Ocean and Coastal Management 203 (2021) 105447

Contents lists available at ScienceDirect

Ocean and Coastal Management

journal homepage: http://www.elsevier.com/locate/ocecoaman

Web-based public decision support tool for integrated planning and management in aquaculture

Aline Gangnery[a,b,*], Cédric Bacher[b], Adele Boyd[c], Hui Liu[d], Junyong You[e], Øivind Strand[f]

[a] Ifremer, LITTORAL, F-14520, Port-en-Bessin, France
[b] Ifremer, DYNECO, F-29280, Plouzané, France
[c] Agri-Food and Biosciences Institute, Fisheries and Aquatic Ecosystems Branch, Newforge Lane, Belfast, BT9 5PX, Northern Ireland
[d] Yellow Sea Fisheries Research Institute, Chinese Academy of Fishery Sciences, Qingdao, 266071, China
[e] Norwegian Research Centre AS, Fantoftvegen 38, 5072, Bergen, Norway
[f] Institute of Marine Research, PO Box 1870 Nordnes, 5817, Bergen, Norway

ARTICLE INFO

Keywords:
Marine spatial planning
Geographic information system
Stakeholder consultation
Indicators

ABSTRACT

The development of spatial planning and management approaches is required to increase the space available for aquaculture production and to support the increasing global demand for food resources. During a European funded project, a large consultation exercise highlighted that stakeholder involvement is a necessity for successful planning and must be a continuous process as part of the development of a decision-making tool. In this study we present a decision support tool built on a web based dynamic interface to Geographic Information Systems which facilitates access to information related to site selection, environmental interactions and management in aquaculture. It is derived from the AkvaVis concept and uses interactive functions that instantly display the results of spatial parameters chosen by the user. We adapted the tool for use within four case studies which deal with very different scales of aquaculture and issues related to aquaculture in four different countries. The key strengths of our tools relate to their capacity to manage and display spatial data from different sources in a transparent way, the ability to use and display a series of built-in indicators, and the long-term development potential made possible by the maintenance strategy of the tools, services and data depository. Consultations and meetings provided an accurate view of stakeholder expectations as well as feedback on the tool development and applicability, therefore helping the tool to meet the prerequisite for operational decision-making tools.

1. Introduction

Aquaculture is expected to be a key solution to the anticipated increased contribution from the marine environment to the future global demand for food resources (SAPEA, 2017). Such an endeavor will require the development of adapted approaches to planning and management at local, regional and transnational levels. Aquaculture production depends on the local environment as well as social, regulatory and economic constraints, which are often poorly understood and not fully considered (Rennie, 2002). As outlined by Corner et al. (2018), the combination of these factors can make the difference between a successful or unsuccessful initiative. The difficulty in implementing effective aquaculture development plans stems from a lack of available information and data on the suitability and availability of space, which has led to the aquaculture sector growing slower than expected in many regions (Brugere et al., 2010). Hofherr et al. (2015) recently found that most of the European (EU) finfish production by volume covers a total of 630 ha, with aquaculture only occupying 3% of EU coastline. They presented evidence that competition for space at a local level with other economic activities, such as tourism, limited growth. Tlusty et al. (2018) estimated that a very small portion of the Gulf of Maine had space characterized as low use that would permit aquaculture siting and suggested that cooperation with existing users will be necessary to support aquaculture expansion. Hersoug (2013) demonstrated how competition for space in Norway acts within a complex management framework at national, regional and local levels. For example, the technological developments that have facilitated the relocation of salmon farms to more exposed and productive sites have resulted in a decrease in number of sites from almost 2000 in 1999 to below 1000 in 2011. Nevertheless, competition for space with other users has

* Corresponding author.
E-mail address: Aline.Gangnery@ifremer.fr (A. Gangnery).

https://doi.org/10.1016/j.ocecoaman.2020.105447
Received 24 May 2020; Received in revised form 4 September 2020; Accepted 8 November 2020
Available online 24 November 2020

increased.

Based on a global analysis of the drivers of aquaculture development in the Mediterranean and Black seas, Corner et al. (2018) highlight the need for improved coastal management which supports the implementation of efficient strategies and plans to increase space for aquaculture whilst improving the communication, understanding and participation of relevant stakeholders and maintaining the sustainability of marine systems. More generally, the exploitation of the coastal zone is increasing with new activities, stakeholders and interests, resulting in a complex set of environmental and socio-economic interactions. To cope with management issues, comprehensive frameworks have been introduced such as integrated coastal zone management, biodiversity maintenance, marine spatial planning (MSP), marine functional zoning (MFZ) and ecosystem based management (Soto et al., 2008; Borja et al., 2010; Aguilar-Manjarrez et al., 2010; Feng et al., 2016; Pınarbaşı et al., 2017; Bacher et al., 2019). MSP (EC, 2014; Pınarbaşı et al., 2017) and MFZ (Feng et al., 2016) provide solutions to spatial conflicts and inter-sectorial requirements. MSP aims to balance the development of maritime activities and increase cross-border cooperation through transparency, clearer legislation, better coordination between administrations, and the early identification of impacts that can arise from the multiple uses of marine space (EC, 2014). At local scales, MSP promotes a public process in the planning of spatial and temporal use of the marine environment, where both ecological and socio-economic issues are usually specified through a political process (Pınarbaşı et al., 2017). MSP would therefore minimize the potential conflicts between stakeholders, improve the licensing procedure, attract investors, maintain ecosystem functions and services and result in a long-term strategy of coastal development (Meaden et al., 2016). In China, the MFZ scheme is aiming to better utilize marine resources and to protect the marine environment (Feng et al., 2016). The current MFZ scheme (2011–2020) for the first time identifies goals for the quantification and increased capacities for comprehensive marine management. Feng et al. (2016) analysed the implementation processes, suggested adjustments to improve the scheme and addressed future revisions.

Implementation of spatial planning and management processes like MSP should be continuous, iterative, participatory, and comprise a set of actions including, but not limited to; research, analysis and planning, financing, monitoring, and evaluation of the plan (see Pınarbaşı et al., 2017). During such a process, users and stakeholders need access to a wide range of information. This information may be of varied scales (individual, local, regional, global) and dimensions (such as, physical, ecological, economic, social/cultural, and management) (Melbourne-Thomas et al., 2017). Tools are also needed to make the processes more efficient, effective and sustainable. Stelzenmüller et al. (2013) reviewed several decision support tools and identified three categories of tools based on their usages. In addition, Coleman et al. (2011) compared existing tools with respect to a series of functions needed to facilitate planning. In all these examples, the management of spatial data, stakeholder engagement and management options are the main components of tools, which are essential to support decision-making with respect to marine planning.

Several decision support tools have been developed to address different issues in relation to the management of aquaculture activities, although there are very few examples of these tools being implemented (Ervik et al., 1997; Kapetsky and Aguilar-Manjarrez, 2007; Ferreira et al., 2007; Corner et al., 2018). Corner et al. (2018) recorded the increasing use of geographic information systems (GIS), remote sensing and mapping as useful tools for zoning, site selection and area management, but noted that there is still a need to improve the ways in which spatial tools can support aquaculture development and spatial management.

In this study we present a concept initially designed as part of the development of a comprehensive aquaculture management approach in Norwegian aquaculture, where demand was identified for improving accessibility and integration of environmental and regulatory information in site selection, spatial planning and licensing (Ervik et al., 2008). The resulting tool named AkvaVis, uses GIS maps and thematic layers with the addition of an interactive function where choices relating to spatial parameters can be made by the user and the tool instantly displays the requested information. The first version for demonstration included a dynamic interface between the user and an integrated system of data compilation, model simulations, coastal zone development plans, regulatory framework analysis and assessments (Ervik et al., 2008; Ferreira et al., 2012).

Since MSP is a participatory and continuous process, we also invited stakeholders at various stages of the adaptation and implementation of AkvaVis. On this basis, we present four case studies (CS) which differ with respect to aquaculture scales and issues, management frameworks and perceptions by stakeholders. This analysis is part of the toolbox developed within the EU project Ecosystem Approach to making Space for Aquaculture (AQUASPACE, 2015–2018) which aimed at understanding spatial and socio-economic constraints on the expansion of aquaculture, and at testing tools to help overcome these constraints. The experience gained in adapting general concepts to local contexts helped us to analyse the pros and cons of our approach. More specifically, we assessed the requirements for making the tool useful for marine spatial planning. This whole process is summarised in the flowchart presented in Fig. 1.

2. Material and methods

The AkvaVis tool has been adapted and expanded upon to enable its application within different national management frameworks and environments. During the course of the AQUASPACE project, our case studies were also part of a global survey with thirteen other regions covering a variety of aquaculture activities and countries (Galparsoro et al., 2020). Stakeholder consultation allowed the determination of the key issues regarding aquaculture growth and produced recommendations on how to manage aquaculture more effectively. The case studies have been compared and analysed within a series of tables (Appendix A) to identify the current stage of implementation related to the conceptual idea, gaps and perspectives for future development of the tool. Table A1 gives a brief overview of aquaculture activities within each CS including current policy regarding this sector and stakeholders involved in its management. Table A2 synthesizes the main aquaculture issues (partially based on stakeholder consultation). Issues were categorized according to four themes as defined in Galparsoro et al. (2020): policy/management, environmental, conflict with other sectors, and society and economic/market issues. Table A3 describes geographic, socio-economic and governance and regulations features of the CS as well as data integrated within the respective tools. Table A4 summarizes the purpose of the tool in each CS and the indicators developed.

2.1. Hardangerfjord CS

In Norway, salmonid farming has grown to become one of the country's largest export industries by economic value and is of significant social importance in many regions (Table A1). The Hardangerfjord is located on the western coast and holds one of the highest production nationwide. This area contains environmental challenges and spatial conflicts, which is common to the main national issues that determines policy and management for development of the industry (Table A2; Sandvik et al., 2016). The physical and biological characteristics of the fjord (Table A3) show large spatial and temporal variability mainly due to the many fjord arms with freshwater input, the advective process with the coast and the large depths (Asplin et al., 2014). Aquaculture planning processes are regulated at both municipally (case study scale), regional and national level. Governmental aquaculture policy involves planning processes for the allocation of space for aquaculture, and an ongoing management regime of regulating production based on impact from salmon lice on the wild salmon (Sandvik et al., 2016; Anon, 2015).

Case studies	Hardangerfjord	Carlingford Lough	Normandy	Sanggou Bay
Aquaculture species & development trend	Atlantic salmon → Rainbow trout →	Pacific oyster → Blue mussel →	Pacific oyster ↘ Blue mussel ↗ Atlantic salmon →	Kelp → Pacific oyster → Scallop →
Main aquaculture issues	• Improve knowledge-based decision making • Reduce salmon-lice, escapes and disease transmission • Potential conflicts for space	• Complex managements issues due to trans-boundary nature of site • Need to improve/ maintain water quality	• Improve water quality and reduce disease outbreaks • Usage conflicts with civil society (salmon production) • Need to develop an eco-aware industry	• Reduce culture areas whilst maintaining outputs • Improve nutrient balances within the bay • Conflict for space with fisheries and tourism
Stakeholder consultation	Long-term engagement with stakeholders helped to shape the evolution of the tool	Small and regular meetings with local stakeholders to ensure their engagement	2 workshops with various stakeholders helped to update a first version of the tool	3 workshops helped to specific technical questions
Tool purpose & functions	• Spatial data display • Web-based functions (all case studies)			
	• Site selection based on exposure and regulatory distances • Risk assessment based on salmon lice dispersion • PDF report	• Site selection based on environment and regulatory distances • Management tool for the operators of currently licensed aquaculture sites • PDF report	• Site selection based on environment and shellfish growth performances	• Site selection based on regulatory spatial plan • Site selection based on environmental suitability
Lessons learned	• Data should be easily accessible, multidimensional and cover a large range of topics • Analysis tools and functions should be flexible to enable adaptations and user oriented • Early and strong stakeholder involvement helps defining their expectations and testing the benefits of the tools for decision-making • Long-term process of tool adaptation and maintenance should be planned			

Fig. 1. Synthesis of the process followed during this study giving for each CS i) an overview of aquaculture (arrows indicate the trend of development for each species; see Table A1 and Section 2), ii) main aquaculture issues (see Table A2 for an exhaustive list), iii) stakeholder consultation (see Sections 3 & 4), iv) tool purpose and functions (see Tables A3 and A4) and vi) lessons learned (see Section 4).

2.2. Carlingford Lough CS

Marine aquaculture within Northern Ireland is currently dominated by shellfish production. Subtidal aquaculture within Carlingford Lough involves the bottom culture of the blue mussel, whilst intertidal aquaculture occurs predominantly in the form of off-bottom (trestle) culture of the Pacific oyster (Table A1). Carlingford Lough is a sea lough at the mouth of the Newry (or Clanrye) River on the east coast of Ireland, bordering both the Republic of Ireland (County Louth) and Northern Ireland (Counties Down and Armagh). As a trans-boundary water body, Carlingford Lough has a range of regulatory and management issues which are further compounded by the multiple users of the Lough. One such example is the spatial conflict between aquaculture and nature conservation (Table A2).

The upper reaches of the Lough are shallow and dominated by fine muddy sand and intertidal mud-flats, whilst the seaward entrance to the Lough is a mixture of boulder, cobble and bedrock forming numerous small islands and reefs (Table A3; Taylor et al., 1999; Mitchell and Service, 2004). Within the Northern Irish area of Carlingford Lough, the Department of Agriculture, Environment and Rural Affairs (DAERA), is responsible for the granting of fish culture licences, shellfish fishery licences and marine fish fishery licences under the Fisheries Act (Northern Ireland) 1966. In the Republic of Ireland area of Carlingford Lough, the Aquaculture and Foreshore Management Division of the Department of Agriculture, Food and the Marine (DAFM) is responsible for aquaculture licensing under the Fisheries (Amendment) Act, 1997. A mechanism for the synergistic management of the Lough between the two government departments is needed.

2.3. Normandy CS

Shellfish culture is a historical activity in France and represents the highest marine aquaculture production, with Normandy, being the second most productive region (Agreste, 2014). In recent years production of Pacific oysters has been impacted by regular mortality outbreaks whilst production of the blue mussel has increased in response to a high demand by French consumers (Table A1). Fish farming is limited but regional authorities actively promote its development. The maintenance of existing shellfish culture and the sustainable development of fish farming along with other usages are typical issues within this case study area (Table A2). This is particularly challenging because Normandy also represents a series of economic, cultural and environmental issues due to a large range of other activities competing for space (Table A3; AAMP, 2009). Normandy includes the Bay of Mont Saint-Michel (listed by UNESCO as world heritage) belonging to the Normand-Breton Gulf, and the Bay of Seine. These two areas are characterized by similar physical properties but also present some differences, for example there is a strong influence of freshwater runoff in the Bay of Seine, which results in a higher level of eutrophication (Table A3). The complexity of governance systems is due to the involvement of several administrations in charge of the regulation of sectoral policies (aquaculture licensing, protection and preservation of environmental areas) and the application of marine spatial planning at the national level (MEDDE, 2014).

2.4. Sanggou Bay CS

China's mariculture dominates global production and is significantly different from other countries in its diversified range of species and culture methods. Sanggou Bay is a major area for the culture of kelp, oysters and scallops (Table A1), located on the eastern tip of Shandong peninsula in northern China. In addition to species named above this area also produces around 2000 t of abalone, 100 t of sea-cucumber and 100 t of finfish. The aquaculture industry employs over 11 thousand people (data from the local Ocean and Fisheries Bureau) and generates 700 million USD (2016). Kelp (the main species) longline culture extends from inside Sanggou Bay to more than 8 km outside of the bay, reaching a water depth of 40 m. Due to the bathymetry and farming structures in the bay, the water exchange is reduced (Table A3). The local MFZ and the Marine Ecosystem Conservation Redline Systems (Red Line) identify conflicts between aquaculture and several other sectors such as tourism, urbanization, navigation and, fisheries (Table A2). Tourism has become a priority within the local development plan and there is now a requirement for the relocation of farms to 1000 m off the shoreline in Sanggou Bay. As a result, aquaculture within the inner bay may see a 10% reduction, and bottom culture may replace suspended longlines in some areas.

2.5. Tool description

AkvaVis is a decision support tool based on GIS that processes data relating to aquaculture management. The AkvaVis tool performs suitability analysis on proposed aquaculture areas through the utilization of a series of indicators and can create virtual farm objects to display and interact with models and environmental data. The tool provides a user-friendly interface and can produce reports of the analysis undertaken for use by a variety of users with differing requirements with regards to aquaculture management, for example governing bodies, farmers and researchers.

AkvaVis follows the Web Map Service (WMS) protocol providing geo-referenced map images within a web application. When implementing the tool, different programming languages were employed, including Java on the server side and Adobe flash (using action scripts), HTML and JavaScript on the client side. From the practical perspective, the following modules have been implemented:

- On the server side: WMS handler (e.g. map handling, data layer rendering), data management (e.g. data parser, analyser), virtual technology for creation of virtual objects (e.g. farms), visualization (e.g. drawing virtual objects with customized settings, drawing indicators), aquaculture models (e.g. growth of organisms, water current, particle dispersion), indicator analysis (e.g., calculating indicators by thresholding the environmental data at the selected farming location based on expert knowledge), Application Programming Interface (API) for easy integration into third-party applications and communication with client through standard WMS protocol;
- On the client side: user request handling (e.g., user interface to receive user demand for farming areas and farm setting) and communication with the server (e.g. sending the received user request to the server and displaying the results generated on the server).

The AkvaVis tool has been modified and applied to the case studies presented. The applications in the Hardangerfjord and Carlingford Lough CS implement almost the same functionalities. While AkvaVis development in Norway resulted from the initial versions (Ervik et al., 2008; Ferreira et al., 2012), the AkvaVis application for Carlingford Lough was developed through the AQUASPACE project. Geo-referenced data files (e.g., netCDF file, shape files) presenting environmental data (e.g., bathymetry, salinity, wave, sea current, existing farms) can be analysed by AkvaVis and displayed on the background map upon user selection. In order to facilitate spatial planning based on indicator analysis, AkvaVis utilizes virtual reality technology which permits users to create a virtual object (e.g. farm) at any location on the map by using functional buttons. Consequently, individual indicators customized by users will be derived based on the environment and other relevant data around the selected location and expert knowledge. For example, the water depth at the selected location, the distance from the location to adjacent aquaculture sites and/or facilities and conservation areas. An overall indicator which determines whether the selected location is a suitable site for a new farm can then be derived based on the weight of individual indicators. Users can also easily modify the settings of the virtual farm, e.g., size, species, shape, and location in AkvaVis. Suitability maps can be generated which indicate suitable space for siting new aquaculture farms based on user defined criteria. Reports which present information about the suitability analysis, e.g., farm settings, location, environment and other available data can then be generated. Whilst the AkvaVis applications for the Hardangerfjord CS and Carlingford Lough CS utilize similar functionalities, different data and consequently the indicator analyses used are different (see Table A4). In this case, a minor modification is required in AkvaVis to reflect such differences between the case studies, e.g., different indicators have been defined with support from different data sources.

Within the Normandy CS the original AkvaVis tool was used as a basis for the development of the Spatial Information System for AQUAculture (SISAQUA) tool. SISAQUA was progressively moved to a platform hosted by Ifremer thanks to the technical facilities that guarantee the maintenance and durability of the application. SISAQUA was then implemented within a spatial data infrastructure for marine environments developed by Ifremer to manage, share and retrieve geographical marine information and synthesize homogeneous marine data for various end-users (Sextant, https://sextant.ifremer.fr/en/). The various technologies used by Sextant are compliant with the Inspire Directive (https://inspire.ec.europa.eu/). This European directive aims to create a spatial data infrastructure for the purposes of EU environmental policies and policies or activities, which may have an impact on the environment. Sextant meets internationally recognized standards from the International Organization for Standardization (ISO) and the Open Geospatial Consortium (OGC) and is interoperable with all geographic information portals. SISAQUA kept all basic functionalities of the original AkvaVis tool such as data visualization and the display of external WMS layers through a web interface. The use of virtual technology through the creation of virtual farms was not included within SISAQUA but new functionalities were added such as a catalogue for metadata and downloading services. A specific module was developed to allow online treatment of georeferenced data and calculation of indicators, through Web Processing Services (WPS) scripts.

The APDSS (Aquaculture Planning Decision Support System) tool was developed for the Sanggou Bay CS in the project Study on Ecosystem-based Aquaculture Spatial Planning, supporting the Chinese partnership in the AQUASPACE project. It is based on a multidisciplinary approach covering ecology, physical oceanography and geographical informatics technology, developed on the ArcGIS Engine. APDSS implements several functionalities including aquaculture data management and suitability assessment, a growth module for cultured organisms, carrying capacity evaluation, physical oceanographic hydrodynamic model and cost-benefit evaluation for aquaculture farms. The AkvaVis tool was used as a basis for the development of APDSS, even though there are important differences between the two tools. Currently there are two versions of APDSS: a standalone application driven by user interaction which must be installed on users' PC, and a web-based application. Different data sources are systematically integrated into APDSS, e.g., survey data from research vessels, laboratory data, and hydrodynamic model data. The survey data can be compared with the physical parameters from the hydrodynamic models, and measured growth data of kelp can be compared with simulations within the individual growth model. Users can retrieve data for different environmental parameters and dates, such as temperature and velocity.

3. Results

3.1. Hardangerfjord CS

AkvaVis was developed for the Hardangerfjord due to the regional focus on aquaculture environmental interactions and the availability of data (Table A3). The tool was designed to target primarily municipal authorities, regional management and industry planning their potential sites. A user survey was carried out to evaluate a conceptual AkvaVis version (Hageberg, 2008). Interviews and test trials with potential users from four regional counties (79 people were interviewed and 12 people undertook the test trial) revealed limitations (available data, information transparency) and opportunities (integration with other data sources, user-friendly, stakeholder interaction) for the tool development. A project steering group for the development of AkvaVis provided technical and research expertise, and stakeholder workshops were held with target users and local and regional planners, to evaluate the usefulness of the tool.

The tool has three indicators, exposure to waves and currents, salmon lice “pressure” and local suitability (Fig. 2, Table A4). There are six thematic sublayers on currents displaying statistical representation from 60 days at two depths (1 and 10 m). These current layers combined with wave height and direction (50 years hindcast data) (Fig. 2A) are the crucial parameters indexing forces related to exposure at the site. The salmon lice “pressure” layer is a spatial visualization of the relative concentrations of salmon lice (infectious copepodites) released from farm sites (13 pre-simulated positions) selected by the user (Fig. 2B). After 60° days of dispersion, the 5% proportion of the area with highest relative concentrations of copepodites was given the value 100 and all other areas are given proportions of the maximum. From this maximum concentration, the area with 35% of the maximum was given a red colour indicating highest risk of infectious copepodites. Wave height and currents are regarded as regional indicators of suitability and AkvaVis displays these parameters as absolute values. A virtual farm can be inserted at any location on the map and its local suitability indicators have thresholds for suitable depth at a site, minimum distance to sewage outfalls and other aquaculture farms (Fig. 2C and D). AkvaVis displays these parameters using traffic light colours according to the given thresholds for acceptable (green), unacceptable (red) and under consideration (yellow). An overall indicator of local suitability is produced based on the weighting of these three parameters. A second user survey on this final version focused on accessibility, functionality, indicator interpretation and improvements. Reports from four users (representing the industry and management organisations) generally

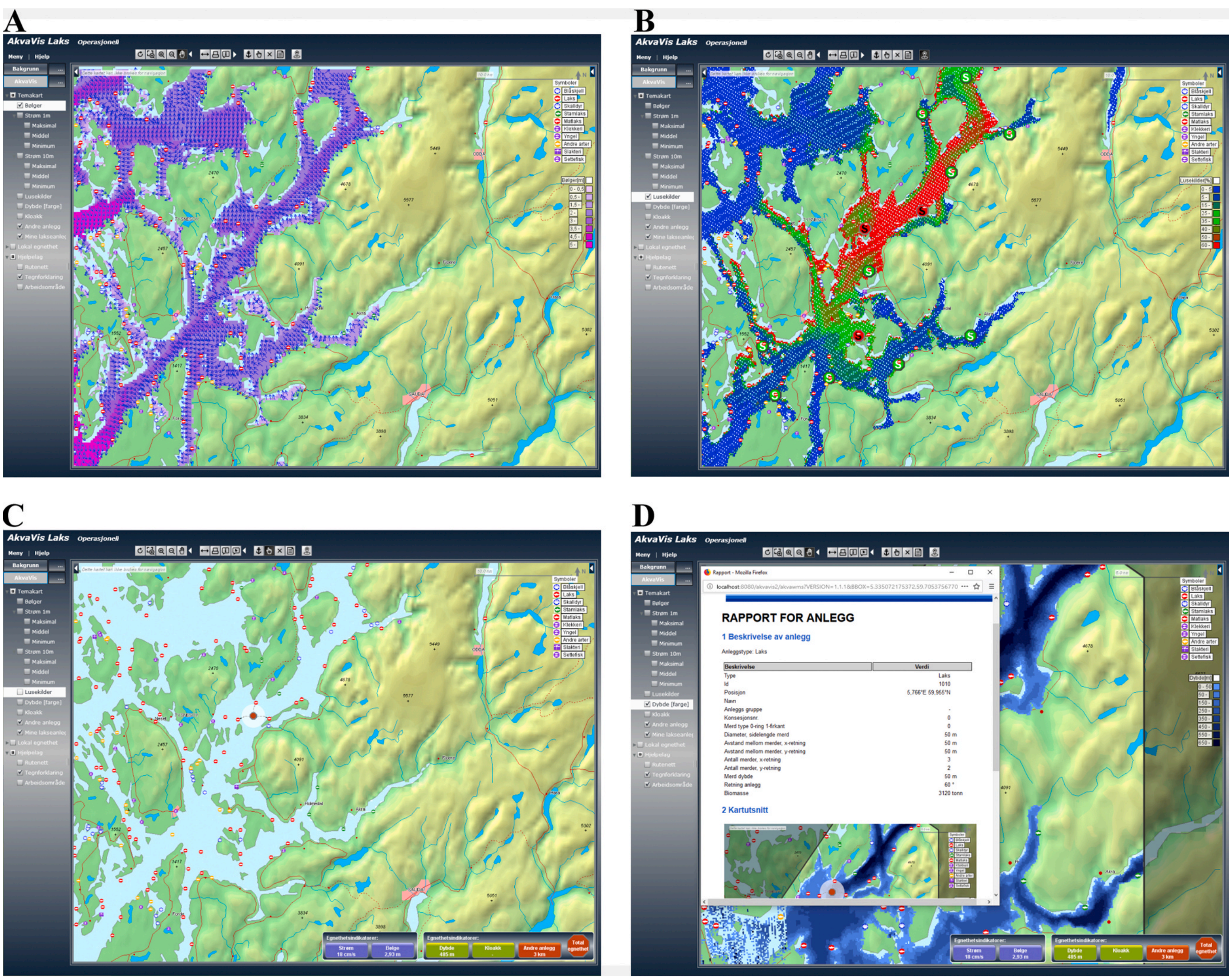

Fig. 2. Screen displays from the Hardangerfjord CS. A. AkvaVis visualization of wave direction indicated by arrows and wave height with colour scale legend on the lower right side. Existing aquaculture locations are selected with legend for species and type on the upper right side. Salmon farms are red dots with a fish outline. B. The salmon lice “pressure” layer with visualization of the red area representing the 35% of the highest accumulated relative concentrations, given release of salmon lice from the red dots with a black S. The green dots with S are pre-simulated positions with salmon lice dispersion results (red dots are selected). C. A virtual farm inserted is labeled by a red dot with a white halo. Suitability indicators are visualized on the bottom right side. Currents and wave height (in blue blocks) are regarded as regional indicators given as absolute values. Suitability indicators with traffic light colours shows that depth and distance to sewage is acceptable, while distance to other farm(s) is unacceptable, the farm(s) identified by stippled lines between farms on the map. The overall indicator of local suitability (hexagon) is red, in this case due to the decisive distance to other farms. D. By selecting a location (red dot with a fish outline) a report option will give a description of farm dimensions, data on position, orientation and biomass. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

praised accessibility and functionality, indicated challenges on the interpretation of salmon lice "pressure" indicator and suggested an extended data display for currents and wave height.

3.2. Carlingford Lough CS

The AkvaVis demonstrator model for Carlingford Lough was established primarily to aid in the aquaculture licensing process. The aim was to provide a means for stakeholders (such as government bodies and aquaculture operators) to quickly and easily determine if an area was suitable for aquaculture development. Therefore, AkvaVis was developed as a risk analysis tool to enable the determination of the optimal location for new aquaculture sites within the CS area. Throughout the period of development regular engagement was undertaken with local stakeholders. This included meetings with local aquaculture producers and local government departments to gain an insight into the issues facing the aquaculture industry and to inform relevant inputs into the model. Upon its completion, the AkvaVis demonstrator model for Carlingford Lough was presented at a meeting of local government stakeholders, which included those responsible for aquaculture licensing and those responsible for designating sites of nature conservation importance.

Data layers within the current iteration of the model include bathymetry, salinity, nutrients, current aquaculture sites and marine protected area boundaries. A virtual farm can be inserted at any location on the map and thresholds have been set for suitable depth, culture technique, distance to conservation designated sites and sensitive species, and distance to currently licensed aquaculture sites (Table A4; Fig. 3A and B). Results are displayed as traffic light colours according to the given thresholds set for the parameters listed above. If the chosen site is deemed suitable based on a parameter it is displayed as green, if unsuitable it is displayed as red and if the site is considered suitable but with constraints it is displayed as orange. The outcome is presented as an information bar indicating the colour of each parameter. An overall suitability indicator is also specified based on weighting of the specified parameters giving the user an instant, easily interpreted result. The overall suitability indicator uses the precautionary principle. The model then produces a PDF report highlighting the results of the suitability of the proposed area for the type of rearing technique selected by the user (Fig. 3C and D).

3.3. Normandy CS

SISAQUA was designed to share information between a large panel of stakeholders and enlighten public debate. For scientists, it is a way to transfer data and knowledge. Both data and indicators utilised within SISAQUA were defined through a consultation process set up with main stakeholders involved in the case study area (Table A1). Two workshops were successively organized with the support of national authorities in charge of the management of marine and coastal activities in the region.

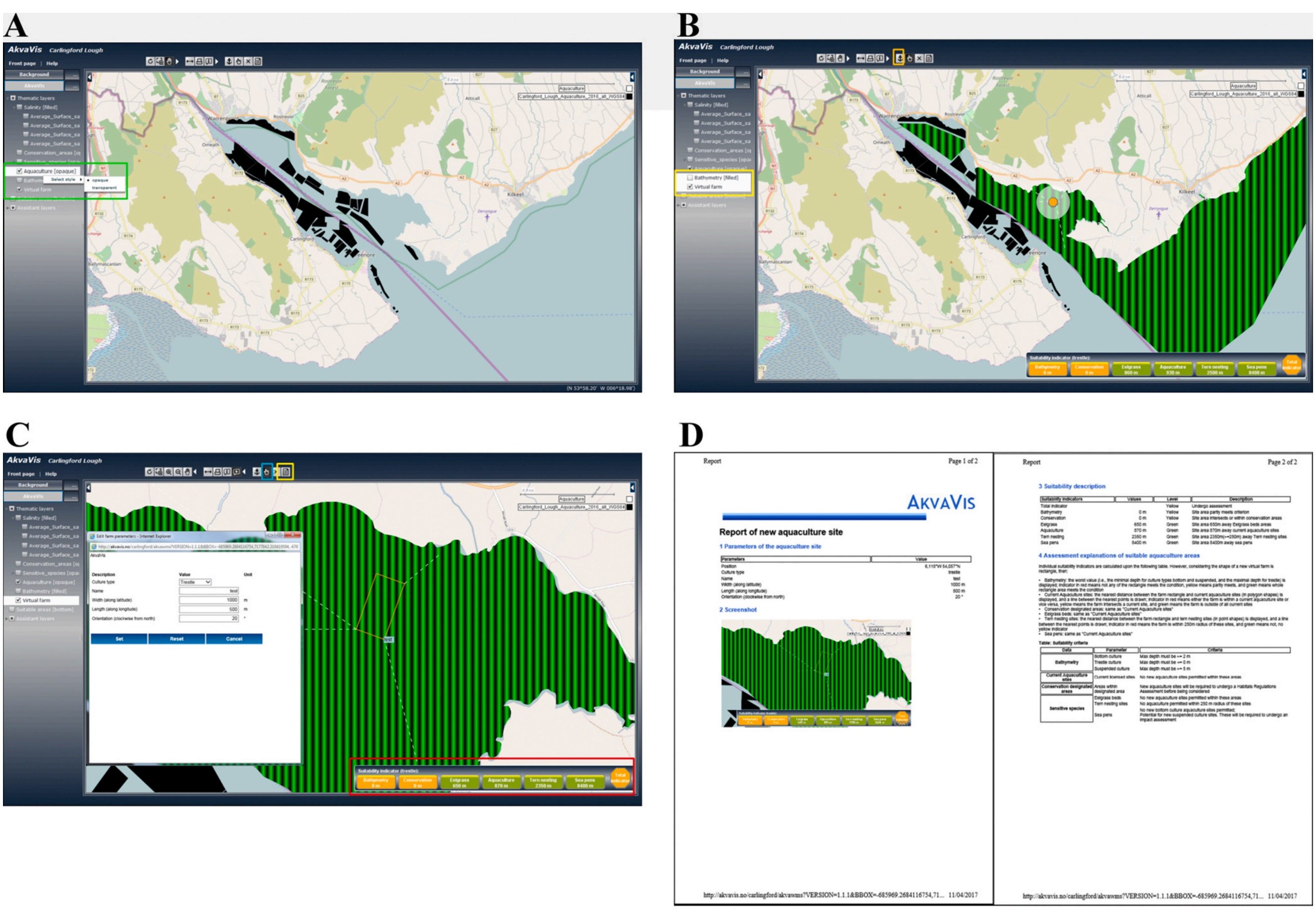

Fig. 3. Screen displays from the Carlingford Lough CS. A. AkvaVis Carlingford Lough visualization of existing aquaculture activities. The green box indicates the layer displayed and options for the layer style. B. Placement of a virtual farm is through the selection of this option as shown within the yellow box, then selecting the anchor icon (shown within the orange box). The user can then place the new virtual farm wherever they desire (shown as an orange dot on the map). C. By selecting the hand icon (blue box) and double clicking on the virtual farm the user can redefine the farm parameters and recalculate the suitability indicators accordingly (red box). The user can then select the report icon (shown in the yellow box). D. Results output report for a new virtual farm location. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

The objective of the first workshop (which was attended by 33 people) was to identify and prioritise information required to plan aquaculture activities. The second workshop (which was attended by 22 people) was dedicated to determining the indicators required to help with planning for both shellfish and fish culture sites.

Currently, 134 data layers are integrated into SISAQUA. These layers have been grouped into the following categories; i) environmental data for terrestrial, coastline and marine domains, ii) regulations on protected areas, iii) information on other usages, iv) water quality and v) information related to aquaculture activities (Table A4 and Fig. 4A and B). Seventy percent of the layers were obtained from organisations such as the French Ministry of Ecological and Solidarity Transition (http://www.geolittoral.developpement-durable.gouv.fr/). The other layers were developed as part of the AQUASPACE project and mainly concern marine environment and shellfish culture activities derived from numerical modelling or remote sensing. A hydrodynamic model of the Bay of Biscay – English Channel region provided the physical parameters (water temperature, salinity, currents) at a spatial resolution of 500 m (Ménesguen et al., 2019). Various statistics (percentiles 10, 90, mean) were computed on 3 depths (surface, bottom, vertical mean) for the period 2010–2015. A hydrodynamic model, centred on the Normandy region, provided mean wave heights for the period 2008–2012 at a spatial resolution of 200 m (Le Gendre et al., 2014). Chlorophyll *a* concentration and suspended matter came from remote sensing (MODIS/Aqua-MERIS/SeaWiFS; Saulquin et al., 2010; Gohin, 2011) and were averaged during the period 1998–2012. Seawater temperature and chlorophyll *a* were used as forcing functions of an ecophysiological model to assess bivalve growth performance (Alunno-Bruscia et al., 2011 for oysters and Thomas et al., 2011 for mussels). Four variables represent bivalve growth: shell length, dry flesh mass and condition index (ratio between total individual mass and flesh mass) obtained after a rearing cycle (March 1st-December 31st for oysters, August 1st year n – August 1st year n+1) and time to reach commercial size of 9.5 cm and 5.5 cm for oysters and mussels, respectively.

Three indicators were developed which are all based on the same approach (Table A4 and Fig. 4C and D). Several criteria, (fixed by the application), are combined with thresholds chosen by the user. Each criterion corresponds to a layer within the tool. The combination which determines suitable areas meeting chosen thresholds addresses several issues such as:

- To determine sites for optimal bivalve (oyster/mussel) growth performances: criteria (layers) used are shell length, condition index and bathymetry,

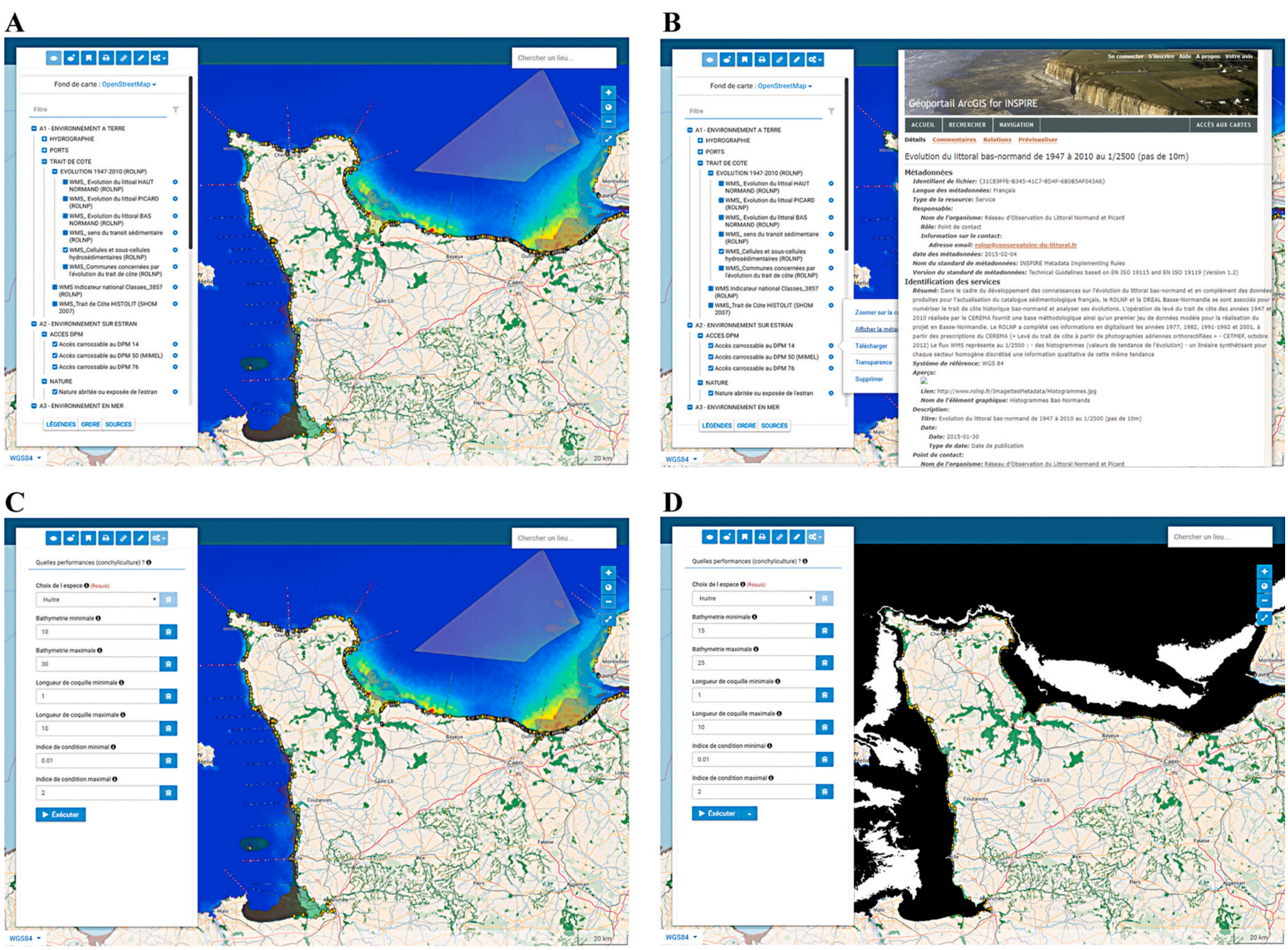

Fig. 4. Screen displays from the Normandy CS. A. SISAQUA visualization portal. On the left, layers are organized by themes (environment, protected areas, aquaculture and other usages) according a tree view. Many options are offered for each layer: layer zoom, metadata display and/or data downloading. B. When clicking on metadata, the user reaches a form summarizing several information related to the layer (contact point, type of spatial data, coordinate system, geographic extent, etc …). C. When clicking on the treatment module (gears button at the top menu), the user can choose between three pre-defined indicators. Each indicator is based on a pre-defined set of parameters. The user can select minimal and maximal values for each quantitative parameter and one type for qualitative parameters. D. When executing the indicator treatment, the result is a two-coloured map: white for suitable areas (i.e. meeting all values set by the user) and black for unsuitable areas.

- To choose specific rearing techniques (useable for both fish and shellfish): criteria used are current velocities, water temperature, bathymetry and type of substrate,
- To minimize the risk of parasitism within salmon culture: criteria used are salinity, bathymetry and type of substrate.

For each indicator the resultant output is a spatial visualization of the suitable area which meets the given thresholds. The final map can be downloaded in a tif format or through standard OGC-WMS/WCS format.

3.4. Sanggou Bay CS

The APDSS was designed to assist the local management authorities with respect to aquaculture spatial planning (re-planning), suitability assessments and the licensing process (Table A2), and for farmers to select the best location and suitable culture density when they undertake planning and management. Due to the heavy exploitation of sea space and high conflict in sea use in China, the tool aims to ensure policy and regulation conformity, environmental suitability and predicted output, rather than selecting locations for new farms. The data layers in APDSS are organized according to modules: 1) environmental data for terrestrial, coastal and marine domains, including field survey data and physical-oceanographic model data, 2) MFZ and Red Line, which are regulations on protected areas and other sea uses (Fig. 5A), 3) aquaculture suitability assessment, according to environmental conditions and physical-ecological requirements of respective species, 4) simulated growth of main aquaculture species, 5) information related to aquaculture activities (culture facilities, raft and longlines). Within APDSS three indicators were developed; regulatory suitability, environmental suitability, and site/area selection based on biological performance (Table A4). The latter consist of simulated growth of kelp, oysters and scallops according to length and weight during the farming cycles (Fig. 5B and C). Production capacity is calculated by simulated weight achieved at the end of the rearing cycle, estimated culture density (survey data) and the farming area (Fig. 5C). Environmental suitability for kelp is based on environmental variables assessed for the

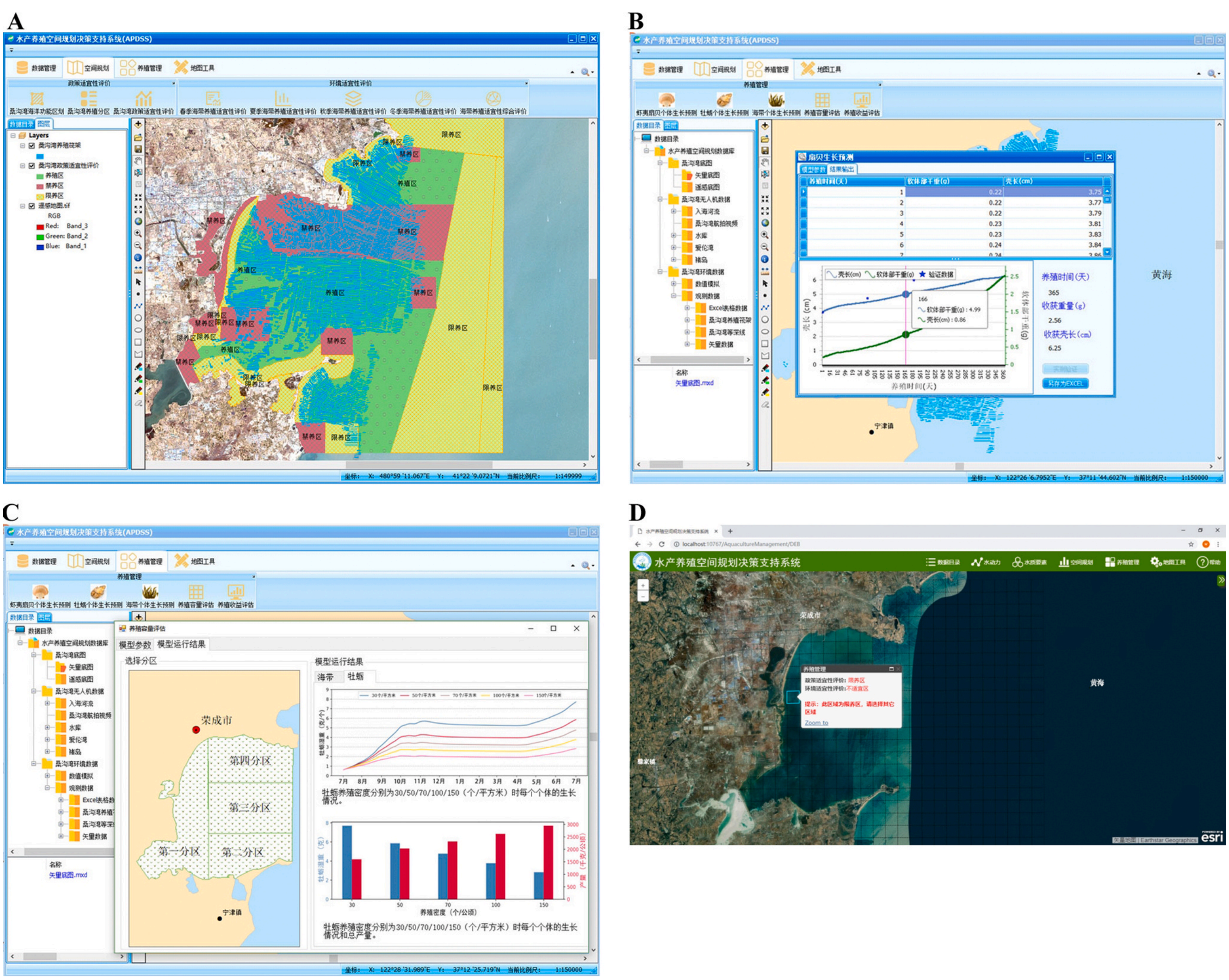

Fig. 5. Screen displays from the Sanggou Bay CS. A. APDSS visualization of layers showing the aquaculture zoning plan characterized under the Marine Functional Zoning and the Red Line System. Permitted aquaculture area (green), restricted aquaculture area (yellow), forbidden aquaculture area (red). Blue polygons indicate existing culture facilities (rafts and longlines). B. By selecting a location for scallop farming, a window displays simulated growth curve of an individual scallop given as length and dry weight and time (days) at harvest. Option to run simulation also by using own environmental parameters (temperature and Chl a). C. By selecting aquaculture species (kelp or oyster, in this case for oyster) in one of the four zones in Sanggou Bay, a window displays simulated growth curves of individuals (upper panel) and production yield (lower panel) for different culture densities (30, 50, 70, 100 or 150 ind/m^2). Production yield given as production (kg wet weight of soft parts per hectare) in red bars and individual growth in blue bars. D. By selecting a raster square area, the policy suitability and environmental suitability is displayed, and a total suitability is concluded based on weighting policy as restrictive and environmental as recommendation. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

physiological needs of growth and development. The current velocity and water temperature data were derived from the FVCOM model (Finite Volume Coastal Ocean Model) (Xuan et al., 2019), and represent the monthly averages in 2011. The irradiance was based on the average sea surface light intensity, calculated by the number of sunny days and the monthly sunshine duration (China Meteorological Administration Rongcheng City). Nutrients, Chl a, Particulate Organic Matter (POM) data and salinity were derived from quarterly field surveys in Sanggou Bay and the surrounding waters (April, August and October 2011 and January 2012). The resulting suitability score using traffic light colours (Table A4) is based on an assessment of scoring curve functions for the environmental variables (Sun et al., 2019).

The application allows the user to determine suitable areas (meeting regulatory requirements and fixed thresholds for environmental parameters) regarding regulatory conformity, environmental suitability for kelp, and growth performance of kelp, oysters and scallops within an area defined by the user (Fig. 5D).

Three workshops were held in Sanggou Bay with participation of 64 attendees representing the aquaculture industry, management and research institutions. Feedback from stakeholders at the workshops suggests that a science-based carrying capacity evaluation and spatial planning is vital to tackle the current productivity bottlenecks in Sanggou Bay. Ecosystem-based aquaculture planning is urgently needed for decision making in the industry, in order to maintain sustained output and profitability. Issues regarding project implementation plans and specific technical questions for developing APDSS were discussed.

4. Discussion

4.1. From tools to management

The four case studies represent decision support tools developed for areas with very different scales of aquaculture and a complex series of issues (Fig. 1). These tools differ in their operational stage of development with respect to applicability in management and spatial planning. Even though the tools have been adapted for specific local issues, stakeholder demands and user expectations, one common feature is that they facilitate access to information needed for assisting in site selection, assessing environmental interactions and the management of aquaculture within the framework of marine spatial planning. The operational demands from management which underline the concept of our tools were met through a public web-based interface, which is dynamic in the sense that it is adaptable to new knowledge, new regulatory frameworks, and requirements from industry and public and private stakeholders. This aligns with suggestions made by Coleman et al. (2011) that decision tools should be data-driven, efficient, explicit, transparent, and flexible, to meet ecosystem and resource use objectives, as well as to identify existing gaps in current management designations. Coleman et al. (2011) reviewed the functions of several planning tools and examined how these functions provide additional value over standard GIS analysis, namely, data access and delivery, design of the planning process and stakeholder engagement. In line with our own experience and lessons learned, we consider that the following four issues must be examined to determine a tools usefulness for management, namely: data access and management; analysis tools and functions; stakeholder involvement; and tool applicability, implementation and maintenance (Fig. 1). Below we analyse the main features of AkvaVis, SISAQUA and APDSS with respect to these issues, and highlight some differences between our tools and existing operational decision-making tools developed for aquaculture planning.

The AquaSpace tool displays a spatial representation of opportunities and risks of a proposed aquaculture site in marine areas exposed to multiple human activities and their respective pressures (Gimpel et al., 2018). It has been utilised within the German portion of the North Sea to assess the potential expansion of aquaculture of the European seabass and blue mussels. Bricker et al. (2016) described how they coupled a local carrying capacity model to an existing web-based mapping tool developed for decision-making to address the question of the potential for growth of the American oyster in predefined suitable areas. The BLUEFARM-2 tool was developed to identify suitable sites for shellfish culture in the Adriatic Sea (Brigolin et al., 2017). Different data were aggregated in a GIS and several scenarios of aquaculture development were tested using a Spatial Multi-Criteria Evaluation framework. Puniwai et al. (2014) developed a web-based tool for siting various aquaculture systems within the Hawaii archipelago. Their tool relies on the integration of various data as layers in a GIS, but the originality of the study was the strong integration of local stakeholders during the whole process of tool development. Finally, we also considered MarineMap which was designed to increase the coherence and effectiveness of marine protected area network and can contribute more broadly to future development of tools and approaches for coastal and marine spatial planning (Merrifield et al., 2013).

4.2. Data access and management

Data used within management tools should be multidimensional and cover a large range of topics including the physical and biological properties of the ecosystem studied, governance and regulatory systems, socio-economic activities/usages (including aquaculture) as well as the cultural aspects of the study area. The range of data used is also broad in terms of complexity, from raw data obtained through direct observation or measurement to more sophisticated data derived from mathematical models.

Availability of and accessibility to physical and biological data has increased in recent years through the development of operational portals like the Marine Environment Monitoring Service Copernicus in Europe (https://www.copernicus.eu/). Copernicus gathers oceanographic modelling and remote sensing data that are increasingly used in tools developed for aquaculture planning and management (Brigolin et al., 2017; Gimpel et al., 2018). However, these data are developed at a large scale and their spatial resolution could be poorly adapted to local needs (regional/aquaculture farm scale). Data analysis or the use of local numerical models may also be required in addition in some areas. The AquaSpace tool includes maps produced by WATER (Where can Aquaculture Thrive in Europe, http://www.longline.co.uk/water/), a web-based application developed to produce maps of regions (at the spatial resolution of the Exclusive Economic Zone) suitable for cultivation of aquatic organisms (Boogert et al., 2017). The tolerance and optimal ranges (for 13 parameters) of 45 species are included within WATER. The species thresholds database is linked to an environmental conditions database to produce suitability maps.

Human activities (e.g. aquaculture, maritime traffic in terms of route locations or intensity, dredge disposal sites and locations of anchorages or submarine cables) as well as governance and regulation systems (e.g. aquaculture licensed areas, sanitary quality of shellfish culture areas, marine protected areas) are often described through the space they occupy. For these aspects, the European portal EMODnet (http://www.emodnet.eu/) is a valuable resource which has already been utilised within some applications (Gimpel et al., 2018). Yet again, access to local data can be more appropriate. For instance, EMODnet shellfish culture areas are simply identified by a presence symbol whereas in SISAQUA, aerial images with a resolution of a few meters enable us to show and delimit precisely the space occupied by aquaculture. The Norwegian Yggdrasil web portal (https://yggdrasil.fiskeridir.no) which provides national data on coastal spatial planning, fisheries and aquaculture, allows for continuous updates of data at site and fish cage resolution.

Globally, these data help to answer the question: where can aquaculture activities be sited? Another question to address deals with the potential production these suitable sites can yield. Bricker et al. (2016) used the Farm Aquaculture Resource Management (FARM) model to estimate time taken for oyster seed to reach harvestable size by considering currents, available food, oyster density and farm dimensions. In Brigolin et al. (2017), individual models were up-scaled to the population level and coupled with a deposition model allowing estimations of the environmental footprint of shellfish farms (i.e. organic enrichment of surface sediment). In the Carlingford Lough CS, a FARM model is available but not yet implemented in AkvaVis. This could be an option for the future development of the tool. SISAQUA and APDSS include maps of oyster, mussel, scallop and kelp growth derived from an eco-physiological model. Simulations are made for one individual and do not consider density dependent processes. A more accurate output would require data related to trophic and ecological carrying capacity which is not fully developed within our tools.

4.3. Analysis tools and functions

The review of decision support tools undertaken by Coleman et al. (2011) highlights the variety of functions and technological backgrounds that make the tools operational and applicable. Accessibility and visualization by users are the basic features required for management tools. In MarineMap, geospatial data are centralized and accessible via a web browser. Visualization tools include classical panning, zooming, querying and identifying data layers and features in a 2 and 3 dimensional space. In AkvaVis and SISAQUA, data are accessible via a webserver through a client/server infrastructure. They are documented with a catalogue of metadata and several of them are automatically updated by the WMS and WFS facilities. Tools should also be thought of in terms of usability. In MarineMap, a great deal of attention was paid to the usability and responsiveness of the application through the development of a user interface that borrowed many conventions, lessons learned, and technologies from applications such as Google Earth. Additionally, developers were involved in the entire planning process, allowing them to customize and refine the application as the planning process evolved and feedback was gathered from stakeholders. The user can draw the proposed locations of Marine Protected Areas (MPAs) and analytical tools process the MPA attributes, e.g. distance matrices between habitats based on connectivity calculation. MarineMap has been used by stakeholders who had little to no experience with traditional GIS software. Running the AquaSpace tool however requires an existing knowledge of GIS (Gimpel et al., 2018). The user defines the study area, the port from which aquaculture business should be transacted, the culture species and corresponding culture system, the constraints (e.g. exclusion zones or other management regulations), and the conflict matrix indicating conflicts or synergies with other human uses. The Assessment Report summarizes general planning, site information, and all inter-sectorial, environmental impact, economic valuation and socio-cultural indicator values. The AquaSpace tool also produces a file to facilitate the comparison of multiple indicator values yielded by different scenarios. Other outputs include maps and graphics, enabling the user to communicate opportunities and risks visually. AkvaVis and APDSS produce reports (that can be downloaded by the user) which present information about the suitability analysis, e.g. farm settings, location, environment and other available data. In SISAQUA the user has the potential to combine several predefined layers to produce indicators and the output can be downloaded in different formats. This treatment module was specifically developed by Sextant for SISAQUA but benefits the whole Sextant community. Reciprocally, SISAQUA benefits from the Sextant infrastructure guarantying interoperability and perennial update.

Corner et al. (2018) and Galparsoro et al. (2020) also pointed out the importance of risk maps to avoid current risks and anticipate future risks for aquaculture. Numerous risks are associated with climate change, disease exposure, connectivity within and between zones, genetic pollution, harmful algal blooms, transport and, eutrophication. In Hardangerfjord, AkvaVis progressively focused on salmon infestation by sea lice and a spatial indicator of salmon lice pressure was developed. This was later expanded to national level in the web based portal Salmon Lice Map (https://www.hi.no/forskning/marine-data-forskningsdata/lakseluskart/html/lakseluskart.html#) which is applied in the annual risk assessment (Taranger et al., 2015) and a production zone management system of the industry (Myksvoll et al., 2018). In Normandy, SISAQUA integrates an indicator of salmon parasitism risk. The AquaSpace tool developed a distance-based function for estimating the risk of disease (Gimpel et al., 2018).

Our tools integrate mainly geobiophysical data essential for potential aquaculture investors, while social and economic aspects are currently only available thorough indirect information. However, a profitability module is under development within the APDSS tool. Economic and social valuation is considered as current gaps and key innovations to the future of marine spatial planning (Brigolin et al., 2017; Pınarbaşı et al., 2017). An economic analysis is proposed in the AquaSpace tool including a function providing i) a direct assessment of an aquaculture activity (e.g. revenue, added value, profit) and ii) an indirect assessment on other sectors related to aquaculture (Gimpel et al., 2018). Based on the functionalities shown for our tools and their analytical capacities for specific aquaculture spatial planning we conclude there are potentials for integrating more social and economic aspects to the tools.

4.4. Stakeholder involvement

Numerous studies highlighted the need for early engagement and the importance of identifying which, when and how stakeholders should be involved (e.g. Ehler and Douvere, 2009; Gopnik et al., 2012). Puniwai et al. (2014) presented a good example of early stakeholder involvement in each step of their assessment of benefits and limitations of using GIS for aquaculture siting. They described in detail how various types of consultation with relevant stakeholders were organized, such as workshops, community meetings and public presentations. Their objectives included: 1) definition of the extent and scale of an area, 2) identification of appropriate aquaculture systems, 3) identification of data requirements (biophysical system requirements; socio-economic characteristics and 4) analysis of the results.

In our project, the first goal of stakeholder consultation was to provide an accurate and local view of stakeholder expectations in each of our CS. Consultation was part of a broader survey over 16 study sites aimed at investigating the constraints to the expansion of the marine aquaculture industry, as well as the main needs and recommendations for better management of this activity from a stakeholder perspective (Galparsoro et al., 2020). This survey covered a wide range of aquaculture management strategies, coastal activities, environmental conditions, production capacity, technological development, and economic, social and policy contexts. It yielded a dataset of criteria which helped identifying aquaculture issues, geographical dimensions and relevant spatial data for each CS. The second goal of stakeholder involvement dealt with the demonstration and testing of our tools through a series of workshops. Our joint work was adapted to the local context and did not follow a standard and uniform protocol. In Norway, user surveys and test trials helped to shape the evolution of the tool. In Normandy, SISAQUA was initially developed as an initiative from researchers, and stakeholders were involved through further development of the tool within the AQUASPACE project. The two workshops organized during the AQUASPACE project were used to update the tool. In Sanggou Bay workshops, the project provided feedback from industry and management on how spatial planning could contribute in decision making to maintain sustained aquaculture outputs and profitability. Workshops were also a forum for project implementation plans and specific technical questions for developing APDSS. In contrast, meetings with individuals and small groups of government representatives were undertaken in Carlingford Lough. A third objective of stakeholder consultation was to build and share common interests on marine spatial planning. In all CS long-term collaborations between scientists and stakeholders are well established and helped build confidence and express different views on the future of aquaculture in these different regions. However, the difficulty in maintaining the link between stakeholders and the scientific teams beyond the duration of the project is a key issue affecting the future application of our tools for management in some CS (e.g. Normandy). The implementation of our tools partially addresses the final objective of scenario assessment. Merrifield et al. (2013) described the involvement of stakeholders in the generation of multiple management scenarios, both individually and in collaboration with other stakeholders at public meetings. They showed that the feedback provided by MarineMap assisted stakeholders in preparing proposals which were submitted for evaluation and consideration by the authorities in charge of fisheries management. Our tools allow criteria for aquaculture siting to be set and bring new information to decision-makers. They contribute to making the consultation process and consideration of new applications more transparent, through the visualization of spatial constraints or available opportunities. Therefore, our tools can help aquaculture gain social licence, improve public perception and reduce conflict between users, one of the major issues emphasized by Galparsoro et al. (2020). However, their use to build and utilize scenarios for management must be demonstrated beyond the duration of the project.

4.5. Tool applicability, implementation and maintenance

Marine spatial planning is a dynamic and complex process where decision support tools provide vital assistance to planners (Meaden et al., 2016; Pınarbaşı et al., 2017). In aquaculture, planners and managers are faced with an industry that is typically dynamic with changes in production, siting of new locations and species or relocation to more favourable areas, improving technologies and more efficient use of licensed areas, all altering spatial requirements. Therefore, there is a requirement for tools to be transparent and easily adaptable to change. The results from our case studies demonstrate the applicability of tools in a range of environments and management frameworks. The development of our tools was facilitated by knowledge transfer between the case studies and emphasized the necessity of open access of data and information. Therefore, our study has exemplified some processes which demonstrate the importance of central criteria that should be applied when developing and establishing other decision support systems, namely; 1) open access to data and information, 2) tool flexibility to enable adaptation and 3) a process involving implementation and 4) long-term maintenance.

The rationale to utilize open source data was addressed by Merrifield et al. (2013) who stated that the use of free and open source software facilitates additional developments and applications to other case studies, permitting other developers to alter the code and deploy at a minimum additional cost. The AquaSpace tool is one of the first open-source tools using datasets at a European scale that allows for a spatially explicit and integrated assessment of indicators reflecting the economic, environmental, inter-sectorial and socio-cultural risks and opportunities for potential aquaculture systems (Gimpel et al., 2018). A license is required for the use of the desktop GIS software, but no additional cost is needed. The principle of the tool utilised within our study comprises publicly accessible web based systems, visualizing data and information from open sources, and an interface which includes functionalities for new applications.

The second criterion related to system flexibility is that it is essential to make tools adaptable to new areas, issues and stakeholder expectations. Development of our tools benefited from the cooperative exchange of expertise between the case studies, from bilateral collaborations and from being part of the AQUASPACE project. The adaptation of the original AkvaVis tool to new environments and aquaculture issues produced drafts of data visualisations, tool functions etc, that were challenged for applicability by the developers, the AQUASPACE teams and through specific feedback from stakeholder workshops. This process involving developers and users was considered critical for achieving relevant tools, and was also experienced by Merrifield et al. (2013) through the development of MarineMap. The development of the tools within each of our cases studies has been partly sequential and showed diverse levels of progress and stages of advancement and complexity, but all the tools worked towards the common goal of implementation in management or spatial planning. The tool in the Hardangerfjord CS was used as a demonstration of the concept for the developments in the other case studies. Similar benefits were experienced when developing MarineMap, where tests in the first study region supported development of the remaining regions (Merrifield et al., 2013).

As our tools are only partially implemented in management, this can be regarded as a gap. In the Normandy CS, SISAQUA has been transferred to an institutional spatial data infrastructure for marine environments which is maintained by Ifremer. This infrastructure guarantees the compatibility with all geographic information portals. Thus, the tool is further operationalized and applied within an institutional structure that can be regarded as prepared for implementation in aquaculture spatial management. In Norway, continued development of the AkvaVis tool was halted after the end of project but the conceptual ideas can be recognized in the existing operational web based portals, the Salmon Lice Map (https://www.hi.no/forskning/marine-data-forskningsdata/lakseluskart/html/lakseluskart.html#) and BarentsWatch (https://www.barentswatch.no/en). Both are implemented and applied in aquaculture management, are available for public use and have shown notable applicability in industry and management.

With the dynamic nature of aquaculture industries and the associated requirements for management to adapt, maintenance of decision support tools is crucial to keep pace with changing circumstances and maintain applicability. Assessments of the resources needed for the development of decision support tools, such as those in our study, should include data availability, development and implementation of functions, and cooperation between developers and stakeholders. This equates to considerable investments which normally needs to be justified by the services provided by the tool after it is operationalized or implemented within management. In this context, Merrifield et al. (2013) consider that the software development cycle is not compatible with grant type funding and that sufficient and continuous funding is critical to build and maintain a system. In their case, partnerships with an academic institution facilitated the deployment of the necessary infrastructure. Such requirements also need to be considered during the development phase, for example in cases when changes in important assumptions can affect conditions for development. This was seen within the Normandy CS when continuation of the development at a certain point required the transfer of the server running the tool, therefore allowing new data and functions to be included. For the Hardangerfjord CS salmon lice dispersion modelling became a national high priority concern, requiring most institutional resources and priorities to focus on developing the Salmon Lice Map (Sandvik et al., 2016; Myksvoll et al., 2018), which resulted in the postponement of the further development of the AkvaVis tool. Merrifield et al. (2013) emphasise the critical role of funding in any software development for spatial decision support tools, an issue of high relevance for the tools developed within our study. In this respect, Salmon Lice Map and BarentsWatch operating at national level in Norway have ministerial financial support. The AkvaVis tool developed for the Carlingford Lough CS was designed with the intention to support decision making within in the aquaculture licensing processes within the CS area which are currently met with complex regulatory and management issues. The issues within this CS were further compounded by the multiple user and trans-boundary nature of the water body, and the limited financial timeframe of the AQUASPACE project which restricted further implementation. The APDSS tool was developed for local management authorities. Feedback from management stakeholders pointed to the urgent need for tools to tackle the current productivity bottlenecks and regulatory conformity. The development of large-scale mariculture operations in China, which have resulted in negative environmental impacts on natural ecosystems (Liu and Su, 2017) and the ongoing implementation of the MFZ framework involving capacities for comprehensive management of marine areas (Feng et al., 2016) highlights the need for the implementation of operationalized spatial decision support systems.

Utilising the best available technologies within decision support tools can facilitate well-informed decision making providing transparency and accountability within governance systems (Merrifield et al., 2013). The complex process of tool implementation and the need for maintenance, require several actions that include interactions with users, research, analysis and planning, financing, monitoring, and evaluation (Pınarbaşı et al., 2017). The cooperative exchange of expertise between the different CS areas in our study demonstrated several important benefits in the development process supporting maintenance of the tools. All of the tools produced through this research are currently accessible online. However, it should be noted that no further development of these tools has been undertaken since the cessation of the AQUASPACE project.

In conclusion, we successfully applied a decision support tool to four case studies, which deal with different scales of aquaculture and address various issues relating to aquaculture spatial planning in different countries. The key strengths of AkvaVis and its companion tools SISAQUA and APDSS relate to their capacity to manage and display spatial data from different sources in a transparent way, the facility to use and display built-in indicators, and the long-term development perspective made possible by the maintenance strategy of tools, services and data depositories. Lessons learned during the AQUASPACE project highlighted that stakeholder involvement is necessary to ensure that the tools developed are beneficial for aquaculture spatial planning.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was supported by AQUASPACE (Ecosystem Approach to making Space for Sustainable Aquaculture) project, funded by the European Union under the H2020 Programme (grant agreement no. 633476).

The first developments of the Norwegian AkvaVis tool were funded by Institute of Marine Research, Aquaculture Program, Norway. We are grateful to A. Ervik, I. Døskeland (Vestland County Council) and A.A. Hageberg (Norwegian Research Center AS) for their fundamental contributions to the development, and to participants in the project steering group and stakeholder workshops for contributions.

Work undertaken in support of the development of the AkvaVis tool for Carlingford was funded by the Department of Agriculture, Environment and Rural Affairs, Northern Ireland and the Agri-Food and Biosciences Institute. We would like to thank H. Moore, M. Service, E. O'Kane and H. Cromie for their contributions.

First developments of SISAQUA were made during the Spatial Information System for Aquaculture in Normandy and Norway (SISQUONOR) bilateral project funded by French-Norwegian Foundation (grant agreement no. FNS Norway 11-02), European Regional Development Fund (grant agreement no. 33520), Hordaland County Council (grant agreement no. 50-11MA) and Basse-Normandie Regional Council (grant agreement no. 15P01065). We are grateful to M. Callier, E. Roque d'Orbcastel, J-P. Blancheton and M. Ropert for their help during preparation and driving of stakeholder workshops in Normandy; C. Satra-Le bris, J. Meillon and M. Ropert for implementation of SISAQUA into Sextant; R. Le Gendre, S. Petton, C. Picoche and M. Vasquez for the production of some layers. We would like to thank P. Le Rolland (Direction Départementale des Territoires et de la Mer - Calvados) and D. Sellam (Direction Inter-Régionale de la Mer Manche Est-Mer du Nord) for hosting the stakeholder workshops and all stakeholders for their participation.

AkvaVis was first demonstrated in China by funding from the collaboration project Environment and Aquaculture Governance (Ministry of Foreign Affairs, Norway, grant agreements no. CHN 2152 and CHN 17/0033). The authors wish to express sincere appreciation to the support from the Key Programme for International Cooperation on Scientific and Technological Innovation, China Ministry of Science and Technology (grant agreement no. 2016YFE0112600) in the development of APDSS. We thank Dr. Jilan Su, Academician of the Chinese Academy of Sciences for his valuable advice on designing of APDSS; Zengjie Jiang, Jilang Xuan, Fan Lin and Feng Zhou for their contributions in field survey and model construction; Liangju Yu, Weitao Shang and Xiaopeng Jiang for their technical contributions on developing the APDSS.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ocecoaman.2020.105447.

References

AAMP, 2009. Analyse des enjeux et propositions pour une stratégie d'aires marines protégées Bretagne Nord/Ouest Cotentin. Agence des Aires Marines Protégées, p. 38 pp + annexes.

Agreste, 2014. Recensement de la conchyliculture 2012. N°316, juillet 2014, p. 6pp.

Aguilar-Manjarrez, J., Kapetsky, J.M., Soto, D., 2010. The potential of spatial planning tools to support the ecosystem approach to aquaculture. In: FAO/Rome Expert Workshop 19–21 November 2008, Rome, Italy. FAO, Rome. FAO Fisheries and Aquaculture Proceedings No 17.

Anon, 2015. The Norwegian Ministry of Trade, Industry and Fisheries. Predictable and Environmentally Sustainable Growth in Norwegian Salmon and Trout Farming (Meld. St. 16 2014±2015). In Norwegian. Available from: https://www.regjeringen.no/contentassets/6d27616f18af458aa930f4db9492fbe5/no/pdfs/stm201420150016000dddpdfs.pdf.

Alunno-Bruscia, M., Bourles, Y., Maurer, D., Robert, S., Mazurie, J., Gangnery, A., Goulletquer, P., Pouvreau, S., 2011. A single bio-energetics growth and reproduction model for the oyster *Crassostrea gigas* in six Atlantic ecosystems. J. Sea Res. 66, 340–348. https://doi.org/10.1016/J.SEARES.2011.07.008.

Asplin, L., Johnsen, I.-A., Sandvik, A.-D., Albretsen, J., Sundfjord, V., Aure, J., Boxaspen, K.-K., 2014. Dispersion of salmon lice in the Hardangerfjord. Mar. Biol. Res. 10, 216–225. https://doi.org/10.1080/17451000.2013.810755.

Bacher, C., Gangnery, A., Cugier, P., Mongruel, R., Strand, Ø., Frangoudes, K., 2019. Spatial, ecological and social dimensions of assessments for bivalve farming management. In: Smaal, A.C., Ferreira, J., Grant, J., Petersen, J., Strand, Ø. (Eds.), Goods and Services of Marine Bivalves. Springer, Cham, p. 591. https://doi.org/10.1007/978-3-319-96776-9_26, pp. 528–550.

Boogert, F.J., Cubillo, A.M., Nunes, J.P., Ferreira, J.G., Corner, R.A., 2017. Online Environmental Feasibility Application and Milestone MS15 Release of Online Environmental Feasibility Application. Longline Environment Ltd.. London and AQUASPACE project (H2020 no. 633476), Oban Deliverable 2.5. Pdf obtainable from. http://www.aquaspace-h2020.eu/

Borja, Á., Elliott, M., Carstensen, J., Heiskanen, A.-S., van de Bund, W., 2010. Marine management – towards an integrated implementation of the European marine strategy framework and the water framework directives. Mar. Pollut. Bull. 60 (12), 2175–2186. https://doi.org/10.1016/j.marpolbul.2010.09.026.

Bricker, S.B., Getchis, T.L., Chadwick, C.B., Rose, C.M., Rose, J.M., 2016. Integration of ecosystem-based models into an existing interactive web-based tool for improved aquaculture decision-making. Aquaculture 453, 135–146. https://doi.org/10.1016/j.aquaculture.2015.11.036.

Brigolin, D., Porporato, E.M.D., Prioli, G., Pastres, R., 2017. Making space for shellfish farming along the Adriatic coast. ICES J. Mar. Sci. 74, 1540–1551. https://doi.org/10.1093/icesjms/fsx018.

Brugere, C., Ridler, N., Haylor, G., Macfadyen, G., Hishamunda, N., 2010. Aquaculture Planning: Policy Formulation and Implementation for Sustainable Development. FAO Fisheries and Aquaculture Technical Paper No. 542. FAO, Rome, p. 70.

Coleman, H., Foley, M., Prahler, E., Armsby, M., Shillinger, G., 2011. Decision Guide: Selecting Decision Support Tools for Marine Spatial Planning. Center for Ocean Solutions. The Woods Institute for the Environment, Stanford University, California.

Corner, R.A., Aguilar-Manjarrez, J., Massa, F., Fezzardi, D., 2018. Multi-stakeholder perspectives on spatial planning processes for mariculture in the Mediterranean and Black Sea. Rev. Aquacult. 1–18 https://doi.org/10.1111/raq.12321.

EC, 2014. European Commission. Directive 2014/89/Eu of the European Parliament and of the council of 23 July 2014 establishing a framework for maritime spatial planning. Official Journal of the European Union 57, 135–145 (L 257/135).

Ehler, C., Douvere, F., 2009. Marine Spatial Planning: a step-by-step approach toward ecosystem-based management. In: Intergovernmental Oceanographic Commission and Man and the Biosphere Programme. IOC Manual and Guides No. 53, ICAM Dossier No. 6. UNESCO, Paris, 2009 (English).

Ervik, A., Hansen, P.K., Aure, J., Stigebrandt, A., Johannessen, P., Jahnsen, T., 1997. Regulating the local environmental impact of extensive marine fish farming. I. The concept of MOM (Modelling - ongrowing fish farms - monitoring). Aquaculture 158, 85–94. https://doi.org/10.1016/S0044-8486(97)00186-5.

Ervik, A., Agnalt, A.-L., Asplin, L., Aure, J., Bekkvik, T.C., Døskeland, I., Hageberg, A.A., Hansen, T., Karlsen, Ø., Oppedal, F., Strand, Ø., 2008. AkvaVis – dynamisk GIS-verktøy for lokalisering av oppdrettsanlegg for nye oppdrettsarter - miljøkrav for nye oppdrettsarter og laks. Fisken Havet 10 (in Norwegian).

Feng, R., Chen, X., Li, P., Zhou, L., Yu, J., 2016. Development of China's marine functional zoning: a preliminary analysis. Ocean Coast Manag. 131, 39–44. https://doi.org/10.1016/j.ocecoaman.2016.08.011.

Ferreira, J.G., Hawkins, A.J.S., Bricker, S.B., 2007. Management of productivity environmental effects and profitability of shellfish aquaculture – the Farm Aquaculture Resource Management (FARM) model. Aquaculture 264, 160–174. https://doi.org/10.1016/j.aquaculture.2006.12.017.

Ferreira, J.G., Aguilar-Manjarrez, J., Bacher, C., Black, K., Dong, S.L., Grant, J., Hofmann, E., Kapetsky, J., Leung, P.S., Pastres, R., Strand, Ø., Zhu, C.B., 2012. Progressing aquaculture through virtual technology and decision-support tools for novel management. In: Subasinghe, R.P., Arthur, J.R., Bartley, D.M., De Silva, S.S., Halwart, M., Hishamunda, N., Mohan, C.V., Sorgeloos, P. (Eds.), Farming the Waters for People and foodProceedings of the Global Conference on Aquaculture 2010, Phuket, Thailand. 22–25 September 2010. FAO, Rome and NACA, Bangkok, pp. 643–704 (also available at: www.fao.org/ocrep/015/i2734e/i2734e00.htm.

Galparsoro, I., Murillas, A., Pınarbaşı, K., Sequeira, A.M.M., Stelzenmüller, V., Borja, Á., O'hagan, A.-M., Boyd, A., Bricker, S., Garmendia, J.-M., Gimpel, A., Gangnery, A., Billing, S., Bergh, Ø., Strand, Ø., Liu, H., Fragoso, B., Icely, J., Ren, J., Papageorgiou, N., Grant, J., Brigolin, D., Pastres, R., Tett, P., 2020. Global stakeholder vision for ecosystem-based marine aquaculture expansion from coastal to offshore areas. Rev. Aquacult. 1, 19. https://doi.org/10.1111/raq.12422.

Gimpel, A., Stelzenmüller, V., Töpsch, S., Galparsoro, I., Gubbins, M., Miller, D., Murillas, A., Murray, A.G., Pınarbaşı, K., Roca, G., Watret, R., 2018. A GIS-based tool for an integrated assessment of spatial planning trade-offs with aquaculture. Sci. Total Environ. 627, 1644–1655. https://doi.org/10.1016/j.scitotenv.2018.01.133.

Gohin, F., 2011. Annual cycles of chlorophyll-a, non-algal suspended particulate matter, and turbidity observed from space and in-situ in coastal waters. Ocean Sci. 7, 705–732. https://doi.org/10.5194/os-7-705-2011.

Gopnik, M., Fieseler, C., Cantral, L., McClellan, K., Pendelton, L., Crowder, L., 2012. Coming to the table: early stakeholder engagement in marine spatial planning. Mar. Pol. 36, 1139–1149. https://doi.org/10.1016/j.marpol.2012.02.012.

Hageberg, A.A., 2008. AkvaVis Brukerundersøkelse. Evaluering Av Programprototyp Og Kartlegging Av Brukerbehov. CMR Computing - Report, p. 67. Ref.nr.: CMR-2008-A52030-RA-1.

Hersoug, B., 2013. The battle for space: the position of Norwegian aquaculture in integrated coastal zone planning. In: Moksness, E., Dahl, E., Støttrup, J. (Eds.), Global Challenges in Integrated Coastal Zone Management. Wiley, West Sussex, UK, pp. 159–168.

Hofherr, J., Natale, F., Trujillo, P., 2015. Is lack of space a limiting factor for the development of aquaculture in EU coastal areas? Ocean Coast Manag. 116, 27–36. https://doi.org/10.1016/j.ocecoaman.2015.06.010.

Kapetsky, J.M., Aguilar-Manjarrez, J., 2007. Geographic Information Systems Remote Sensing and Mapping for the Development and Management of Marine Aquaculture. FAO, Rome. FAO Fisheries Technical Paper No 458.

Le Gendre, R., Morin, J., Maheux, F., Fournier, F., Simon, B., Cochard, M.-L., Pierre-Duplessix, O., Dumas, F., Harmel, B., Paul, C., Riou, P., 2014. DILEMES, Dispersion Larvaire de *Mytilus edulis* en baie de Seine. Rapport final 75 pp + Annexes. https://archimer.ifremer.fr/doc/00188/29916/.

Liu, H., Su, J., 2017. Vulnerability of China's nearshore ecosystems under intensive mariculture development. Environ. Sci. Pollut. Res. 24, 8957–8966. https://doi.org/10.1007/s11356-015-5239-3.

Meaden, G.J., Aguilar-Manjarrez, J., Corner, R.A., O'Hagan, A.M., Cardia, F., 2016. Marine Spatial Planning for Enhanced Fisheries and Aquaculture Sustainability – its Application in the Near East. FAO Fisheries and Aquaculture Technical Paper No. 604. FAO, Rome.

MEDDE, 2014. Plan Stratégique National : Développement des aquacultures durables 2020. Ministère de l'Ecologie, du Développement Durable et de l'Energie avec la contribution de l'Association des Régions de France, p. 103 pp + annexes.

Melbourne-Thomas, J., Constable, A.J., Fulton, E.A., Corney, S.P., Trebilco, R., Hobday, A.J., Blanchard, J.L., Boschetti, F., Bustamante, R.H., Cropp, R., Everett, J. D., Fleming, A., Galton-Fenzi, B., Goldsworthy, S.D., Lenton, A., Lara-Lopez, A., Little, R., Marzloff, M.P., Matear, R., Mongin, M., Plaganyi, E., Proctor, R., Risbey, J. S., Robson, B.J., Smith, D.C., Sumner, M.D., van Putten, E.I., 2017. Integrated modelling to support decision-making for marine social–ecological systems in Australia. ICES (Int. Counc. Explor. Sea) J. Mar. Sci. https://doi.org/10.1093/icesjms/fsx078.

Ménesguen, A., Dussauze, M., Dumas, F., Thouvenin, B., Garnier, V., Lecornu, F., Répécaud, M., 2019. Ecological model of the Bay of Biscay and English Channel shelf for environmental status assessment. I. Nutrients, phytoplankton and oxygen. Ocean Model. 133, 56–78. https://doi.org/10.1016/j.ocemod.2018.11.00.

Merrifield, M., McClintock, W., Burt, C., Fox, E., Serpa, P., Steinback, C., Gleason, M., 2013. MarineMap: a web-based platform for collaborative marine protected area planning. Ocean Coast Manag. 74, 67–76. https://doi.org/10.1016/j.ocecoaman.2012.06.011.

Mitchell, A., Service, M., 2004. Northern Ireland Nearshore Subtidal Habitat Mapping Project. Report by the Environment and Heritage Service. The Department of Agriculture and Rural Development and The Queen's University of Belfast.

Myksvoll, M.S., Sandvik, A.D., Albretsen, J., Asplin, L., Johnsen, I.A., Karlsen, Ø., Kristensen, N.M., Melsom, A., Skardhamar, J., Ådlandsvik, B., 2018. Evaluation of a national operational salmon lice monitoring system. From physics to fish. PloS One 13 (7), e0201338. https://doi.org/10.1371/journal.pone.0201338.

Pınarbaşı, K., Galparsoro, I., Borja, Á., Stelzenmüller, V., Ehler, C.N., Gimpel, A., 2017. Decision support tools in marine spatial planning: present applications, gaps and future perspectives. Mar. Pol. 83, 83–91. https://doi.org/10.1016/j.marpol.2017.05.031.

Puniwai, N., Canale, L., Haws, M., Potemra, J., Lepczyk, C., Gray, S., 2014. Development of a GIS-based tool for aquaculture siting. ISPRS Int. J. Geo-Inf. 3, 800–816. https://doi.org/10.3390/ijgi3020800.

Rennie, H.G., 2002. A Geography of Marine Farming Rights in New Zealand: Some Rubbings of Patterns on the Face of the Sea. Doctoral thesis. Department of Geography, University of Waikato, New Zealand, p. 492.

SAPEA, 2017. Food from the oceans: how can more food and biomass be obtained from the oceans in a way that does not deprive future generations of their benefits?. In: Evidence Review Report No. 1. Science Advice for Policy by European Academies, Berlin, p. 99.

Sandvik, A.D., Bjørn, P.A., Ådlandsvik, B., Asplin, L., Skardhamar, J., Johnsen, I.A., Myksvoll, M., Skogen, M.D., 2016. Toward a model-based prediction system for salmon lice infestation pressure. Aquac Environ Interact 8, 527–542. https://doi.org/10.3354/aei00193.

Saulquin, B., Gohin, F., Garrello, R., 2010. Regional objective analysis for merging high-resolution MERIS, MODIS/Aqua, and SeaWiFS chlorophyll-a data from 1998 to 2008 on the European Atlantic shelf. IEEE Trans. Geosci. Rem. Sens. 12. https://doi:10.1109/TGRS.2010.2052813.

Soto, D., Aguilar-Manjarrez, J., Hishamunda, N., 2008. In: Building an ecosystem approach to aquaculture FAO/Universitat de les Illes Balears Expert Workshop 7–11 May 2007 Palma de Mallorca Spain. FAO Fisheries and Aquaculture Proceedings, No 14. FAO, Rome.

Stelzenmüller, V., Lee, J., South, A., Foden, J., Rogers, S.I., 2013. Practical tools to support marine spatial planning: a review and some prototype tools. Mar. Pol. 38, 214–227. https://doi.org/10.1016/j.marpol.2012.05.038.

Sun, Q.W., Liu, H., Shang, W.T., Yu, L.J., Jiang, X.P., Cai, B.Y., Chang, L.R., Xiao, L.Y., 2019. GIS-based assessment for culture suitability of kelp (*Saccharina japonica*) in Sanggou Bay and the surrounding waters. Progress in Fishery Sciences. https://doi.org/10.19663/j.issn2095-9869.20181024001.

Taranger, G.L., Karlsen, Ø., Bannister, R.J., Glover, K.A., Husa, V., Karlsbakk, E., Kvamme, B.O., Boxaspen, K.K., Bjørn, P.A., Finstad, B., Madhun, A.S., Morton, H.C., Svåsand, T., 2015. Risk assessment of the environmental impact of Norwegian Atlantic salmon farming. ICES J. Mar. Sci. 72, 997–1021. https://doi.org/10.1093/icesjms/fsu132.

Taylor, J., Charlesworth, M., Service, M., 1999. Nutrient Inputs and Trophic Status of Carlingford Lough. Report by the Queen's university of Belfast and the Department of Agriculture (NI).

Thomas, Y., Mazurié, J., Alunno-Bruscia, Y., Bacher, C., Bouget, J.F., Gohin, F., Pouvreau, S., Struski, C., 2011. Modelling spatio-temporal variability of Mytilus edulis (L.) growth by forcing a dynamic energy budget model with satellite-derived environmental data. J. Sea Res. 66, 308–317. https://doi.org/10.1016/j.seares.2011.04.015.

Tlusty, M.F., Wikgren, B., Lagueux, K., Kite-Powell, H., Jin, D., Hoagland, P., Kenney, R. D., Kraus, S.D., 2018. Co-occurrence mapping of disparate data sets to assess potential aquaculture sites in the Gulf of Maine. Reviews in Fisheries Science & Aquaculture 26, 70–85. https://doi.org/10.1080/23308249.2017.1343798.

Xuan, J., He, Y., Zhou, F., Tang, C., Zheng, X., Liu, H., Yu, L., Chen, J., 2019. Aquaculture-induced boundary circulation and its impact on coastal frontal circulation. Environ. Res. Commun. https://doi.org/10.1088/2515-7620/ab22cd, 051001.