; Fig. 15) by referencing to your generated data via layer properties as now there will be a relevant data source to link to (Fig. 23)
    - Right click on "Constraints" in the Table of contents, = Properties, => Source
    - Set Data Source and direct the link to your personally created and named conflict matrix
    - Click ok. Please repeat the same for Conflicts and Synergies.

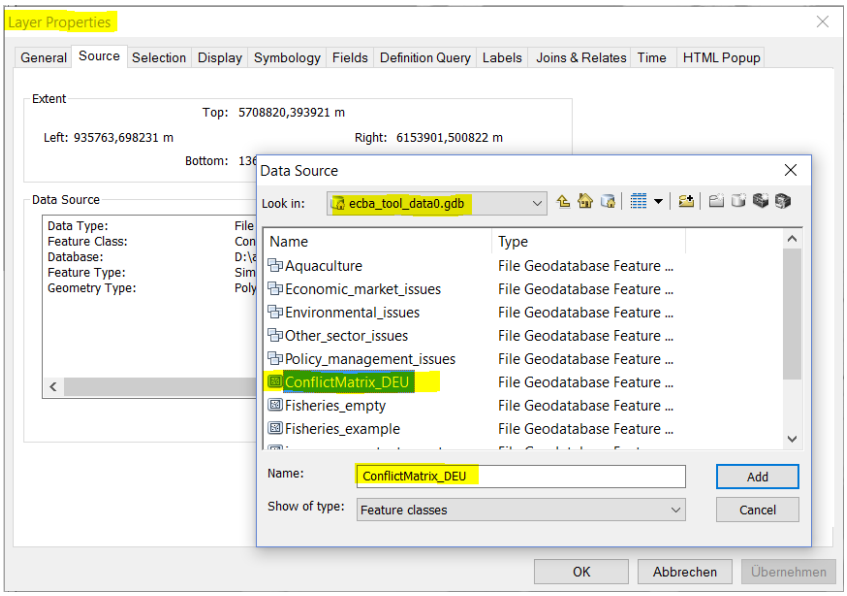


Figure 23: Adjust the layer properties of Conflicts, Constraints and Synergies by pointing to your personally created Interaction matrix.

5.3.2. Add your economic input

- Open the mxd to define general economic values for your case study to be tested
- Change the view of the table of contents to "list by source", right click on the "economic_input_figures" (Fig. 24) and choose => Edit features => Start Editing
- Put it the values requested in column => VALUE
    - An example for all input values (in Euro) can be found under Indicators => Economic effects => Table 8
    - Input values not available (such as Investments) require a value of 0
    - Input factors and quantifier (in %) can be found under Indicators => Economic effects => Table 7
- Stop editing => Stop Editing, save your changes made to the interaction matrix and close the editor

Table

economic_input_figures

OBJECTID *	NAME	PARAMETER	UNIT	VALUE
1	ui1	Investment equipment (per cage/trestle/longline)	Euro	1173000
2	ui2	Other investments (excl. Equipment, land facilties and properties)	Euro	19000000
3	ui3	Investment land facilties	Euro	1500000
4	ui4	Investment property	Euro	1272452.5
5	ui5	Market value culture species per ton	Euro/tons	5500
6	ui6	Annual expenditure on wages/salaries	Euro	399960
7	ui7	Annual intermediate costs (variable, e.g. juveniles/seeds/food)	Euro	2070
8	ui8	Annual rate on capital resources (e.g. 1%=0,01)	%	0.07
9	ui9	Annual intermediate costs (fixed, e.g. insurance/maintenance and repair ship)	Euro	48125
12	AER	Interest rates (e.g. 1%=0,01)	%	0.075455
13	ui10	Other costs (variable)	Euro	481428.75
14	ui11	Other costs (fixed)	Euro	3482352.5
15	ui12	Average no. of days at sea/culture site	days	53
16	ID	Induced direct impact multiplier (e.g. 1%=0,01)	%	0.26
17	II	Induced indirect impact multiplier (e.g. 1%=0,01)	%	0.45
18	OM	Output multiplier (e.g. 1%=0,01)	%	1.45
19	IM	Income multiplier (e.g. 1%=0,01)	%	0.16
20	IE	Income effects (e.g. 1%=0,01)	%	0.27
21	ui13	Average fuel costs	Euro/km	4.58

1 (0 out of 19 Selected)

economic_input_figures

Figure 24: The AquaSpace Economic input table. Values taken from the German case study.

5.3.3. Perform site assessment

The AquaSpace AquaSpace toolbar simplifies to perform a site assessment. Follow the toolbar inputs from left to right (excl. the purple button 'create interaction matrix', this was done in chapter 5.3.1) and make your choices (which need to be renewed for each tool run) regarding:

- The selection of the extent (Country) => selection is optional, you can also zoom into the mxd to choose your favoured site
- The harbour from which the aquaculture site will be supplied (Port) => selection required
- The aquaculture species you want to assess (Species) => selection required
- The background layer which shall be highlighted in the result map (Map Layer) => selection optional
- The extent defined for the assessment (blue button) => selection required
- The provision of sites to be assessed using the siting tool (Site Location; Fig. 25)

    - Choose a => Model Run ID (e.g. your name)
    - Choose a => Production cycle (years)
    - Choose a => Production density (tons/m³ or tons/ha)
    - Choose a => Cage size (m³) or Area (ha)
    - Choose a => Production quantity (tons)
    - Click on the feature set of the species you want to assess and click a point on the map to define the site to be assessed
    - Click "Ok"

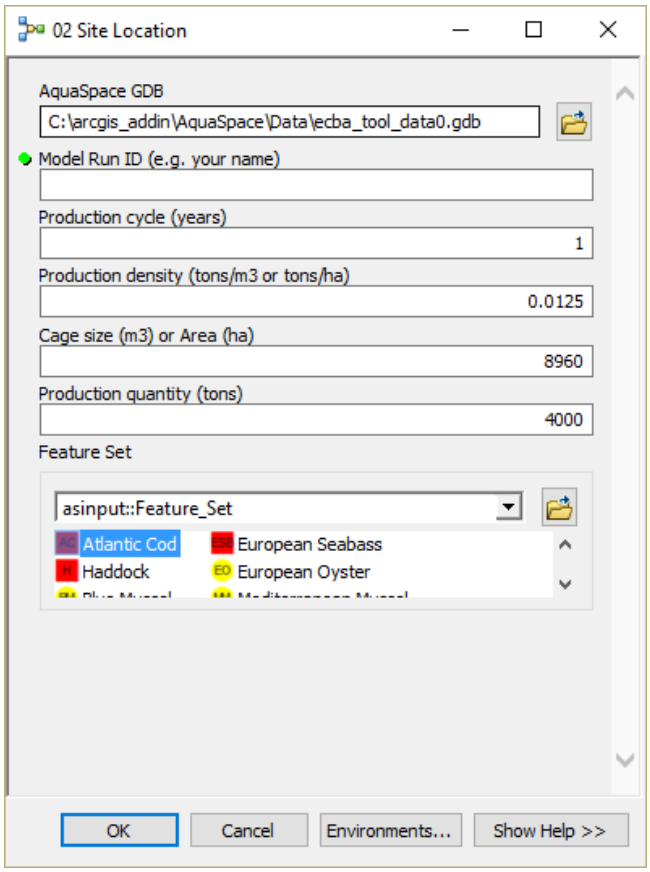


Figure 25: The AquaSpace siting tool (Site Location), available from the AquaSpace toolbar (Fig. 10) facilitates the site assessment using the AquaSpace tool.

5.3.4. Scenario building

As mentioned in section 4, the number of scenarios which can be assessed is not limited. Instead of clicking one point on the map, the user defines several points (Fig. 8).

The visualisation of tool outputs for up to five scenarios is ensured on the basis of a pdf-formatted report, generated for each tool run (Fig. 6), which is provided with additional charts facilitating the comparison of different scenarios assessed (Fig. 7) at specific sites (Fig. 8). In case of calculating more than five scenarios simultaneously, the tool emits a csv file (Tab. 10). Based on this, scenarios can be compared individually (Fig. 26).

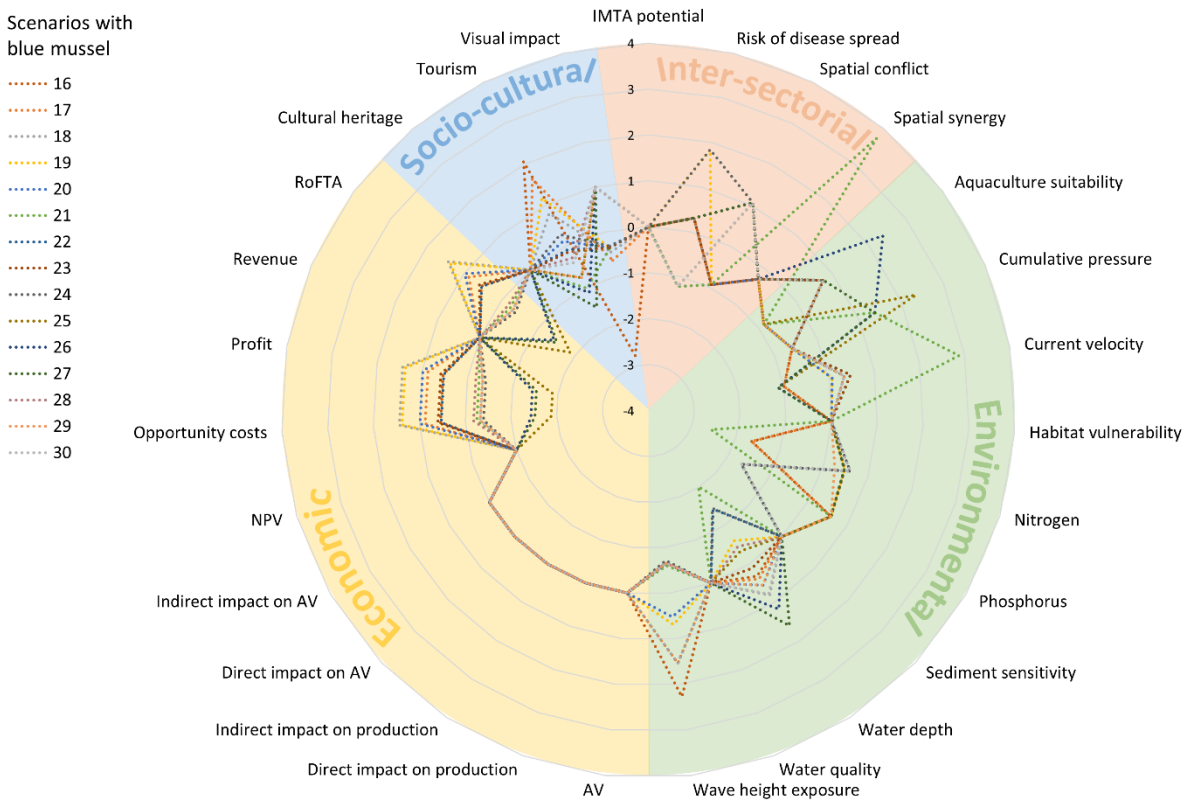


Figure 26: Spatially explicit performance of inter-sectorial, environmental, economic and socio-cultural indicators for 15 different aquaculture planning scenarios with *M. edulis*. Shown are potential trade-offs in between the AquaSpace tool indicators by comparing data normalised in application of a z-transformation. Indicators required merely to assess the growth performance of a species (i.e. chlorophyll a concentration at surface, temperature and salinity) are not included (AV = Added Value, IMTA = Integrated Multi-Trophic Aquaculture, NPV = Net Present Value, RoFTA = Return on Fixed Tangible Assets).

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ABBREVIATIONS

AV	Added Value
AER	Annual Equivalent Rate
CBA	Cost and Benefit Analysis
CMS	Cardiomyopathy Syndrome
DPSI	Driver-Pressure-State-Impact model
EAA	Ecosystem Approach to Aquaculture
EEZ	Exclusive Economic Zone
EUNIS	European Nature Information System
GDB	Geodatabase
GCS	Geographic Coordinate System
GIS	Geographic Information System
ICZM	Integrated Coastal Zone Management
IMTA	Integrated Multi-Trophic Aquaculture
ISAV	Infectious Salmon Anaemia Virus
MPA	Marine Protected Area
MSP	Marine Spatial Planning
N	Nitrogen
NPV	Net Present Value
P	Phosphorus
PD	Pancreas Disease
RoFTA	Return on Fixed Tangible Assets
SAC	Special Area of Conservation
SCI	Site of Community Importance
UNCLOS	United Nations Convention on the Law of the Sea
WATER	Where Can Aquaculture Thrive in Europe
WFS	Web Feature Service

ACKNOWLEDGEMENTS AND DISCLAIMER

We would like to thank Ismael Núñez-Riboni for processing environmental datasets. Further we thank Longline Environment Ltd. for the provision of Europe-scale suitability maps in GeoTiff format, available for the AquaSpace tool. Further information and online resources could be find in Boogert et al. (2017) and under http://www.longline.co.uk/water/.

The tool was customised, applied and further developed in collaboration with several AquaSpace case studies, operating at different spatial scales. The expertise of the AquaSpace consortium contributed to implemented tool functionality in relation to stakeholder requirements, case study issues, and current state of the art of the assessment of risks and opportunities of planned aquaculture activities. Further, such collaboration encouraged the amendments of the tool functionalities, the test phase by case studies, the development of the tool manual and the promotion of the tool.

Information contained here has been derived from several data sources which are listed in the AquaSpace tool Metadata (Annex I). While tool indicators, parameters and functions are standardised, the utility and applicability of the geodata rely heavily on the quality of the data available and the users' interpretation of the results. It is the duty of the tool user to understand the limitations of the data sets used and the scientific understanding applied by the tool. The authors take no responsibility for the interpretation of the results and the consequence of its use.

ANNEX I AQUASPACE TOOL METADATA

AquaSpace tool metadata overview. Please note, that for each item in the GDB metadata have been acquired that describe the item (feature class or GDB table) itself as well as the content of each field of table scheme. In ArcGIS the metadata can be viewed via the user interface by selecting => Item description from a layer's => properties menu. It can also be accessed from ArcMap, Catalog Window => right click desired feature class => Item description (Fig. 11).

CATEGORY	AQUASPACE INDICATOR	UNITS OF MEASURE	SOURCE	PORTAL	TITLE	ONLINE	EFFECTIVE
SITE SPECIFIC INFORMATION							
	Ecosystem	marine or freshwater	User input				
	Water depth	m	EMODNET (European Marine Observation and Data Network)	Bathymetry	DTM coverage	http://www.emodnet-bathymetry.eu/content/content.asp?menu=0040000_000000	2015
	Water quality	1-3; 3=high	AquaSpace tool function				
MANAGEMENT INFORMATION							
	UNCLOS area	country; maritime boundary	EMODNET (European Marine Observation and Data Network)	Human Activities	Maritime boundaries		2016
	Conservation area	conservation status	EMODNET (European Marine Observation and Data Network)	Environment	Nationally Designated Areas & Natura 2000	http://emodnet-humanactivities.eu/search-results.php?dataname=Nationally+Designated+Areas; http://emodnet-humanactivities.eu/search-results.php?dataname=Natura+2000	2015
AQUACULTURE SPECIFIC INFORMATION							
	Aquaculture suitability layer	0-1; 1=suitable	Longline Environment Ltd		WATER suitability sites	http://www.longline.co.uk/water/	2017
	Aquaculture site to be assessed	user input polygon buffered by a species-specific environmental footprint (finfish 800m, shellfish 50m)	User input				
INTERSECTORIAL EFFECTS							

CATEGORY	AQUASPACE INDICATOR	UNITS OF MEASURE	SOURCE	PORTAL	TITLE	ONLINE	EFFECTIVE
	Spatial conflict potential	2-5, 5=high	AquaSpace tool function				
	Spatial synergy potential	0-1, 1=synergy	AquaSpace tool function				
	IMTA potential	0- 1, 1=IMTA potential	AquaSpace tool function				
	Risk of disease spread	1-3, 3=high	AquaSpace tool function				
	Existing farms Shellfish		EMODNET (European Marine Observation and Data Network)	Human Activities	Shellfish production areas	http://emodnet-humanactivities.eu/search-results.php?dataname=Shellfish+Production	2015
	Existing farms Finfish		EMODNET (European Marine Observation and Data Network)	Human Activities	Finfish farming sites	http://emodnet-humanactivities.eu/search-results.php?dataname=Finfish+Production	2016
	Fisheries		Joint Research Centre (JRC)	European Commission, DG Maritime Affairs and Fisheries, Joint Research Centre	STECF Fishing effort 2016	https://stecf.jrc.ec.europa.eu/dd/effort/graphs-quarter	2016
	Ocean energy		EMODNET (European Marine Observation and Data Network)	Human Activities	Ocean Energy Projects	http://emodnet-humanactivities.eu/search-results.php?dataname=Project+Locations	2016
	Platforms		EMODNET (European Marine Observation and Data Network)	Human Activities	Hydrocarbon extraction - Offshore Installations	http://emodnet-humanactivities.eu/search-results.php?dataname=Offshore+Installations	2015
	Cables		EMODNET (European Marine Observation and Data Network)	Human Activities	Telecom cables	http://emodnet-humanactivities.eu/search-results.php?dataname=Kis+Orca+Subsea+Cables	2015
	Pipelines		WorldMap Harvard	WorldMap	Natural Gas Pipelines in Europe, Asia, Africa & Middle East	http://worldmap.harvard.edu/data/geonode:natural_gas_pipelines_j96	2017
	Sediment extraction		EMODNET (European Marine Observation and Data Network)	Human Activities	Dredging	http://emodnet-humanactivities.eu/search-results.php?dataname=Dredging	2014
	Marine traffic		NCEAS (National Center for Ecological Analysis and Synthesis)	KNB - The Knowledge Network		https://knb.ecoinformatics.org/#view/doi:10.5063/F1S180FS	2008

CATEGORY	AQUASPACE INDICATOR	UNITS OF MEASURE	SOURCE	PORTAL	TITLE	ONLINE	EFFECTIVE
	Waste disposal		EEA (European Environment Agency); EMODNET (European Marine Observation and Data Network)	Human Activities	E-PRTR (The European Pollutant Release and Transfer Register); Dredge dumping sites; Dredge dumping munition sites	http://www.eea.europa.eu/data-and-maps/data/member-states-reporting-art-7-under-the-european-pollutant-release-and-transfer-register-e-prtr-regulation-12; http://emodnet-humanactivities.eu/search-results.php?dataname=Dredge+Spoil+Dumping+%28Polygons%29#Metadata_Information; http://emodnet-humanactivities.eu/search-results.php?dataname=Dumped+Munitions+%28Polygons%29	2016; 2015
ENVIRONMENTAL EFFECTS							
	Wave height specific exposure	m	ECMWF (European Centre for Medium-Range Weather Forecasts)		Significant height of combined wind waves and swell	European Centre for Medium-Range Weather Forecasts (ECMWF)	2016
	Current velocity	m/s	COPERNICUS (Marine environment monitoring service)		Global Observed Ocean Physics Temperature Salinity Heights and Currents Reprocessing (1993-2014)	http://marine.copernicus.eu/services-portfolio/access-to-products/?option=com_csw&view=details&product_id=OCEANCOLOUR_GLO_CHL_L4_REP_OBSERVATIONS_009_082	2016
	Sediment type	1-5; 5 = rocky	EMODNET (European Marine Observation and Data Network)	Geology	Seabed Substrate 1m	http://www.emodnet-geology.eu/geonetwork/srv/dut/catalog.search#/home	2016
	Chlorophyll a (surface)	mg/m³; surface	COPERNICUS (Marine environment monitoring service)		Global Ocean, Chlorophyll GlobColour-OSS2015 products: Monthly, 8-days and Daily-Interpolated (1997-2014)	http://marine.copernicus.eu/services-portfolio/access-to-products/?option=com_csw&view=details&product_id=OCEANCOLOUR_GLO_CHL_L4_REP_OBSERVATIONS_009_082	2016
	Temperature	°C	COPERNICUS (Marine environment monitoring service)		Global Observed Ocean Physics Temperature Salinity Heights and Currents	http://marine.copernicus.eu/services-portfolio/access-to-products/?option=com_csw&view=details&product_id=GLOBAL_REP_PHYS_001_013	2016

CATEGORY	AQUASPACE INDICATOR	UNITS OF MEASURE	SOURCE	PORTAL	TITLE	ONLINE	EFFECTIVE
					Reprocessing (1993-2014)		
	Salinity	PSU	COPERNICUS (Marine environment monitoring service)		Global Observed Ocean Physics Temperature Salinity Heights and Currents Reprocessing (1993-2014)	http://marine.copernicus.eu/services-portfolio/access-to-products/?option=com_csw&view=details&product_id=GLOBAL_REP_PHYS_001_013	2016
	Nitrogen (surface)	mol/L NO3; surface	COPERNICUS (Marine environment monitoring service)		Global Ocean Biogeochemistry NON ASSIMILATIVE Hindcast (PISCES) (1998-2014)	http://marine.copernicus.eu/services-portfolio/access-to-products/?option=com_csw&view=details&product_id=GLOBAL_REANALYSIS_BIO_001_018	2016
	Phosphorus (surface)	mol/L PO4; surface	COPERNICUS (Marine environment monitoring service)		Global Ocean Biogeochemistry NON ASSIMILATIVE Hindcast (PISCES) (1998-2014)	http://marine.copernicus.eu/services-portfolio/access-to-products/?option=com_csw&view=details&product_id=GLOBAL_REANALYSIS_BIO_001_018	2016
	Cumulative pressures	1-8; 8=high magnitude of pressure	AquaSpace tool function				
	Habitat vulnerability	1-3, 3=highly vulnerable	EMODNET (European Marine Observation and Data Network)	Seabed habitats	EUNIS habitat maps from surveys	http://www.emodnet-seabedhabitats.eu/default.aspx?page=1953	2015
ECONOMIC & MARKET EFFECTS							
	Economic performance	Euro					
	Economic effectiveness	%	AquaSpace tool function				
	Economic efficiency	Euro	AquaSpace tool function				
	Economic impact	Euro	AquaSpace tool function				
	Port selected	euclidean distance (km)	Natural Earth Data		Ports	http://naturalearthdata.com	2016
SOCIO-CULTURAL EFFECTS							
	Visual impact	local population in 5.5 km radius	AquaSpace tool function based on EUROSTAT (Statistical office of the European Union) data	GEOSTAT	GEOSTAT-grid-POP-1K-2011-V2-0-1.zip	http://ec.europa.eu/eurostat/web/gisco/geodata/reference-data/population-distribution-demography/geostat	2011

CATEGORY	AQUASPACE INDICATOR	UNITS OF MEASURE	SOURCE	PORTAL	TITLE	ONLINE	EFFECTIVE
	Cultural heritage offshore/ onshore	distance to cultural heritage site (km):	AquaSpace tool function based on EMODNET (European Marine Observation and Data Network) data	Human Activities		http://emodnet-humanactivities.eu/view-data.php	2016
	Tourism	distance to touristic attractions (km):	AquaSpace tool function based on EMODNET (European Marine Observation and Data Network) data	Human Activities	State of Bathing Waters	http://emodnet-humanactivities.eu/search-results.php?dataname=State+of+Bathing+Waters	2015

ANNEX II CALCULATION OF INPUT-OUTPUT TABLES USING THE LEONTIEF MODEL

Annex II: Calculation of Input-Output Tables using the Leontief model.

Input–output tables are an instrumental part of national accounts and calculated using the Leontief Input-Output model (IO model), which is defined as followed:

$$X = AX + D \ (1),$$

where *X* is the total output (production) matrix, *A* is the IO model matrix, that is, *A* is the technical coefficients (a_{ij}) matrix, *D* is the demand matrix.

Each $a_{ij}\ coefficient$ shows the amount of input from economy sector *i* needed to produce one additional production unit of sector *j*.

The production matrix is then solved by using the following equation:

$$X = (I - A)^{-1}D \ (2),$$

where $(I - A)^{-1}$ is the Leontief inverse matrix (*L*).

Production multipliers: the sum of the Leontief matrix coefficients by column provides the total production increase of the wide-economy when increasing in one unit the production of one specific activity. These multipliers allow assessing the economic impact of one activity on the rest of the economy (induced impacts).

The induced economic impact of one specific activity on the wide-economy can be divided into two induced impact types i) induced direct impacts and ii) induced indirect impacts.

To quantify those effects it is used the Input Output Model:

$$X = (I - A)^{-1}D \ (3),$$

$$\Delta D \rightarrow \Delta X \ (4),$$

$$\Delta X = DI \ (5),$$

$$\Delta X = (I + A + A[(I - A)^{-1} - I])DI \ (6),$$

$$\Delta x = DI + ADI + \mathrm{A}[(I - A)^{-1} - I]\ DI \ (7),$$

where DI is the Direct Impact (e.g. revenues).

ANNEX III CASE STUDY EXPERIENCES

The broader applicability of the AquaSpace tool has been tested in six European case studies: The Aegean Sea, Greece; Alicante, Spain; Basque Country, Spain; Argyll, Scotland, UK; Northern Adriatic, Italy; and the Southern North Sea, Germany. Application of the tool has been demonstrated at multiple spatial scales, taking into account different aquaculture systems and development constraints. While applications related to finfish cultures are mostly located in offshore areas, applications relating to oyster and mussel cultures are located nearshore (Fig. 1).

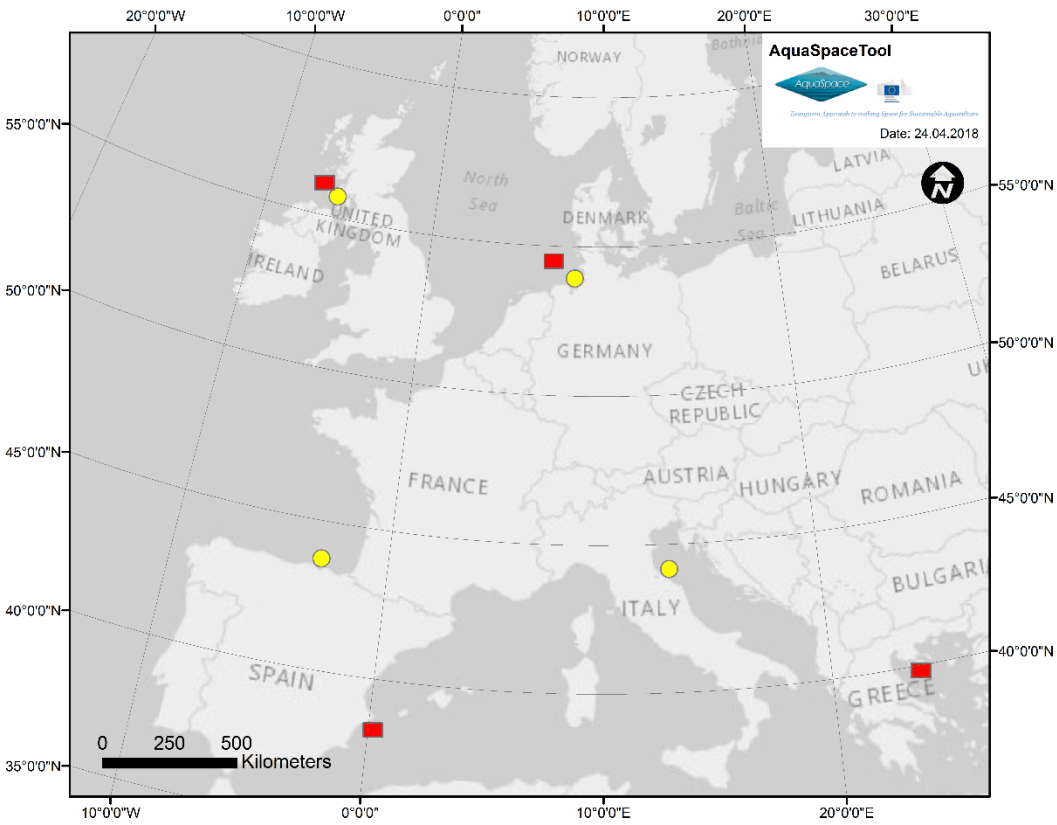

Figure 1: Map of the six case studies where the AquaSpace tool has been applied: The Aegean Sea, Greece; Alicante, Spain; Basque Country, Spain; Argyll, Scotland, UK; Northern Adriatic, Italy; and Southern North Sea, Germany. Shellfish cultures are highlighted in yellow (Blue mussel, Mediterranean mussel, European oyster and Pacific oyster), finfish cultures are highlighted in red (Atlantic salmon and European seabass). Source: Gimpel et al. (in prep.).

Case study specifications

The general scope of each case study is strongly linked to the case study-specific national strategies and further described and synthesised in Galparsoro et al. (2018). The application of the AquaSpace tool was driven by a variety of specific research questions. While the implementation in Scotland followed a practical approach to spatial management to identify suitable sites for new farms, the applications in Spain were more challenging. Here, a trade-off analysis was conducted to compare aquaculture sites with other potential sites (Basque country), and site selection within designated but already occupied areas (Alicante). Adopting a practical implementation of the National Strategy to Aquaculture (NASTAQ), the tool was tested at small and medium scales in Germany, i.e. within areas designated for aquaculture nearshore and co-location of aquaculture with wind farms offshore.

The production quantity, which varies across the aquaculture systems and species tested, is limited by the case study size (Fig. 2). The aquaculture species and locations tested include Blue mussel (*Mytilus edulis*) in Germany and the UK, Mediterranean mussel (*Mytilus galloprovincialis*) in Italy and Spain, European oyster (*Ostrea edulis*) in the UK, Pacific oyster (*Crassostrea gigas*) in Italy and the UK, Atlantic salmon (*Salmo salar*) in the UK and European seabass (*Dicentrarchus labrax*) in Germany, Greece and Spain. The size of the case studies were based upon management regulations, such as designated areas for blue mussel production in the German part of the North Sea, or flexible, such in the case of the Aegean Sea, Greece, where multiple sites were tested for European seabass cultures at a large geographical scale in an area with a very high production of cultured fish (Fig. 2).

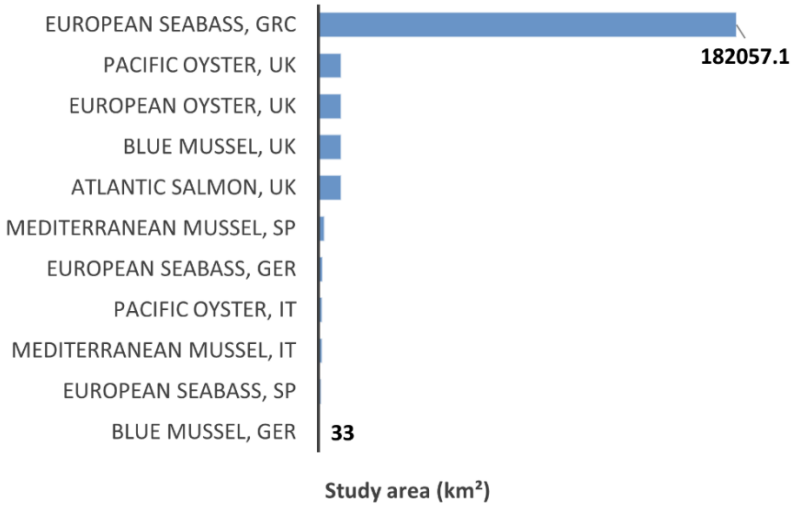

Figure 2: Case study area (km²) of Aegean Sea, Greece; Alicante, Spain (European seabass); Basque Country, Spain (Mediterranean mussel); Argyll, Scotland, UK; Northern Adriatic, Italy; and Southern North Sea, Germany.

The aquaculture systems tested in relation to finfish production were cages with different sizes and longline systems with different specifications for shellfish production. Case study-specific production quantities for the present annual production and the assumed annual production as tested in the AquaSpace tool are shown in figure 3. The values shown for the Mediterranean mussel are for the Basque Country case study, and the European seabass are for Alicante.

The highest increase in production was tested in the German case study, where the present annual production of 5,000t is intensified up to an expected annual production of 40,000t. New aquaculture species are tested in the UK (European and Pacific oyster), Germany (seabass), Spain (Mediterranean mussel) and Italy (Pacific oyster). The most conservative production quantities were assumed in Spain

with the Mediterranean mussel and the UK with the European oyster (both 2,080t), and the most progressive ones in Germany with the Blue mussel production of 40,000t.

The assumed market prices were taken from the literature and based on expert knowledge: 1,000€/t for blue mussel, 650€/t for Mediterranean mussel, 4,000€/t for European oyster and Pacific oyster, 7000€/t for salmon, and 5,500€/t for seabass. Other economic assumptions varied from case to case. For example, the maintenance for cultivation (i.e. the days at sea per year), varied from 53d/yr for seabass up to 240d/yr for Mediterranean mussel. Economic results were also driven by factors such as the costs of equipment, distance to port (i.e. fuel costs), and staff wages.

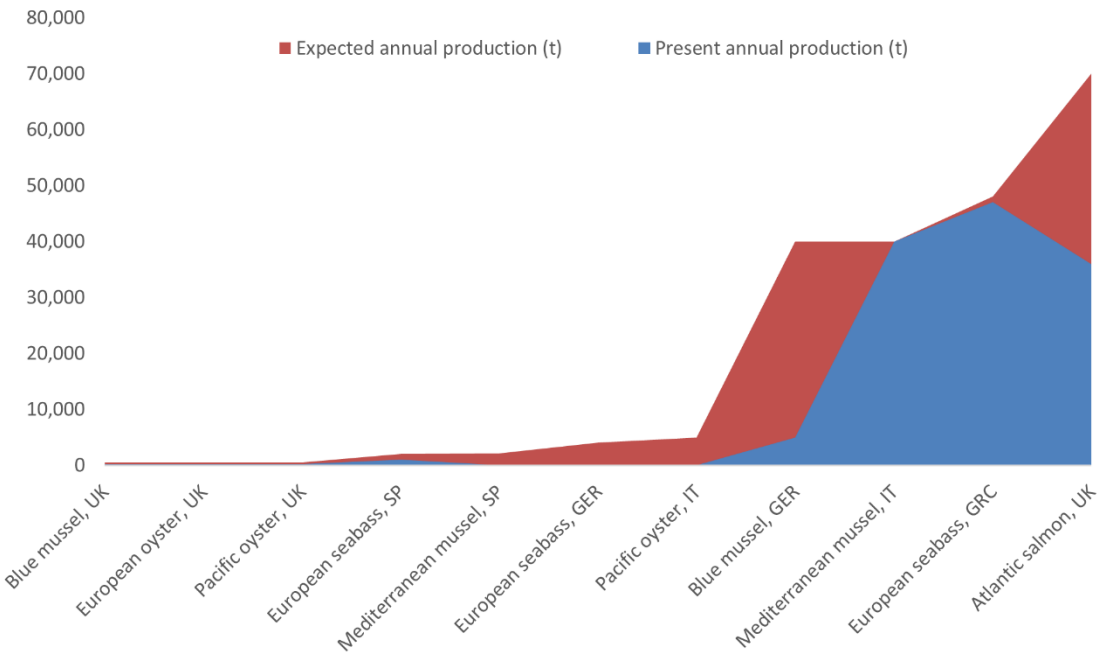

Figure 3: Case study-specific production quantities from tests in the AquaSpace tool. Given are the present annual production and the expected annual production for the six case studies Aegean Sea, Greece; Alicante, Spain (European seabass); Basque Country, Spain (Mediterranean mussel); Argyll, Scotland, UK; Northern Adriatic, Italy; and Southern North Sea, Germany.

The interaction matrices have been completed using case study-specific data to enable the definition of spatial constraints (score 6), conflicts (score 2-5) and opportunities (e.g. spatial synergy potential due to co-location; score 1) before testing scenarios for aquaculture in a wider MSP context. The scoring schemes varied, which confirms the assumption that input has to be kept flexible in order to incorporate the high variability of MSP implementation processes in different regions. For example, whereas areas designated for marine conservation constituted a constraint in most of the case studies, it was rated as causing a low likelihood of conflict for aquaculture with blue mussel in Germany and seabass in Greece and a medium likelihood of conflict for seabass in Spain. In contrast, wind energy development (i.e. ocean energy) offers the possibility for spatial synergies with aquaculture for nearly all case studies, except the Mediterranean mussel in Spain. The AquaSpace tool offers the opportunity to distinguish between high intensity fishing effort ('Fisheries q3') and medium to low fishing effort ('Fisheries') per country, when completing the interaction matrix. This opportunity was exploited for the majority of aquaculture systems tested (Tab. 1).

Table 1: Input for the AquaSpace tool interaction matrix per culture system, based on regional expert knowledge and literature review. Scoring of interactions with tested aquaculture systems for the six case studies Aegean Sea, Greece; Alicante, Spain (European seabass); Basque Country, Spain (Mediterranean mussel); Argyll, Scotland, UK; Northern Adriatic, Italy; and Southern North Sea, Germany: 0 =not considered; 1 = synergy potential; 2 = low likelihood of conflict; 3 = medium likelihood of conflict; 4 = high likelihood of conflict; 5 = very high likelihood of conflict; 6 = constraint. *Policy/Management covers Marine Protected Areas (MPA), but can be extended with other spatial management options or uses.

	Blue mussel, GER	*Blue mussel, UK*	*Mediterranean mussel, IT*	*Mediterranean mussel, SP*	*European oyster, UK*	*Pacific oyster, IT*	*Pacific oyster, UK*	*Atlantic salmon, UK*	*European seabass, GER*	*European seabass, GRC*	*European seabass, SP*
Aquaculture finfish	1	1	1	1	1	1	1	1	6	6	1
Aquaculture shellfish	0	1	2	1	1	2	1	1	1	1	1
Cable	5	5	5	6	5	5	5	5	5	2	5
Fisheries	2	5	4	0	5	4	5	5	2	2	0
Fisheries q3	5	6	4	0	6	4	6	6	5	5	6
Ocean energy	1	1	1	6	1	1	1	1	1	1	1
Pipeline	5	5	6	0	5	6	5	5	5	2	5
Platform	5	5	5	6	5	5	5	5	6	2	5
*Policy/Management**	2	6	6	6	6	6	6	6	6	2	3
Sediment extraction	5	5	6	6	5	6	5	5	5	2	5
Shipping	5	5	6	5	5	6	5	5	6	5	5
Tourism	2	3	1	3	3	1	3	3	3	5	3
Waste disposal	6	5	6	6	5	6	5	5	6	6	5

Scenario assessment

Case study specific research questions were addressed by assessments of inter-sectorial, environmental, economic and socio-cultural indicators. This used implementation of the case study-specific economic input, with the AquaSpace tool interaction matrix and information from the GIS-mapping, accompanied with an exclusion of management-related constraints and an examination of local aquaculture suitability (section 5.2.2, Fig. 15). In the case of the Alicante, Spain, the indicators determining those scenarios with seabass were, for example (in priority order) a low risk of disease spread, a high IMTA potential, proximity to the port and a high distance to tourism attractions (Fig. 4).

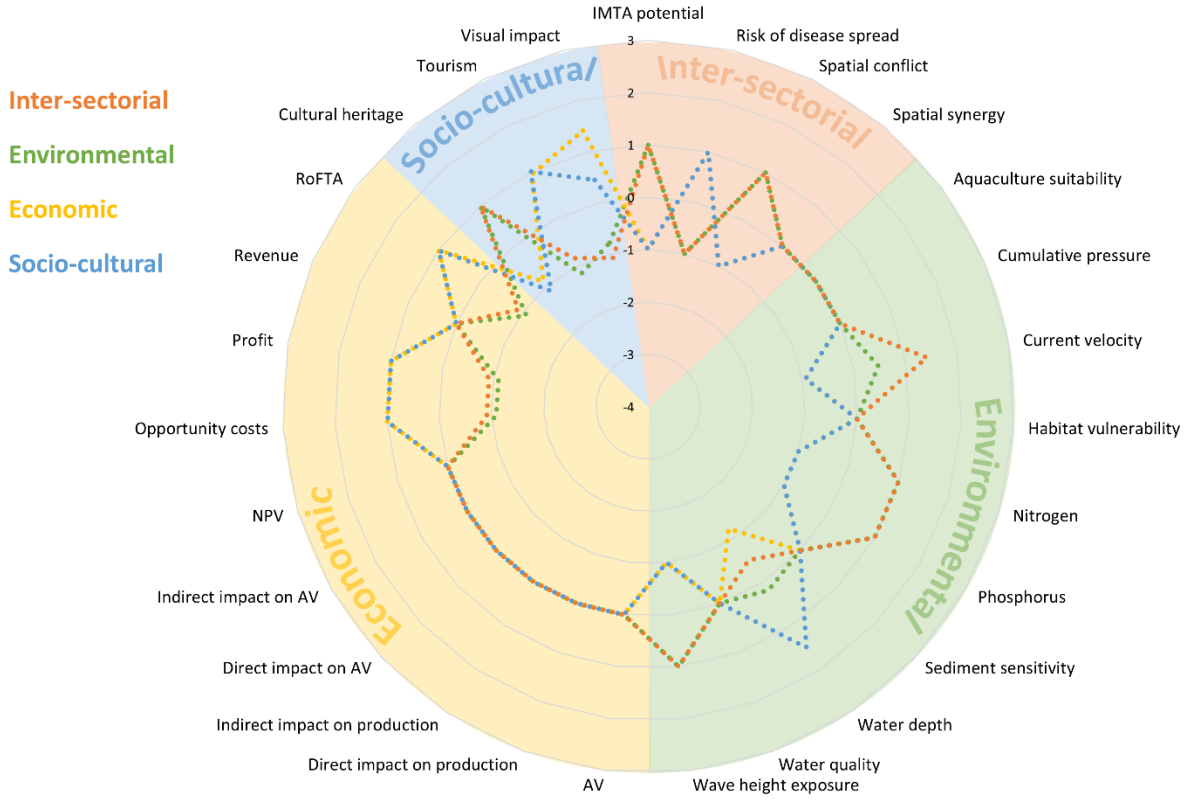

Figure 4: Spatially explicit performance of inter-sectorial, environmental, economic and socio-cultural indicators (categories highlighted in red, green, yellow and blue; in a present order) for 4 different aquaculture planning scenarios with European seabass in Alicante, Spain. The potential trade-offs between the indicators in the AquaSpace tool are shown, comparing data normalised by application of a z-transformation. The indicators required only to assess the growth performance of a species (i.e. chlorophyll concentration at surface, temperature and salinity) are not included (AV = Added Value, IMTA = Integrated Multi-Trophic Aquaculture, NPV = Net Present Value, RoFTA = Return on Fixed Tangible Assets).

In the German case study, those indicators included low potential for conflict and high potential for synergy (inter-sectorial), a low cumulative pressure load (environmental), high potential for profit due to the proximity to the port (economic), and a low visual impact (socio-cultural). Figure 5 presents a visualisation of the spectrum of results obtained comparing the outputs of the AquaSpace tool for the case studies of European seabass production in Spain (40,000t; Alicante) and Germany (4,000t;

North Sea). The figure presents a comparison of the four scenarios described above, based on values normalised using a z-transformation (Rowell, 2008). The data were further aggregated in order to show the positive and negative performance of the inter-sectorial (red), environmental (green), economic (yellow) and socio-cultural (blue) indicator categories assessed. Although German production is equivalent to only 10% of that by Spain, the economic assumptions in the case studies suggest that it is the German production which is more profitable. On the other hand, none of the efforts to keep the impact on socio-cultural indicators low seemed to be as effectives as in Spain. Nevertheless, such a comparison (and aggregation) approach (i.e. the z-transformation) can lead to risks of over- or underestimating individual indicator values.

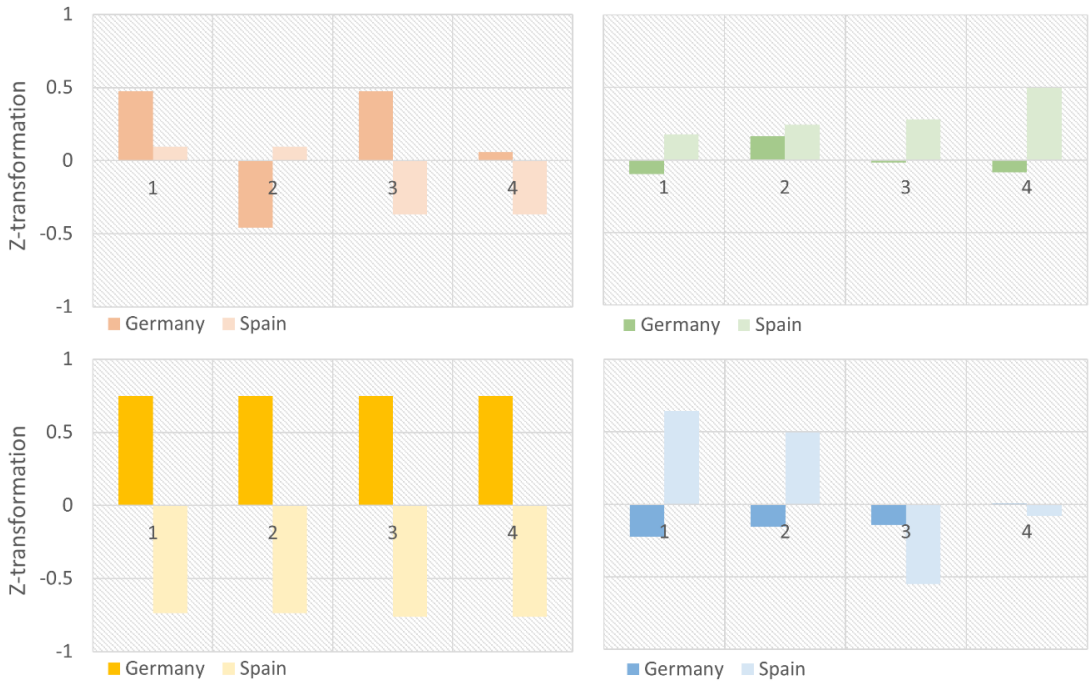

Figure 5: Case study-specific AquaSpace tool outputs, z-transformed for four different scenarios. The graphs show the aggregated positive and negative trends of inter-sectorial (red), environmental (green), economic (yellow) and socio-cultural (blue) indicator values for European seabass production in Spain (40,000t; Alicante) and Germany (4,000t; North Sea).

Overall case study findings

To introduce the AquaSpace tool and showcase its functionality, a detailed description was published in a study by Gimpel et al. (2018). Findings, based on the computation of aquaculture planning scenarios and the assessment of their trade-offs in the Southern North Sea, showed that it is feasible to identify aquaculture sites that correspond to multiple potential challenges such as those with a low potential of conflict, a low risk of disease spread, a comparably high economic profit and a low impact on tourist attractions.

In the Basque Country, implementation of the tool has enabled, in a systematic way, an integrated analysis and comparison of a set of indicators relating to aquaculture activity. In this process the results obtained in the aquaculture activity development pilot site were compared with those for the surrounding areas in which aquaculture expansion options are being analysed by the promoter (local government). The tool enabled as comparison between the sites. Analysis of the indicators showed slight differences between the two sites when they were selected on the basis of different environmental, economic or social criteria. The main differences, for the same types of aquaculture

production system, related to the RoFTA and profits. When environmental conditions were prioritised, there were lower values for profit and RoFTA. If economic performance was prioritised, cumulative impact and conflicts with other uses (mainly artisanal fisheries), increased as did visual impact and conflicts with tourism interests.

The findings of the Alicante case study validate those of the Basque Country. The profit was maximized in the locations situated closer to the coast. Looking at the maximum difference between the farms closest and the farthest from the coast, the profit differed by 10,757€. For farms further from the coast the visual impacts become non-existent, however these sites had to sustain higher exposure to waves. Most locations show similar values with respect to the tourism indicator, and awareness of habitat vulnerability informed selection of suitable locations. Testing a location close to the port with IMTA potential resulted in a higher potential of spatial conflict than in the other scenarios, explained by the fact that this location overlapped with a MPA or tourism site (both defined as having a medium level of potential for conflict) (Fig. 4).

Strengths and weaknesses of the AquaSpace tool

(Weaknesses marked by '-'; strengths marked by '+')

Installation

+ The tool comes with a detailed manual and tool settings (the Arc GIS mxd project, the tool bar and the GDB) ready to use
- The user needs sufficient knowledge of the use and technical characteristics of ArcGIS in order to be able to install the tool successfully

Data

+ The tool builds on open datasets at a European scale, improving reproducibility and collaboration in aquaculture science and research
+ Proved to be flexible as tool settings and datasets can be freely changed
- The spatial resolution of environmental data provided with the tool (GDB) is low
- Aquaculture suitability layers are not precise enough. Species growth rates and potential biomass should be provided (consider this as future needs for improvement)
- Information about important environmental factors and inter-sectorial information for the Mediterranean region are lacking
- Aquaculture suitability maps are not suitable for the entire Mediterranean region
- Benthic habitat data are only available for the shallower part of the aquaculture zone and therefore benthic vulnerability scores can only be calculated in shallower areas

Functions

+ Integrated assessment of a number of relevant indicators
+ Integrates indicators which are sufficiently robust to give a first overview
+ Informs about economic performance, effectiveness and results of impact analysis
+ Allows holistic scenario comparison and trade-off assessments
+ Facilitates the presentation of associated opportunities and risks / management decisions
- Limited choice of aquaculture species to be tested
- Economic assumptions and background calculations not sufficiently transparent
- Most economic indicators driven by 'distance to port' calculations

Handling

+ Tool settings can be changed individually and datasets replaced
+ The tool outputs comprise detailed reports and graphical outputs
+ AquaSpace tool outputs easy to interpret by users and different types of stakeholders
+ Background concept of trade-off analysis easy to understand and interpret (e.g. by managers)
- Lacking information about the correct application of the tool
- Integration of separate data rated as difficult for unskilled users (knowledge about data availability, formatting and integration in GDB)

Scale

+ Informs about the spatial extent of management effects
+ Aquaculture spatial planning in small or larger areas is very useful for producing valuable data for managers and policy makers
- AquaSpace tool currently designed to be used only in European countries, so excluding analysis in major producing countries such as Turkey

Development of the AquaSpace tool: Lessons learned

The AquaSpace tool provides a first screening tool, focusing on an overall assessment of the management effects of planning with aquaculture and therefore on the phase which follows that of a suitability assessment based solely on ecological indicators. Nevertheless, in order to improve collaboration in aquaculture science and research, the coupling with other models such as growth models is encouraged. In future, the AquaSpace tool could be improved by using data formats that enable free data access, and the incorporation of data required for: (i) the designation of suitable sites (e.g. quantified eutrophication effects of fish farms from spatially explicit predictive models), (ii) data required for monitoring aquaculture activities (e.g. pelagic and benthic nutrient and oxygen concentration, benthic keystone species etc.), and (iii) visualisation of spatially explicit data (geographic representation, object categories, symbols etc.) (Gimpel et al., 2018).