AQUASPACE

Ecosystem Approach to making Space for Aquaculture

EU Horizon 2020 project grant no. 633476

Deliverable 2.5

Online Environmental Feasibility Application

And

Milestone MS15 Release of on-line Environmental Feasibility Application

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Deliverable authors	F.J. Boogert, A.M Cubillo, J.P. Nunes, J.G Ferreira, R.A Corner
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Change log

Version	Date	Author	Reason for change
0.1	20/01/2017	A.M. Cubillo	Initial draft
0.2	21/01/2017	F.J. Boogert, J.P. Nunes	Delivered report on environment aspects
0.3	25/01/2017	A.M. Cubillo	Add references for Species database and provide examples of how the data can be leveraged
0.4	30/01/2017	J.G. Ferreira	Final draft

Review log

Version	Date	Reviewer	Comments
1.0	31/01/2017	R. Gomes Ferreira, Longline Environment Ltd.	

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Introduction and objectives

The AquaSpace project has the goal of providing increased space for aquaculture, to encourage and allow increased aquaculture production in marine and freshwater systems.

AquaSpace Work Package 2, *Accurately Identify Industry-Wide Issues and Options*, aims to identify issues and options that condition aquaculture development in Europe in general, and in the EU in particular. The consortium felt the need to do this in a quantitative manner, in order for the work to be of direct practical use to industry, managers, and policy-makers, as well as to other AquaSpace work packages.

The main environmental analysis is developed in Task 2.2, excerpted below.

> Task 2.2 – Quantitative Assessment of Aquaculture-Environment issues (Lead LLE)
>
> *This task will evaluate how the environment limits cultured species (and infrastructure) selection and spatial deployment due to natural (e.g. bathymetry, current speed, temperature, dissolved oxygen), and anthropogenic factors.*
>
> *This will be executed following a systems approach, starting with the development and population of an online relational database of cultivated species, gear, and mooring types, and identification and definition of ranges for all relevant factors at the European scale. Where possible, we will build on existing applications such as www.aquaculture.scotland.gov.uk. This work will be developed into a web application which will allow anyone to examine the potential Europe-wide development of culture from the environmental standpoint (feasibility). It will focus on the potential feasibility in coastal waters, and will not address the influence of aquaculture on the environment, because the final siting decision is multi-sectorial by nature of the definition of carrying capacity (production, ecological, social, governance).*

Because we aim to perform a quantitative assessment, several tools needed to be developed for task implementation. These are not necessarily tools *sensu* WP3, the dedicated AquaSpace *Tools* package, but they do reinforce the overall toolbox provided by the project.

This report is not a requirement of AquaSpace, but it is nevertheless important in outlining the various steps of the work executed, together with the principal outcomes. As such, it focuses mainly on the methodology, but a few examples are provided to help the reader understand the outcomes of the task.

Three components are essential for the quantitative analysis of the influence of the environment on aquaculture (Fig. 1).

The fundamental components are represented in the lower part of the figure:

- A species thresholds database;
- An environmental conditions database.

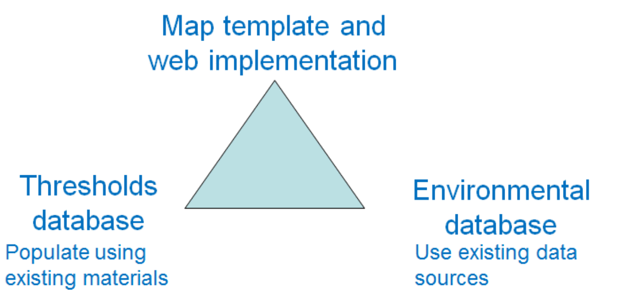

Fig. 1. General schematic of components of the WATER platform.

The final element is a web platform that combines both of these, entitled WATER – Where Can Aquaculture Thrive in Europe. The main focus of this report is on the first two components, since these constitute the science base for the quantitative analysis.

Environmental thresholds for cultivated species

Data acquisition

Data were collected for the top 45 species produced in the EU from 2010 to 2014 (Table 1).

Table 1. List of aquaculture species considered, classified by culture group and environment.

Common Name	Genus	Species	Culture Group	Environment
Atlantic salmon	*Salmo*	*salar*	Finfish	Marine[1]
Gilthead sea bream	*Sparus*	*aurata*	Finfish	Marine
European seabass	*Dicentrarchus*	*labrax*	Finfish	Marine
Turbot	*Psetta*	*maxima*	Finfish	Marine
Sea trout	*Salmo*	*trutta m. trutta*	Finfish	Marine
Atlantic bluefin tuna	*Thunnus*	*thynnus*	Finfish	Marine
Meagre	*Argyrosomus*	*regius*	Finfish	Marine
Shi drum	*Umbrina*	*cirrosa*	Finfish	Marine
Grey mullet	*Mugil*	*cephalus*	Finfish	Marine
Senegalese sole	*Solea*	*senegalensis*	Finfish	Marine
Red porgy	*Pagrus*	*pagrus*	Finfish	Marine
Atlantic halibut	*Hippoglossus*	*hippoglossus*	Finfish	Marine
Common sole	*Solea*	*solea*	Finfish	Marine
Rainbow trout	*Oncorhynchus*	*mykiss*	Finfish	Freshwater
Common carp	*Cyprinus*	*carpio*	Finfish	Freshwater
North African catfish	*Clarias*	*gariepinus*	Finfish	Freshwater
Bighead carp	*Hypophthalmichthys*	*nobilis*	Finfish	Freshwater
European eel	*Anguilla*	*anguilla*	Finfish	Freshwater
Silver carp	*Hypophthalmichthys*	*molitrix*	Finfish	Freshwater
Grass carp	*Ctenopharyngodon*	*idella*	Finfish	Freshwater
Roach	*Rutilus*	*rutilus*	Finfish	Freshwater
European catfish	*Silurus*	*glanis*	Finfish	Freshwater
European whitefish	*Coregonus*	*lavaretus*	Finfish	Freshwater
Tench	*Tinca*	*tinca*	Finfish	Freshwater
Brook trout	*Salvelinus*	*fontinalis*	Finfish	Freshwater
Pike perch	*Sander*	*lucioperca*	Finfish	Freshwater
Northern pike	*Esox*	*lucius*	Finfish	Freshwater
Nile tilapia	*Oreochromis*	*niloticus*	Finfish	Freshwater
Arctic char	*Salvelinus*	*alpinus*	Finfish	Freshwater
Danube sturgeon	*Acipenser*	*gueldenstaedtii*	Finfish	Freshwater
Siberian sturgeon	*Acipenser*	*baerii*	Finfish	Freshwater
European perch	*Perca*	*fluviatilis*	Finfish	Freshwater
Mediterranean mussel	*Mytilus*	*galloprovincialis*	Bivalve shellfish	Marine
Blue mussel	*Mytilus*	*edulis*	Bivalve shellfish	Marine
Pacific Oyster	*Crassostrea*	*gigas*	Bivalve shellfish	Marine
Manila clam	*Ruditapes*	*philippinarum*	Bivalve shellfish	Marine
Good clam	*Ruditapes*	*decussatus*	Bivalve shellfish	Marine
European flat oyster	*Ostrea*	*edulis*	Bivalve shellfish	Marine
Pullet carpet shell	*Venerupis*	*pullastra*	Bivalve shellfish	Marine
Queen scallop	*Aequipecten*	*opercularis*	Bivalve shellfish	Marine
Great Atlantic scallop	*Pecten*	*maximus*	Bivalve shellfish	Marine
Common cockle	*Cerastoderma*	*edule*	Bivalve shellfish	Marine
Winged kelp	*Alaria*	*esculenta*	Macroalgae	Marine
Sea belt	*Saccharina*	*Lattisima*	Macroalgae	Marine
Sea lettuce	*Ulva*	*Lactuca*	Macroalgae	Marine

[1] Marine may in some cases also include brackish water (estuaries or lagoons)

The species considered account for 85% and 95% of current EU aquaculture production in tonnage and revenue, respectively (FAO Fishstat Plus database - FIGIS).

Data were organized in multiple spreadsheets, and include 32 species of finfish, 10 species of bivalve shelfish, and 3 seaweed species. We have considered the same common names used by FAO, but in addition have inserted various *local name* fields, in order to build a multilingual database.

For each of these 45 farmed species, we have performed an extended literature review on tolerance and optimal ranges for thirteen environmental parameters (Table 2).

Table 2. Environmental parameters for defining the aquaculture potential of candidate species on land and open-water sites across the European Exclusive Economic Zone.

Parameter name	Unit	Category
Water temperature	ºC	Physical
Salinity	psu	Physical
pH	-	Chemical
Total Ammonia Nitrogen (TAN)	mg L^{-1}	Chemical
Un-ionized ammonia	mg L^{-1}	Chemical
Nitrite	mg L^{-1}	Chemical
Nitrate	mg L^{-1}	Chemical
Cultivation depth	m	Physical
Dissolved oxygen	mg L^{-1}	Chemical
Current speed	m s^{-1}	Physical
Chlorophyll	ug L^{-1}	Biological
Suspended solids	mg L^{-1}	Physical
Carbon dioxide	mg L^{-1}	Chemical

The spreadsheet includes other qualitative parameters, such as the countries where species are farmed, the production systems employed, and the seeding methods. We have specified four *Culture Types* (land-based, suspended, off-bottom, and bottom culture) and considered ten different *Culture Structures* or production systems at the on-growing stage (cages, ponds, tanks, raceways, pens, rafts, longlines, stakes, trestles, and bottom). The *Seeding Method* refers to the way the seeds are obtained (hatchery, wild catch, spat collectors, or nursery).

The *Species* data relate the core species names to their scientific names, and to the common names used in different countries (United Kingdom, France, Italy, Spain, Portugal, Norway, USA, and China).

The source(s) of information for each threshold defined are collated by means of a *Reference List* that associates each parameter value to its literature reference(s): author(s), date, study title and publication journal, and provides hyperlink(s), where applicable (see Annex II for the complete listing).

Table 3 shows some examples of optimal and threshold ranges. Every parameter has four categories (threshold low; optimal low; optimal high, and threshold high).

Table 3. Examples of optimal and threshold ranges for water temperature and salinity.

Genus	Species	Water temperature (ºC)				Salinity (psu)			
		Threshold low	Optimal low	Optimal high	Threshold high	Threshold low	Optimal low	Optimal high	Threshold high
Salmo	salar	2	10	16	24	0	22	28	35
Sparus	aurata	6	17	25	32.5	5	15	38	44
Dicentrarchus	labrax	2	19	25	32	4	13	30	40
Oncorhynchus	mykiss	1	12	18	25	0	0	20	35
Cyprinus	carpio	4	20	25	36	0	0	2.5	12
Mytilus	galloprovincialis	5	14	20	30	8	25	30	39
Mytilus	edulis	2	8	18	27	4	22	30	40
Venerupis	philippinarum	0	20	22	40	14	20	30	38

WATER species database

Although a spreadsheet format is useful for raw data collection, it does not constitute a database in the true sense, but is rather a collection of unrelated flat-file tables. In order to leverage the power of the data collected, and to make it available to the type of mapping framework illustrated in Fig. 1, the different data entities need to be structured as a relational (or some other type of) database.

The second stage of this work was therefore to design a framework for the organisation of the species database (Fig. 2).

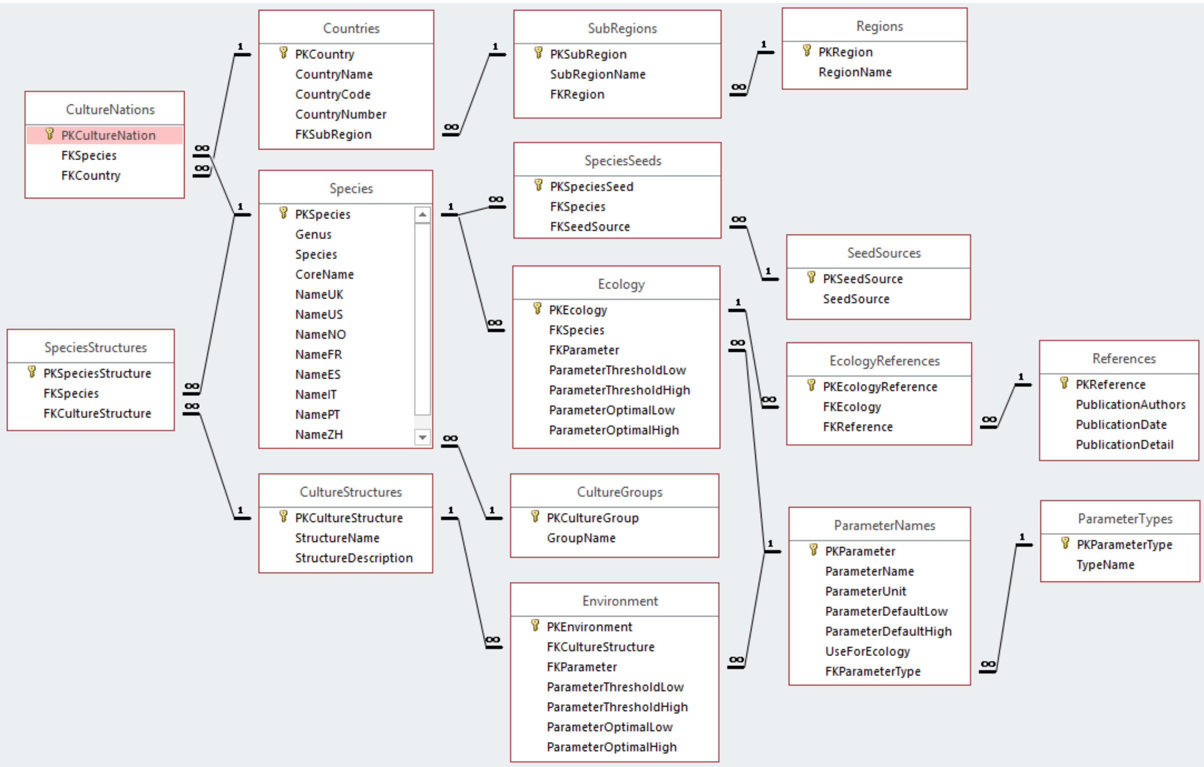

Fig. 2. Framework for the species relational database.

The framework shown in Fig. 2 contains 16 tables, all of which are populated from the core spreadsheet. The database was designed using MS-Access, but it can subsequently be easily imported and used in any Structured Query Language (SQL) platform, such as MySQL, MS-SQL, or ORACLE.

In the third stage of the work, a bespoke software application (Fig. 3) was developed in Visual C++ to automate the loading of all data from the spreadsheet format into the SQL database. This application is part of the toolset required for the web-based application WATER (Where can Aquaculture Thrive in Europe), and bears the same name.

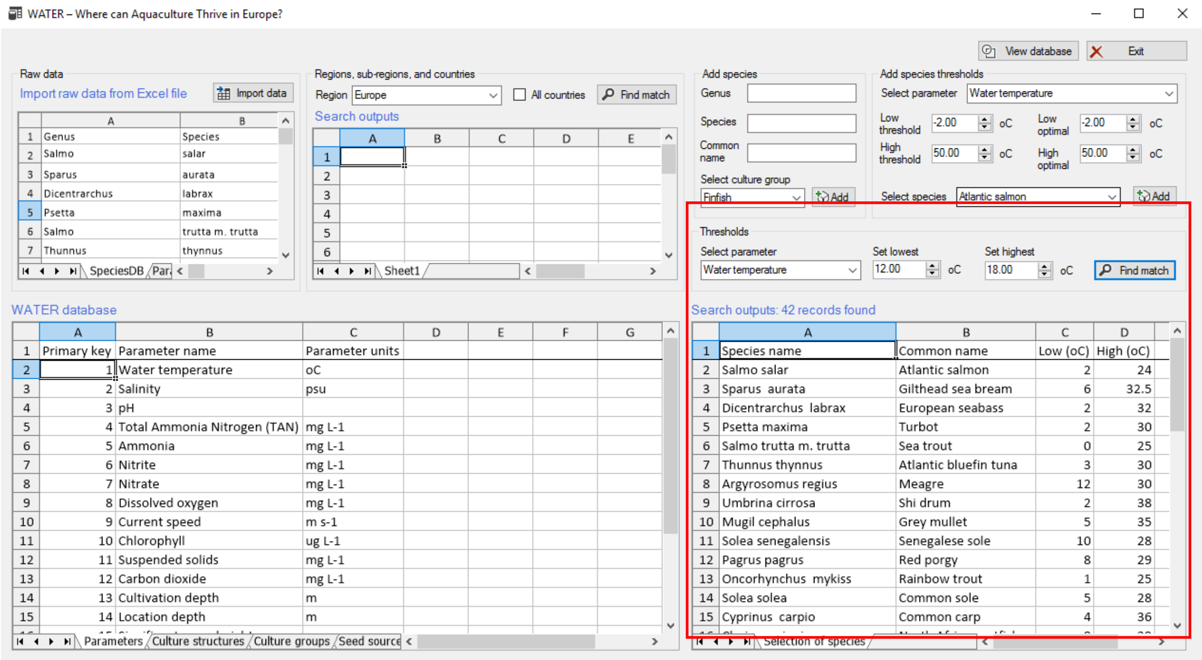

Fig. 3. The WATER species import application, which can also be used for species selection (see red rectangle).

This software can also be used to search for the suitable species that can be cultivated in a particular area based on their tolerance range for the environmental parameters, e.g. temperature.

Fig. 3 shows an example table of the species that would perform well in the average temperature range of Galician Rias (12-18°C). The WATER (species) application has found that 42 out of the 45 species considered could be potentially cultivated in Galician waters, if we only take temperature into account. All marine species of the database would survive in Galicia, but this does not mean that aquaculture would be commercially viable. For that, this temperature range would need to fall within the optimal growth range for each species.

WATER is a complex product that combines big data with online processing to provide information for industry, management, and the public. It is written in SQL (Structured Query Language) used to query a database.

The software uses mapping tools, species and parameter thresholds and individual growth models to identify the environmental potential for aquaculture with an emphasis on sites, both on land and open water, where different cultivated species can be grown.

Environmental database: Ocean and freshwater data

The aim of WATER is to provide Europe-wide mapping of a combination of environmental and economic possibilities for aquaculture siting. WATER deals with a database of 40 gigabytes for marine waters (full European EEZ) at a scale of squares of one nautical mile, and 54,000 spatial records for freshwater (all the major European lakes and reservoirs).

Design

The database created is based and expanded upon work by the FAO (Kapetsky, Aguilar-Manjarrez, & Jenness, 2013). The spatial data used for classification in this paper is separated into two categories, physical and Environmental parameters as shown in Table 4.

Table 4: data sources used by FAO (Kapetsky et al., 2013)

Physical parameters	
Currents	Ocean surface currents that are wind- or tidally driven. Suitability assessment and site selection for offshore mariculture needs long-term historical information on the speed and variability of currents because currents disperse aquaculture wastes and possibly lessen the prevalence of certain ectoparasite infections; however, currents that are too strong can impact the safety of the installation and the cost of marine transport and access and servicing of the facilities, as well as the cultured organisms themselves (e.g. energy expended on swimming rather than growth)
Wind	Average wind speed. Suitability assessment and site selection for offshore mariculture may benefit from long-term information on the exposure of an area to strong winds and storms given the impact on wave heights and currents. There is also a direct wind effect on service boat operations apart from wave height. Monitoring for warnings and forecasts regarding the expected track and severity of storms may also be useful.
Wave height	Technically defined as the difference in elevation between the crest of an ocean wave and the neighbouring trough; significant wave height (SWH) is a commonly used measure and is the average height of the one-third largest waves. Suitability assessment and site selection for marine aquaculture needs long-term information on SWH because of its importance for cost-effective and robust engineering of the marine aquaculture structures.
Environmental parameters	
Sea surface temperature (SST)	Sea surface temperature is physically determined by the incidence of solar radiation, ocean circulation and the depth of the mixed layer, which is affected by upwelling, surface winds and bathymetry. Offshore mariculture requires data and information on sea temperatures because fish and shellfish growth rates (and survival) are affected by average temperature and temperature variability. SST is the temperature of the water close to the surface, or the ocean "skin", and SST data are most likely applicable for suitability assessment and monitoring, the latter because models of ocean productivity need temperature data.
Primary production	Production of organic compounds from carbon dioxide through the process of photosynthesis, primarily by microscopic algae. Net primary production accounts for losses due to processes such as cellular respiration. Primary production is mostly determined by the availability of light and mineral nutrients, the latter being affected by stratification and mixing of the water column. Offshore mariculture requires data and information on the primary production of an area because shellfish are filter-feeders that rely on sufficient concentration of food particles such as phytoplankton for their growth. Chlorophyll-a concentration products that remote sensing can support are suitability assessment, zoning and site selection, and monitoring. Fish farmers may be interested in historical data and monitoring extremes of primary production, which may be harmful to fish health through oxygen depletion or production of toxic compounds.
Turbidity	Indicator of seawater transparency. Turbidity can be affected by local and regional currents and waves, coastal erosion, bottom type, phytoplankton concentration and river plumes. Offshore mariculture requires data and information on turbidity of an area because high concentrations of inorganic suspended matter can negatively affect fish and shellfish growth and health. The primary interest would be historical data.
Salinity	Content of dissolved salts, and variations can result from rainfall, evaporation, river discharge and ice formation. Offshore mariculture needs to understand the variable levels of salinity because feeding, growth and survival of shellfish can be affected by low salinity. Freshwater river plume distribution is an important site section issue and the interest is in historical data.
Dissolved oxygen	Concentration of oxygen that is dissolved in a given medium. Marine aquaculture needs to understand the typical levels of DO and the presence of "dead zones" (i.e. hypoxic areas in the world's oceans) because hypoxia may have detrimental effects on fish physiology (feed intake, growth), well-being, and survival.

Going from global scale to a regional scale, in this case Europe, and the use of several different species means that several data sources needed to be changed and added. The spatial data used in water can be separated into three sections: ocean data, lake data and environmental data.

Table 5: Ocean data sources

Type	Source	Description	Units
Bathymetry	www.gebco.net	Bathymetry (water depth)	m
Chlorophyll	http://marine.copernicus.eu/	A hind cast model was used for the years 1998 to 2014	mg m^{-3}
Currents	http://marine.copernicus.eu/	A hind cast model was used for the years 1993 to 2014	m s^{-1}
Dissolved Oxygen	http://marine.copernicus.eu/	A hind cast model was used for the years 1998 to 2014	mmol m^{-3}
SST	http://marine.copernicus.eu/	A hind cast model was used for the years 1993 to 2014	ºC
Significant wave height	https://wwz.ifremer.fr/	A hind cast was used for the years 2007, 2008, 2009, 2012, 2013, 2014, 2015, and April 2016	m

As seen in Table 5, 3 different sources have been used for ocean data. These sources provide over 15 years of data that need to be adapted for use in the classification. Table 6 shows 15 parameters from 2 sources, though it has to be noted that, as there are over 50000 lakes in Europe, it is impossible to get a complete set of data for any of these parameters. In Table 7, environmental vector data sources are given. These provide location-based information that will allow for querying and spatial analysis. The Corine landcover map of 2012 was used for extracting the location and shape of all lakes in Europe that are larger than 25 hectares.

Table 6: Lake data sources

Data	Units	Source
General[2]		Water Framework Directive (http://www.eea.europa.eu)
Alkalinity	mmol L^{-1}	Water Framework Directive (http://www.eea.europa.eu)
Chlorophyll	mg m^{-3}	Water Framework Directive (http://www.eea.europa.eu)
Dissolved oxygen	mg L^{-1}	Water Framework Directive (http://www.eea.europa.eu)
Oxygen saturation	%	Water Framework Directive (http://www.eea.europa.eu)
Lake surface temperature[3]	ºC	MODIS MYD11C3
Organic nitrogen	mg L^{-1}	Water Framework Directive (http://www.eea.europa.eu)
pH		Water Framework Directive (http://www.eea.europa.eu)
Secchi depth	M	Water Framework Directive (http://www.eea.europa.eu)
Total ammonium	mg L^{-1}	Water Framework Directive (http://www.eea.europa.eu)
Total nitrogen	mg L^{-1}	Water Framework Directive (http://www.eea.europa.eu)
Total organic carbon	%	Water Framework Directive (http://www.eea.europa.eu)
Total oxidised nitrogen	mg L^{-1}	Water Framework Directive (http://www.eea.europa.eu)
Total phosphorus	mg L^{-1}	Water Framework Directive (http://www.eea.europa.eu)
Pressures		Water Framework Directive (http://www.eea.europa.eu)

All parameters needed for this database are freely available, except for the lake surface temperature, which has been calculated from land surface temperature satellite imagery from the MODIS land surface temperature data product (The Land Processes Distributed Active Archive Center, 2016).

[2] General information about sampling stations and lakes, such as location, depth, and area.

[3] Temperatures calculated from MODIS land surface temperature data.

Table 7: Environmental data sources

Name	Source	Description
Corine landcover 2012	Land.copernicus.eu	The Corine landcover vector map was obtained from Copernicus land monitoring services land.copernicus.eu. It has a mapping unit of 25ha and is in the process validation.
Economic exclusive zones	www.marineregions.org	published on February 2th 2014. The EEZ map is a list of georeferenced place names and areas based on information from VLIMAR Gazetteer and MARBOUND.
Protected zones	www.protectedplanet.net	Published in May 2016, the protected planet website is a source for protected areas around the world.
World port index	msi.nga.mil	The maritime safety information website provides the port index to aid maritime navigation.

Data formats

For the data, two formats where chosen, NetCDF (Network common data form) for raster data and SHP (shape) for vector data.

The NetCDF file format offers several advantages over the more traditional Geotiff format. The main advantage is that it is a self-describing file ("Unidata," n.d.). Several conventions can be used to describe the data and this allows easy sharing without metadata getting lost. Another advantage is that large datasets can be queried faster in comparison to Geotiff files because there is a smaller number of files to deal with. However, the main reason to use NetCDF is for its ability to handle multidimensional data. Multidimensional data handling is preferred so that datasets of one or several parameters could be included in one file containing information for several months.

For the parameters that contain temporal variation, long-term "normal" maps where created. This was done by calculating for each parameter a mean and standard deviation for each month from all years of available data, resulting in a total of 24 maps per parameter which are then integrated into a single NetCDF file.

The ESRI SHP format for vector files was chosen because the attribute tables used to describe the data also allow multidimensional data and is a common data format with may.

Preparation

In order to create a database that allows for easy use and integration of all these different parameters all data needed to be prepared; several scripts where created and utilised to address the very large amount of data to be processed. The preparation of data was achieved by utilizing the tools provided by UNIDATA and GRASS (See Annex I).

For the creation of the lake surface maps, the MODIS Terra Land Surface Temperature and Emissivity version 4 dataset and data from the water framework directive where used. The MODIS dataset provides an average land surface temperature for each month from 2002 to 2016. Several method have been described to estimate lake surface temperature from land surface temperature or other satellite sources (Chavula, Brezonik, Thenkabail, Johnson, & Bauer, 2009; Liu et al., 2014; Piccolroaz, Toffolon, & Majone, 2013; Reinart & Reinhold, 2008). Most methods are based on extensive knowledge of the waterbody in question and the papers indicate that there is a fairly linear correlation between land and lake surface temperature. A small investigation was done comparing the MODIS dataset with available data from the water framework directive on lake surface temperature. A comparison between 98 measurements from the WFD database (including only annual averages created from at least 6 samples taken throughout the year) with processed land surface temperature maps from MODIS shows a linear correlation with an R^2 of 0.73 as seen in Fig. 4.

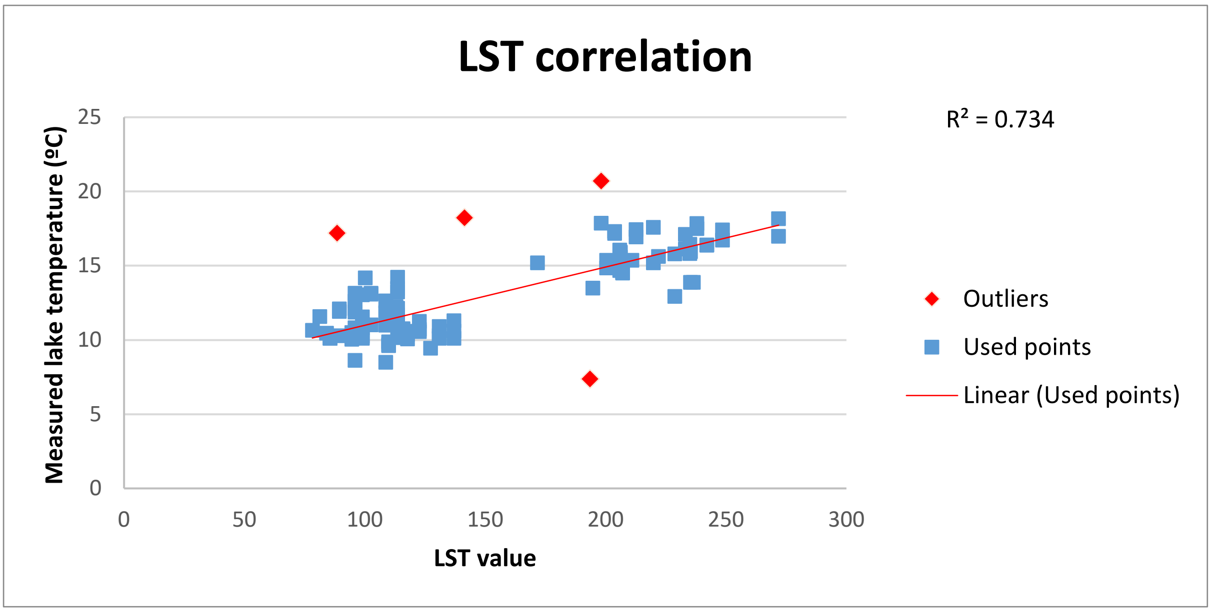

Fig. 4. Land surface temperature to water surface temperature correlation

From this analysis Eq. 1 was derived, where LST is Lake Surface Temperature and T_{land} is the raw MODIS land surface temperature.

$$LST = 0.8142 * (0.02T_{land} - 273.15) + 2.9963 \quad \text{(Eq. 1)}$$

Using this equation, the monthly surface temperature for 50722 lakes was calculated from MODIS land surface temperature products from 2002 to 2016.

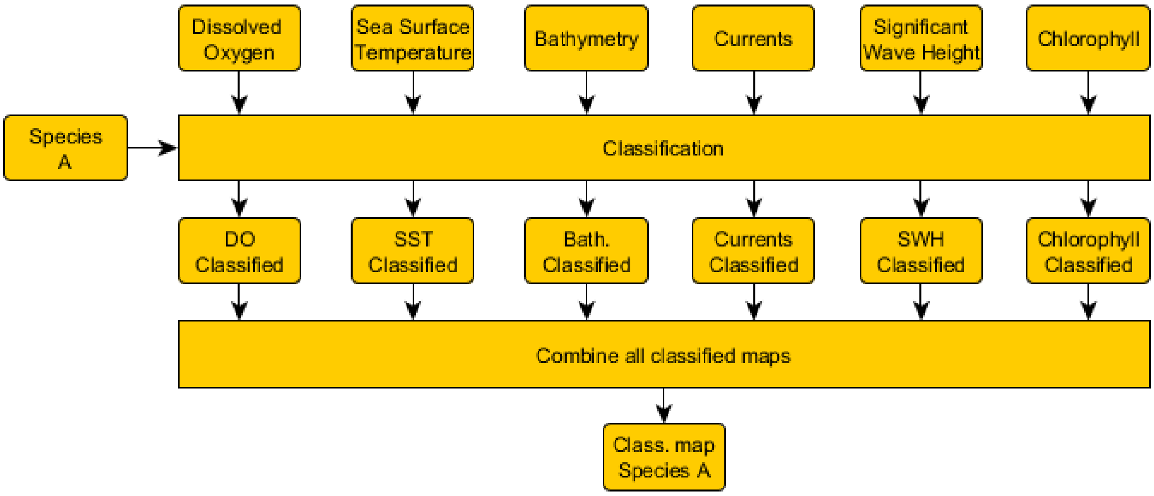

Fig. 5. Classification flowchart.

The long-term normals for all parameters are calculated using NCO and CDL packages (Unidata, n.d.), GDAL and GRASS in a Linux environment. In short, all existing data for a certain period (e.g. from 1998 to 2014 for chlorophyll concentration) is aggregated by month (irrespective of year), and then the average and standard deviation are calculated as can be seen in ANNEX 1.

With both the Species database and the spatial database complete areal classifications can be created. This is shown in Fig. 5.

The intermediate results from this process are shown in Fig. 6 and Fig. 7 with a potential final result shown in Fig. 8.

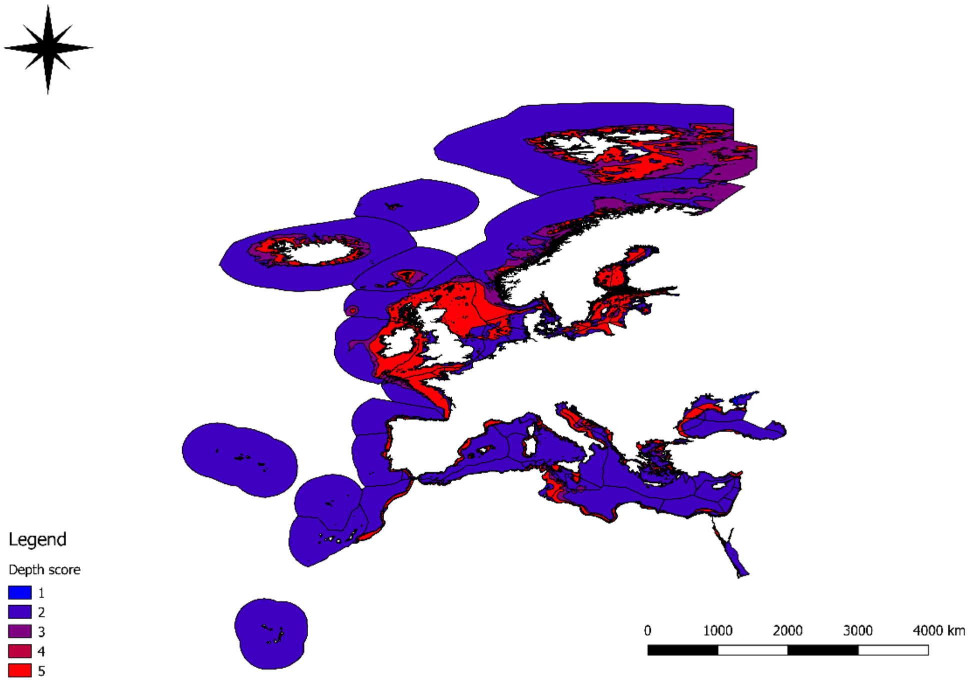

Fig. 6. Classified depth map.

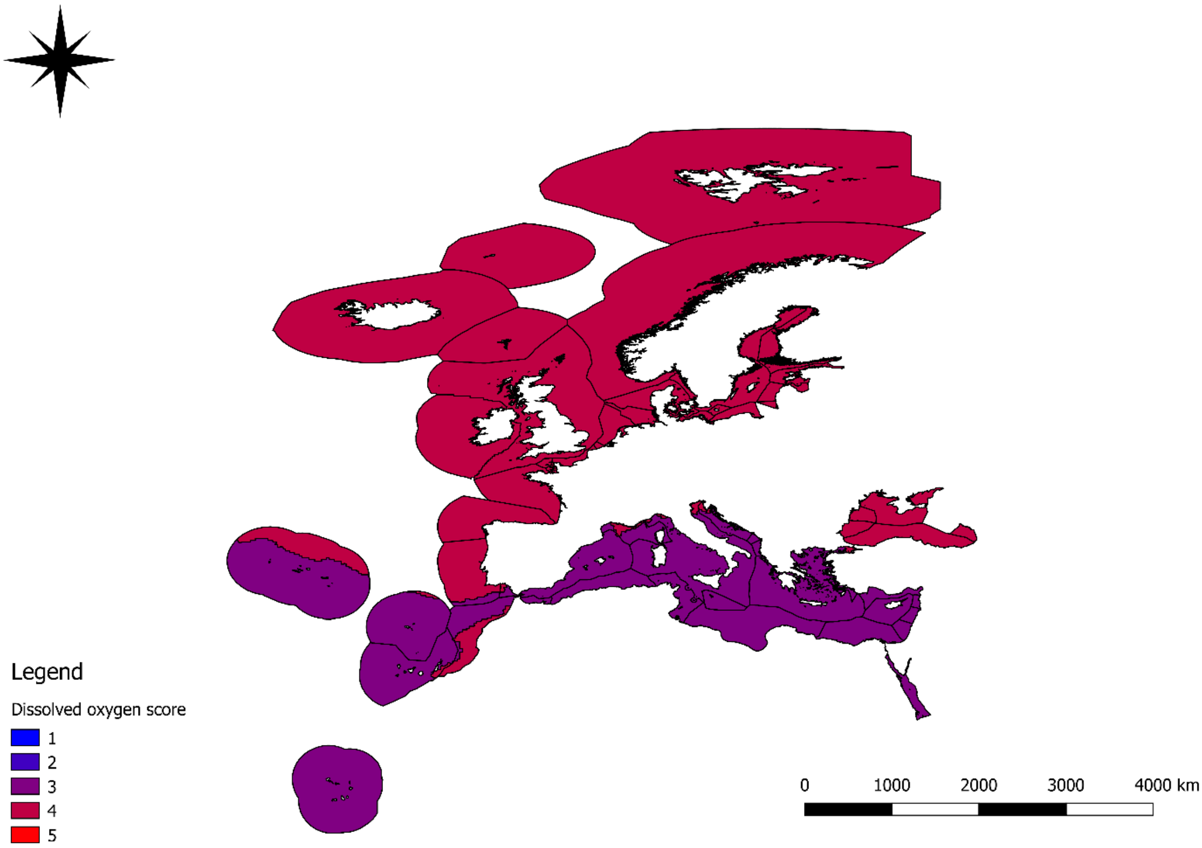

Fig. 7. Classified dissolved oxygen map.

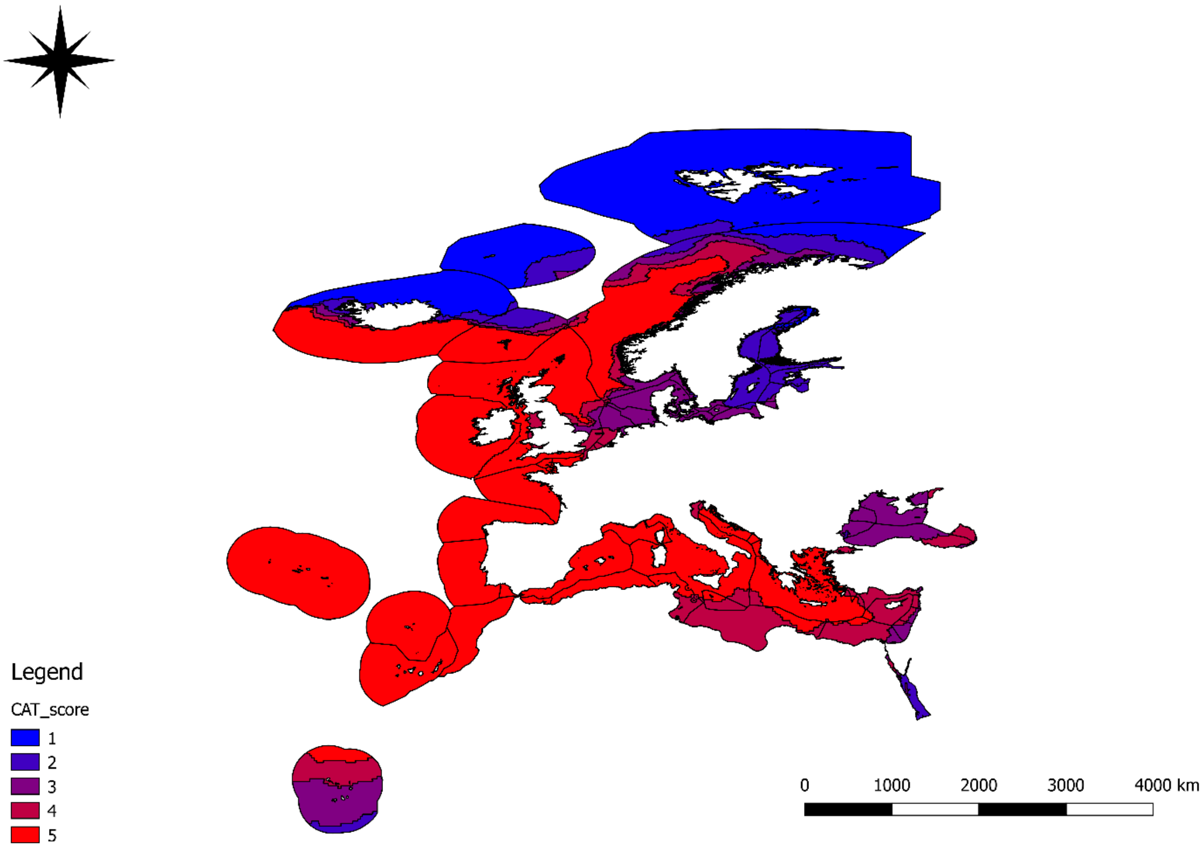

Fig. 8. Final classified map for sample species.

Data volume

Table 8 and Table 9 summarize the volume of environmental data collected for the WATER application in marine and freshwater respectively.

Table 8: Volume of data collected for the entire European Exclusive Economic Zone.

Parameter	Units	Resolution	File size	Source
Depth	m	1km	911 MB	GEBCO
Chlorophyll a	mg m^{-3}	1km	5636 MB	Copernicus MEMS
Dissolved oxygen	mmol m^{-3}	1km	5636 MB	Copernicus MEMS
Significant wave height	m	1km	5636 MB	IFREMER
Current speed	m s^{-1}	1km	5636 MB	IFREMER
Sea surface temperature	ºC	1km	5636 MB	Copernicus MEMS
Turbidity	m	-	± 5636 MB	Copernicus MEMS
Total nitrogen	mg m^{-3}	-	± 5636 MB	Copernicus MEMS

The species database contains 586 records for different farmed organisms, although not all records contain all fields (i.e. threshold low; optimal low; optimal high, and threshold high). These are limitations imposed by the existing experimental data, and provide valuable guidelines for research, particularly in the context of climate change.

Table 9: Volume of data collected for freshwater systems.

Parameter	Units	Nº lakes	Source
Mean lake depth	m	257	WFD
Chlorophyll	mg L-1	739	WFD
Dissolved oxygen	mg L-1	100	WFD
Lake surface temperature	oC calculated by using Modis land surface temperature images	50722	MODIS LST
Secchi depth	m	67	WFD
Total nitrogen	mg L-1	51	WFD
Total ammonium	mg L-1	20	WFD
Total organic carbon	mg L-1	43	WFD
Total oxidized nitrogen	mg L-1	1825	WFD
Total phosphorus	mg L-1	60	WFD
pH	-	27	WFD

A detailed representation of lake data can only be viewed in a zoomed image on the Geographic Information System, or in the WATER application, due to the small size of the water bodies in relation to the overall land masses of different European countries.

Nevertheless, Fig. 9 provides a snapshot for dissolved inorganic nitrogen (DIN), marked in red for freshwater systems throughout Europe. The image provides a sense of scale, particularly in countries such as Finland, and illustrates the value of the freshwater dataset.

As for marine systems, the data e.g. for lake surface temperature, where almost 60,000 datapoints exist, can be tested against species thresholds, and this is of great value in determining the potential for aquaculture expansion in inland waters. Furthermore, this dataset can be exploited to account for a changing climate, by using Eq. 1 in combination with relevant IPCC scenarios.

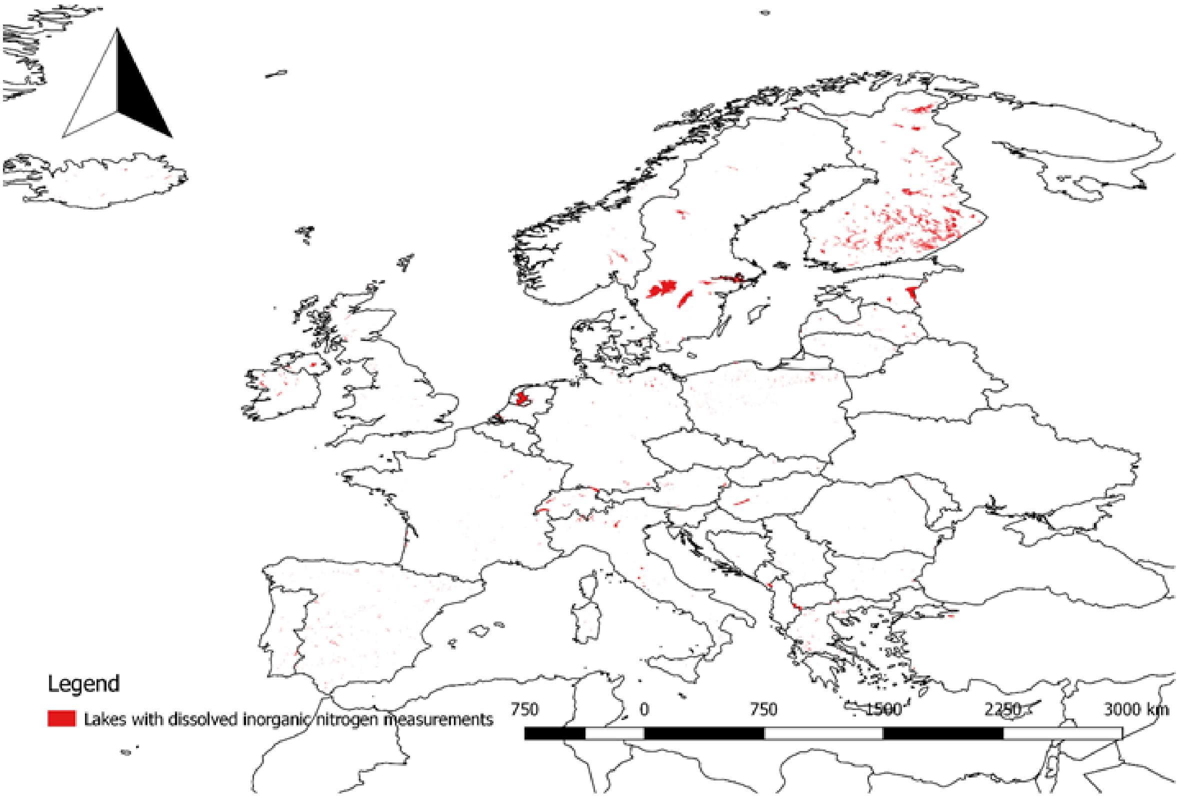

Fig. 9. Illustration of the freshwater datapoints (water bodies) stored in the Environment component of WATER.

These enviromental datasets are of great value *per se*, and the maps shown above for depth and dissolved oxygen have already been used to generate suitability maps for different species, and were applied in the development of the Aquaculture Investor Index (AquaSpace Deliverable 2.5).

Web Application

WATER can be used to examine the feasibility and suitability of cultivating a particular species in a selected area within the European Exclusive Economic Zone. Triage is based on species-specific tolerance ranges and a pre-defined set of conditions for cultivation, such as culture depth, production system or type of culture – land, suspended, off-bottom and bottom, e.g. an area may have environmental conditions to grow salmon, but not physical conditions to moor cages.

Table 10. GIS decision-support system examples.

Example	Website
Connecticut shellfisheries mapping atlas	http://seagrant.uconn.edu/whatwedo/aquaculture/shellmap.php
Scottish Executive aquaculture areas	http://aquaculture.scotland.gov.uk/
DEFRA shellfish areas	http://www.magic.gov.uk/magicmap.aspx
IPMA HAB maps	http://www.ipma.pt/en/pescas/bivalves/prev.toxinas/
NASA SST anomaly	http://data.giss.nasa.gov/gistemp/maps/
EU maritime atlas	http://ec.europa.eu/maritimeaffairs/atlas/index_en.htm

The general architecture is represented in Fig. 10, which illustrates the connection between the two databases: *Main Database* is the environmental repository, held in NetCDF, and it interacts with the *Species Database*. "*GeoServer is an open source server for sharing geospatial data. Designed for interoperability, it publishes data from any major spatial data source using open standards*."

Substantial discussions were held within Longline Environment Ltd., and with other AquaSpace partners with expertise in this area, to determine what would be the best way to implement the web application.

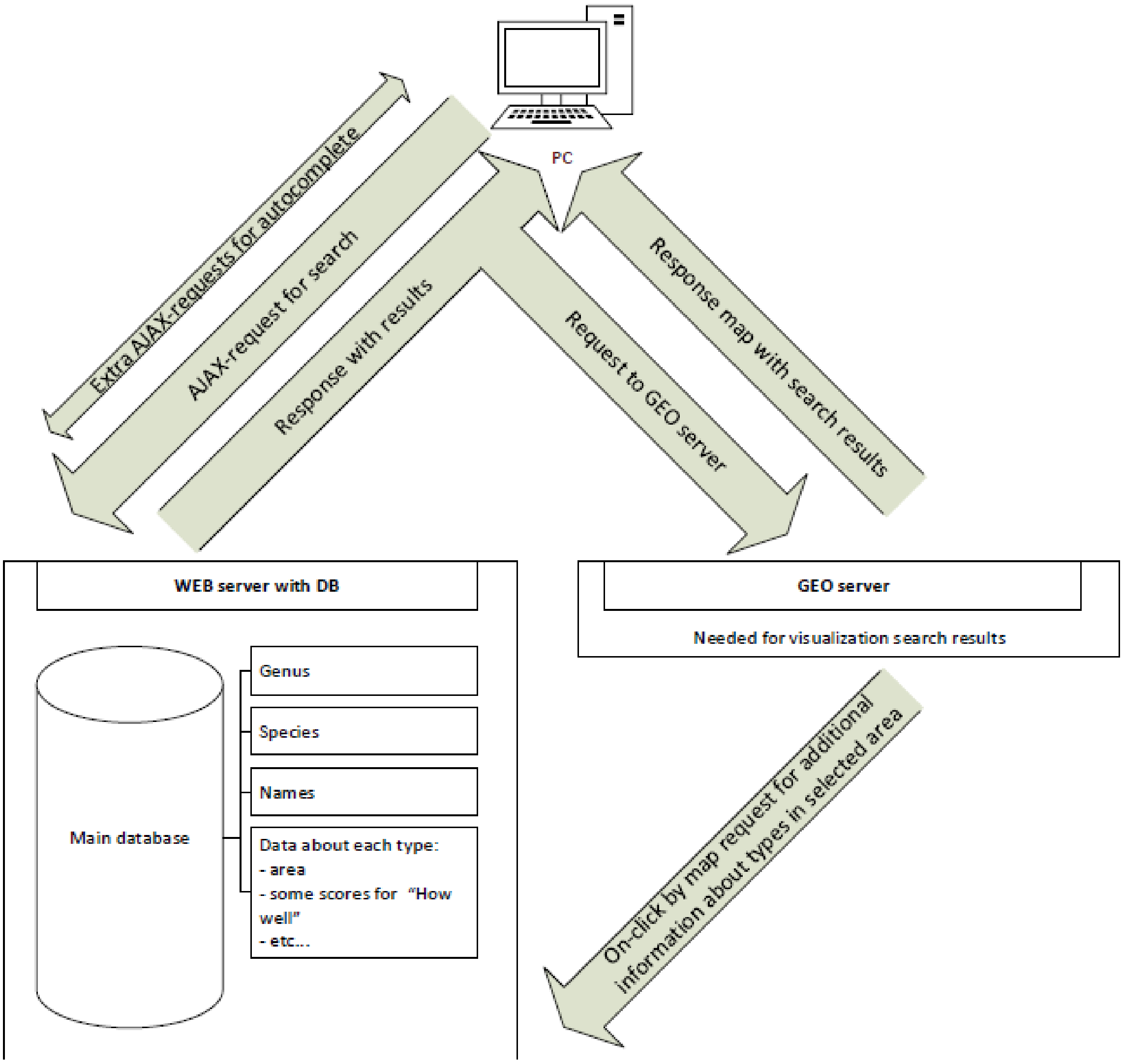

Fig. 10. Software architecture of the WATER web application.

There was a consensus that we would not want to produce another GIS application, with a similar approach to e.g. Google Earth, which provides a capacity to overlay multiple layers (see examples in Table 10). The alternative was to develop a 'question-based' system, which would query the databases and produce mapped results in response to specific questions such as:

- *Where can I grow salmon in Europe?*
- *How well will this (these) species grow here?*
- *What can I grow in this area?*
- *How well will these species grow in this area*
- *Aquaculture near me*
- *EEZ-specific outputs*
- *Climate change driven questions*

The system is implemented on a dedicated server, which can be queried through any web browser, and provides a response based on the question asked and the data retrieved by crossing the species requirements with the environmental conditions.

The core outputs are georeferenced maps, but synthesis data are also produced, aggregating total areas, percentage of EEZ, and other statistics. Shapefiles of outputs are available as an input to the cost-benefit analysis tool in AquaSpace Work Package 3 (Tools), which will then impose other limitations which extend beyond the way in which the environment limits aquaculture, and deal with co-use and impacts.

WATER was designed to support the analysis of available areas for farming, and will be maintained and extended as part of the AquaSpace legacy programme, to include other kinds of models, such as dynamic growth and environmental effects simulations.

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ANNEX 1

Annex I provides a detailed example of how the processing was done using open-source tools. Though only one parameter is described most steps followed are identical for others.

Execute bash

This file steers the whole process of preparation and calls upon several tools (NCO, CDL, GDAL and GRASS) to execute the preparation.

```
!/bin/bash
#This batch is for preparing the Chlorophyll files for use in grass.

#########Parameters########
#script location
loc_s=/example_scripts_location/
#grass mapset location
loc_m=/Grass_mapset_location/
#input location
loc_i=/example_data_location/CHL
#temporary file location
loc_t=/Temporary_output_location/CHL

#GRASS mapset to be used
mapset=PERMANENT

###netcdf variables
var1=CHL_M
var2=CHL_STDDEV
##script names##
S1=setup_mapset.sh
S2=CHL.sh
S3=import.sh
S4=calc_stats.sh
########Export_Variables########
# here these variables are temporarily made global so they can be used in other scripts called upon by
      this script.

export loc_s
export loc_i
export loc_t

###create folders###
#Here temprorary folders are created in case they do not excist yet.
mkdir -p $loc_t/v1
mkdir -p $loc_t/v2
mkdir -p $loc_t/v3
mkdir -p $loc_t/v4
mkdir -p $loc_t/v5
mkdir -p $loc_t/v6
mkdir -p $loc_t/v7
mkdir -p $loc_t/v8
mkdir -p $loc_t/v9
mkdir -p $loc_t/v10

###########prepare mapset and delete files in the mapset###########

      #run GRASS with script
      echo "run SETUP_MAPSET.SH"
      chmod u+x $loc_s$S1
      export GRASS_BATCH_JOB=$loc_s$S1
      grass70 $loc_m$mapset

###########run batch chlorophyll preperation and import###########

for file in $loc_i/*.nc
do
      echo "run CHL.sh"
      export file
      #run GRASS with script
      chmod u+x $loc_s$S2
      export GRASS_BATCH_JOB=$loc_s$S2
      grass $loc_m$mapset
done

for file in $loc_t/v2/*
do
      echo "run import.sh"
```

```
      export file
      #run GRASS with script
      chmod u+x $loc_s$S3
      export GRASS_BATCH_JOB=$loc_s$S3
      grass $loc_m$mapset
done


###########calculate stats###########
      #run GRASS with script
      chmod u+x $loc_s$S4
      export GRASS_BATCH_JOB=$loc_s$S4
      grass70 $loc_m$mapset

###Remove files from mapset and reset environment
      #run GRASS with script
      echo "run SETUP_MAPSET.SH"
      chmod u+x $loc_s$S1
      export GRASS_BATCH_JOB=$loc_s$S1
      grass70 $loc_m$mapset


###########Clip to boundary###########
for file in $loc_t/v3/*
do
      echo "clip" $(basename $file) "to boundary raster extent"
      gdalwarp -cutline /media/fjboogert/Disk1/Aquaspace/Disk1/Temp/boundary.shp -crop_to_cutline $file
      $loc_t/v4/$(basename $file)
done

###########Create NetCDF files###########
for file in $loc_t/v4/*
do
      echo "transform " $(basename $file) "to *.nc"
      gdal_translate -of netCDF -co "FORMAT=NC4" $file $loc_t/v5/$(basename $file .tiff).nc
done

###########Add time dimension and variable names###########
for file in $loc_t/v5/*.nc
do
      echo "add time dimension and variable names to" $(basename $file .nc)
t=`expr substr $(basename $file) 1 2`
Y=2000
x="$(echo $t | sed 's/^0//')"
f=00
d=$(($x*30))

      if echo $(basename $file) | grep -q "_M";
      then
      echo "using mean"
      ncrename -v Band1,CHL_M $loc_t/v5/$(basename $file)
      echo "renamed Band1"

      ncap2 -Oh -s "tin=$d;" -S mean.nco $loc_t/v5/$(basename $file)  $loc_t/v6/$(basename $file)
      ncatted -O -a long_name,CHL_M,o,c,chlorophyll_concentration_in_sea_water_mean
      $loc_t/v7/$(basename $file) #CHange to new values!
      cdo settime,$d $loc_t/v6/$(basename $file) $loc_t/v7/$(basename $file)

      else
      echo "using stddev"
      ncrename -v Band1,CHL_STDDEV $loc_t/v5/$(basename $file)
      echo "renamed Band1"

      ncap2 -Oh -s "tin=$d;" -S stddev.nco $loc_t/v5/$(basename $file)  $loc_t/v6/$(basename $file)
      ncatted -O -a long_name,CHL_STDDEV,o,c,chlorophyll_concentration_in_sea_water__stddev
      $loc_t/v6/$(basename $file)
      cdo settime,$d $loc_t/v6/$(basename $file) $loc_t/v7/$(basename $file)

      fi

      ncks -O --mk_rec time $loc_t/v7/$(basename $file) $loc_t/v8/$(basename $file)
done

###########Combine to last NetCDF file##########
```

```
echo "Create final NetCDF files"
cdo mergetime $loc_t/v8/*_M.nc $loc_t/v9/mean.nc
cdo mergetime $loc_t/v8/*_Stddev.nc $loc_t/v9/Stddev.nc
ncks -A $loc_t/v8/mean.nc $loc_t/v9/Stddev.nc
mv $loc_t/v9/Stddev.nc $loc_t/v10/CHL.nc
```

Setup map set

This script clears all previous data that is loaded in the GRASS map set, this is done to avoid clutter and conflicting filenames or region settings.

```
#!/bin/bash
#####empty mapset######
echo "emptying mapset"
#This removes all maps with all names and types from the mapset.
g.remove -f type=all pattern="*"

#####set environment parameters to mapset######
echo "setting projection"
g.proj -c epsg=4326

############set mask###############
#This imports the mask to be used, in this case it is the exclusive economic zones raster file
     for europe.
r.in.gdal -o --overwrite --quiet input=/source/EEZ.tif output=region
echo "Setting mask and region"
r.mask raster=region
g.region rast=region
```

CHL

Because most data used is projected in the ORCA grid used by the Copernicus marine service this needs to be adapted to a more commonly used coordinate system. In this case it will be the universal Mercator WGS84 projection or EPSG 4326.

```
!/bin/bash
######File######
#Create output filename for source filename.
F1=$(basename "$file")
Year=`expr substr $F1 22 4`
Month=`expr substr $F1 26 2`
U="_"
name="$Year$U$Month"
temp=temp
T2=t2

######remove dimensions#########
#This part utilises the ncks command to only extract the sea surface, coordinates and chlorophyll
     data.
ncks -O -v CHL,nav_lon,nav_lat -d deptht,0.50576 $file $loc_t$name.nc
echo "Finished extraction of data"
#####create vrts######
# This command creates vrt files.
gdal_translate -of VRT NETCDF:"$loc_t$name.nc":nav_lon $loc_t/v1/lon.vrt
gdal_translate -of VRT NETCDF:"$loc_t$name.nc":nav_lat $loc_t/v1/lat.vrt
gdal_translate -of VRT NETCDF:"$loc_t$name.nc":CHL $loc_t/v1/name.vrt
echo "Created vrt files"

######edit vrt########
# edit name.vrt
sed -i.bak -e '2,47d' $loc_t/v1/name.vrt
sed -i.bak -e '7d' $loc_t/v1/name.vrt
sed -i.bak -e '13,32d' $loc_t/v1/name.vrt

#edit lat.vrt
sed -i.bak -e '2,33d' $loc_t/v1/lat.vrt
sed -i.bak -e '3,12d' $loc_t/v1/lat.vrt
sed -i.bak '1 a <SRS>GEOGCS["WGS 84",DATUM["WGS_1984",SPHEROID["WGS
     84",6378137,298.257223563,AUTHORITY["EPSG","7030"]],TOWGS84[0,0,0,0,0,0,0],AUTHORITY["EPSG","6326
     "]],PRIMEM["Greenwich",0,AUTHORITY["EPSG","8901"]],UNIT["degree",0.0174532925199433,AUTHORITY["EP
```

```
    SG","9108"]],AUTHORITY["EPSG","4326"]]</SRS>' $loc_t/v1/lat.vrt
sed -i.bak -e '3d' $loc_t/v1/lat.vrt
sed -i.bak '1 a <VRTRasterBand dataType="Float32" band="1">' $loc_t/v1/lat.vrt

# edit lon.vrt
sed -i.bak -e '2,33d' $loc_t/v1/lon.vrt
sed -i.bak -e '3,12d' $loc_t/v1/lon.vrt
sed -i.bak '1 a <SRS>GEOGCS["WGS 84",DATUM["WGS_1984",SPHEROID["WGS
    84",6378137,298.257223563,AUTHORITY["EPSG","7030"]],TOWGS84[0,0,0,0,0,0,0],AUTHORITY["EPSG","6326
    "]],PRIMEM["Greenwich",0,AUTHORITY["EPSG","8901"]],UNIT["degree",0.0174532925199433,AUTHORITY["EP
    SG","9108"]],AUTHORITY["EPSG","4326"]]</SRS>' $loc_t/v1/lon.vrt
sed -i.bak -e '3d' $loc_t/v1/lon.vrt
sed -i.bak '1 a <VRTRasterBand dataType="Float32" band="1">' $loc_t/v1/lon.vrt
echo "Edited vrt files"

########gdalwarp#########
#The edited vrt the files are now used to create a tiff that is projected in EPSG 4326. With a
    resolution of 0.0090437173 degrees (-tr)
gdalwarp -srcnodata 9969209968386869000000000000000000000.000000 -dstnodata
    9969209968386869000000000000000000000.000000 -geoloc -t_srs epsg:4326 $loc_t/v1/name.vrt
    $loc_t/v2/$name.tiff
echo "Finished creating reprojected tiff"

####delete files########
rm -f $loc_t/v1/name.vrt
rm -f $loc_t/v1/name.vrt.bak
rm -f $loc_t/v1/lon.vrt
rm -f $loc_t/v1/lat.vrt
rm -f $loc_t/v1/lon.vrt.bak
rm -f $loc_t/v1/lat.vrt.bak
```

Import

This step imports all created tiff files into grass for further processing.

```
!/bin/bash
r.in.gdal -o --overwrite --quiet -l input=$file output=$(basename $file .tiff)
```

Calculate statistics

Here 24 maps are created describing the mean and standard deviation of each month.

```
!/bin/bash
echo "calculate statistics"
# here a set is created for all rasters that have a name corresponding to a month and an average and
    standard deviation map are created.

r.series input="`g.list type=raster pattern='*_01' sep=,`" output=01_M,01_Stddev method=average,stddev
r.series input="`g.list type=raster pattern='*_02' sep=,`" output=02_M,02_Stddev method=average,stddev
r.series input="`g.list type=raster pattern='*_03' sep=,`" output=03_M,03_Stddev method=average,stddev
r.series input="`g.list type=raster pattern='*_04' sep=,`" output=04_M,04_Stddev method=average,stddev
r.series input="`g.list type=raster pattern='*_05' sep=,`" output=05_M,05_Stddev method=average,stddev
r.series input="`g.list type=raster pattern='*_06' sep=,`" output=06_M,06_Stddev method=average,stddev
r.series input="`g.list type=raster pattern='*_07' sep=,`" output=07_M,07_Stddev method=average,stddev
r.series input="`g.list type=raster pattern='*_08' sep=,`" output=08_M,08_Stddev method=average,stddev
r.series input="`g.list type=raster pattern='*_09' sep=,`" output=09_M,09_Stddev method=average,stddev
r.series input="`g.list type=raster pattern='*_10' sep=,`" output=10_M,10_Stddev method=average,stddev
r.series input="`g.list type=raster pattern='*_11' sep=,`" output=11_M,11_Stddev method=average,stddev
r.series input="`g.list type=raster pattern='*_12' sep=,`" output=12_M,12_Stddev method=average,stddev

echo "Finished calculating statistics"

###resample
# Here all empty areas are filled based on the pixels with values closest to them. This happes because
    the edges of the mask used do not correspond a 100% with the maps used.

r.fillnulls input=01_M output=01_M2 method=bilinear
r.fillnulls input=02_M output=02_M2 method=bilinear
r.fillnulls input=03_M output=03_M2 method=bilinear
r.fillnulls input=04_M output=04_M2 method=bilinear
r.fillnulls input=05_M output=05_M2 method=bilinear
r.fillnulls input=06_M output=06_M2 method=bilinear
```

```
r.fillnulls input=07_M output=07_M2 method=bilinear
r.fillnulls input=08_M output=08_M2 method=bilinear
r.fillnulls input=09_M output=09_M2 method=bilinear
r.fillnulls input=10_M output=10_M2 method=bilinear
r.fillnulls input=11_M output=11_M2 method=bilinear
r.fillnulls input=12_M output=12_M2 method=bilinear

r.fillnulls input=01_Stddev output=01_Stddev2 method=bilinear
r.fillnulls input=02_Stddev output=02_Stddev2 method=bilinear
r.fillnulls input=03_Stddev output=03_Stddev2 method=bilinear
r.fillnulls input=04_Stddev output=04_Stddev2 method=bilinear
r.fillnulls input=05_Stddev output=05_Stddev2 method=bilinear
r.fillnulls input=06_Stddev output=06_Stddev2 method=bilinear
r.fillnulls input=07_Stddev output=07_Stddev2 method=bilinear
r.fillnulls input=08_Stddev output=08_Stddev2 method=bilinear
r.fillnulls input=09_Stddev output=09_Stddev2 method=bilinear
r.fillnulls input=10_Stddev output=10_Stddev2 method=bilinear
r.fillnulls input=11_Stddev output=11_Stddev2 method=bilinear
r.fillnulls input=12_Stddev output=12_Stddev2 method=bilinear

######Export intermediate files#####
echo "export statistics"
#Here the mean and stdev are exported in float 32 tiff raster format to the v3 Folder.
r.out.gdal --overwrite --quiet -c type=Float32 -f format=GTiff input=01_M2
      output=$loc_t/v3/'01_M.tiff'
r.out.gdal --overwrite --quiet -c type=Float32 -f format=GTiff input=02_M2
      output=$loc_t/v3/'02_M.tiff'
r.out.gdal --overwrite --quiet -c type=Float32 -f format=GTiff input=03_M2
      output=$loc_t/v3/'03_M.tiff'
r.out.gdal --overwrite --quiet -c type=Float32 -f format=GTiff input=04_M2
      output=$loc_t/v3/'04_M.tiff'
r.out.gdal --overwrite --quiet -c type=Float32 -f format=GTiff input=05_M2
      output=$loc_t/v3/'05_M.tiff'
r.out.gdal --overwrite --quiet -c type=Float32 -f format=GTiff input=06_M2
      output=$loc_t/v3/'06_M.tiff'
r.out.gdal --overwrite --quiet -c type=Float32 -f format=GTiff input=07_M2
      output=$loc_t/v3/'07_M.tiff'
r.out.gdal --overwrite --quiet -c type=Float32 -f format=GTiff input=08_M2
      output=$loc_t/v3/'08_M.tiff'
r.out.gdal --overwrite --quiet -c type=Float32 -f format=GTiff input=09_M2
      output=$loc_t/v3/'09_M.tiff'
r.out.gdal --overwrite --quiet -c type=Float32 -f format=GTiff input=10_M2
      output=$loc_t/v3/'10_M.tiff'
r.out.gdal --overwrite --quiet -c type=Float32 -f format=GTiff input=11_M2
      output=$loc_t/v3/'11_M.tiff'
r.out.gdal --overwrite --quiet -c type=Float32 -f format=GTiff input=12_M2
      output=$loc_t/v3/'12_M.tiff'

####stddev
r.out.gdal --overwrite --quiet -c type=Float32 -f format=GTiff input=01_Stddev2
      output=$loc_t/v3/'01_Stddev.tiff'
r.out.gdal --overwrite --quiet -c type=Float32 -f format=GTiff input=02_Stddev2
      output=$loc_t/v3/'02_Stddev.tiff'
r.out.gdal --overwrite --quiet -c type=Float32 -f format=GTiff input=03_Stddev2
      output=$loc_t/v3/'03_Stddev.tiff'
r.out.gdal --overwrite --quiet -c type=Float32 -f format=GTiff input=04_Stddev2
      output=$loc_t/v3/'04_Stddev.tiff'
r.out.gdal --overwrite --quiet -c type=Float32 -f format=GTiff input=05_Stddev2
      output=$loc_t/v3/'05_Stddev.tiff'
r.out.gdal --overwrite --quiet -c type=Float32 -f format=GTiff input=06_Stddev2
      output=$loc_t/v3/'06_Stddev.tiff'
r.out.gdal --overwrite --quiet -c type=Float32 -f format=GTiff input=07_Stddev2
      output=$loc_t/v3/'07_Stddev.tiff'
r.out.gdal --overwrite --quiet -c type=Float32 -f format=GTiff input=08_Stddev2
      output=$loc_t/v3/'08_Stddev.tiff'
r.out.gdal --overwrite --quiet -c type=Float32 -f format=GTiff input=09_Stddev2
      output=$loc_t/v3/'09_Stddev.tiff'
r.out.gdal --overwrite --quiet -c type=Float32 -f format=GTiff input=10_Stddev2
      output=$loc_t/v3/'10_Stddev.tiff'
r.out.gdal --overwrite --quiet -c type=Float32 -f format=GTiff input=11_Stddev2
      output=$loc_t/v3/'11_Stddev.tiff'
r.out.gdal --overwrite --quiet -c type=Float32 -f format=GTiff input=12_Stddev2
      output=$loc_t/v3/'12_Stddev.tiff'
echo "finished exporting statistics"
```

ANNEX II

References for species thresholds

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