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Use of Geographic Information Systems (GIS) for aquaculture and recommendations for development of spatial tools

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Abstract

There are many spatial issues associated with aquaculture which must be understood in order to support sustainable development and mitigate other potential issues. Geographic Information Systems (GIS) are used for investigation, analysis and modelling of aquaculture and there have been a considerable number of studies since the late 1980's. However, despite the range of applications, GIS is still often underutilised and stakeholders have requested more GIS-based tools to support management and regulation of the sector. Consequently, there is a need to establish a knowledge base of existing applications and identify the challenges and opportunities to encourage development of tools that address user needs. This study presents a quantitative analysis of primary scientific literature, focusing on over 200 studies, to enable a comprehensive overview of the application of GIS and the trends associated with its use for aquaculture. Furthermore, there is a detailed assessment of the considerations when developing GIS-based tools for aquaculture which culminates in five key recommendations regarding 1) Usability of the tool, 2) Data requirements, 3) Accessibility to end user, 4) Capabilities and training requirements, and 5) Longevity of the tool. These recommendations can guide future development and application of tools to support aquaculture planning and management and assess spatial issues relevant for the sector.

Key words: Aquaculture, Decision support, Geographic Information Systems, Location, Spatial, Tool

1. Introduction

From farm to fork, throughout the value chain, many aspects of aquaculture have a spatial element. Key decisions in the planning phase regarding what site, species, system and technology to use are outlined by geographical issues. These include the heterogeneity of natural resources (Sequeira et al., 2008; Silva et al., 2011), the physical environment (Falconer et al., 2013a), social aspects such as effects on visual amenity (Pérez et al., 2005; Falconer et al., 2013b), job creation and improved livelihoods, and economics, such as market access (van Brakel and Ross, 2011). In operation, aquaculture management practices and production cycles have spatial or spatio-temporal differences that affect the quantity, quality and profitability of the farmed product. Moreover, there is frequently a spatial element to health and welfare issues, such as the spread of disease (Tavornpanich et al., 2012). Consequently, the development of cost-efficient sustainable aquaculture is dependent on spatial analysis for environmental impacts, optimising productivity and day-to-day management.

It is of upmost importance to understand the spatial issues associated with aquaculture because for the foreseeable future aquaculture is expected to continue to expand, intensify and increase production (FAO, 2018), while other activities will also compete for the finite space and resources (Godfray et al., 2010). In addition, ambitious plans for Blue Growth require spatial management of multiple interacting economies (Klinger et al., 2018). Consequently, to ensure sustainable planning and management of aquaculture, spatial issues must be investigated, analysed and assessed. Though there are several ways to achieve this the most commonly used is Geographic Information Systems (GIS). GIS can be broadly defined as an organised collection of computer hardware, software, people and organisational infrastructure that enables the acquisition and storage of geographic and related attribute data for processing, analysis, synthesis and visualizing spatial information (Kennedy, 2013; Longley et al., 2015). Use of GIS can range from simple spatial queries to more complex analysis and modelling (Longley et al., 2015; Falconer et al., 2018) and often the process and outcomes are used in decision support, allowing stakeholders to make informed choices.

The use of tools and models for aquaculture decision-making varies throughout the world, leading to inconsistent approaches to aquaculture management and regulation, which can affect aquaculture development and sustainability. In recent years there has been increasing use of GIS for aquaculture and many, including the Food and Agriculture Organization of the United Nations (FAO), recognise GIS as an important tool for the sector (Aguilar-Manjarrez et al., 2008; Ross et al., 2013). Nevertheless, GIS is still often underutilised, and the wide range of potential applications of the technology is not fully exploited, particularly as a statutory tool for management and regulation.

A recent consultation on aquaculture licensing and regulation found that many European aquaculture stakeholders would like more GIS-based tools available for aquaculture planning and management (Kane et al., 2017), suggesting that existing applications are insufficient, not easily accessible or stakeholders are not aware of what is available. The European Commission has also identified availability of space and conflict with other users as limiting factors to sustainable development of European aquaculture and coordinated spatial planning is one of the four priority areas that must be addressed (European Commission, 2013).

Clearly, there is a need to assess how GIS has been used for aquaculture so that existing or potential applications that support sustainable planning and management can be identified and made more widely available. However, to date, though there have been several general overviews and reviews of GIS use for aquaculture (including Nath et al., 2000; Ross, et al, 2009; Aguilar-Manjarrez et al., 2010; Falconer et al., 2018), there has been little quantitative assessment of primary scientific literature regarding its application. Consequently, while it has been demonstrated since the mid-1990s that GIS is useful for aquaculture development, it is timely to analyse the scientific knowledge base and to evaluate how GIS-based tools can be developed and made more widely available for stakeholders to use.

The aims of this study were to 1) examine primary scientific literature in the form of peer-reviewed journal articles to identify and quantify the trends associated with the use of GIS for aquaculture, and 2) to evaluate the use of GIS as a tool for aquaculture stakeholders and make recommendations for its future tool development and application for aquatic food production.

2. Assessment of primary scientific literature

2.1 Methodology and scope

The literature search followed guidance set by Preferred Reporting Items for Systemic Reviews and Meta-Analysis (PRISMA) (Moher et al., 2009) and an overview of each step is provided in Figure 1. A search of the Scopus database using the terms 'GIS' AND 'aquaculture' in 'All fields' from the earliest record until the end of 2016 revealed 2511 items. The search used 'All fields' to allow for a greater search extent as this also searched the associated reference lists. To allow for journals that were not indexed in the Scopus database, a second search was conducted, using the Web of Science database and the terms '*GIS*' AND '*aquaculture*' in the abstract, keywords, title and topic. The Web of Science search revealed 326 items. All searches were restricted to peer reviewed journal articles that were written in English. After duplicates (186 items) were removed, there was an initial screening of the title and abstract and items outside of the topic area of "aquaculture and GIS" were rejected from the process. Review articles were also excluded. In the final eligibility assessment, the full text of the remaining 435 articles was assessed to identify those that would be considered within the study.

This study focused on the application of GIS software so although spatial analysis can be performed using other programmes and software environments, only studies that made specific reference to GIS and GIS software were included. Furthermore, it must be acknowledged that the usual caveats apply and studies may have been missed due to the limitations of the search and database contents. Nevertheless, the results from the search are based on a substantial sample that provides an overview and assessment of the trends of GIS use for aquaculture.

2.2. Overview

At least 211 journal articles published between 1988 and 2016, involved the use of GIS to assess or study an aspect(s) of aquaculture (Appendix I). Of these studies, aquaculture was the primary focus for 139 articles (66%), while the remaining 72 articles (34%) included aquaculture in their analysis, but it was not the main focus. The articles were published in 101 journals, although 64 journals only published a single study. Most of the journals were in the research areas of aquaculture, environment or marine science. Two journals, Aquaculture and Ocean & Coastal Management, were the dominant titles publishing 19 and 17 articles respectively.

The earliest publication found in the search was from 1988 (Kapetsky et al., 1988). The increase in GIS publications from 1988 onwards could have been driven by several factors, including growth of aquaculture production and also technological advances which made GIS software more accessible and easier to use. . It must also be acknowledged that other studies that were not published in primary scientific literature, and not included in this analysis, have also contributed to this area of research (e.g. Kapetsky et al. 1987).

Some articles (n=49, 23%) did not identify the GIS software that was used, while others used several different softwares in the same study, but the most common software provider was ESRI [ESRI, Redlands, California, USA] as ArcINFO or a version of the ArcGIS suite was used in at least 120 (57%) studies. Another notable software provider is Clark Labs as IDRISI [Clark Labs, Worcester MA, USA] was used in at least 24 (11%) studies. Although many used commercial software it was not always the most up to date version for that time; this could be due to familiarity with older versions or the cost of upgrading. In recent years free and open source GIS have become more popular (Longley et al., 2015), examples found in the search being QGIS [QGIS development team, www.qgis.org] (Brigolin et al., 2015; Dapueto et al., 2015; Ramos et al., 2015) and SPRING GIS [Brazilian National Institute for Space Research (INPE), São Paulo, Brazil] (Santos et al., 2014; Virdis et al., 2014).

Most articles (n = 206, 98%) focussed on a study area(s) in one country, although six studies (3%) considered multiple countries, either as separate case studies (Sequeira et al., 2008; Liu et al., 2014), or as part of a regional (Giakoumi et al., 2013; Hofherr et al., 2015) or global analysis (Campbell and Pauly, 2013). As the focus of the present study was on aquaculture, where the research presented had additional case studies for other sectors (e.g. Tammi and Kalliola (2014)), then only the aquaculture case study was considered. One study, Moreno Navas et al. (2012), did not specify a country or area and instead described a neuro-fuzzy classification method within GIS that was used to determine environmental vulnerability of coastal aquaculture.

Ignoring the regional and global analyses, in total there were study areas in at least 44 countries throughout the World (Figure 2). The administrative boundaries in Figure 2 were obtained from

Eurostat (European Commission Eurostat, 2017), the statistical office of the European Union, so the countries had to correspond to those recognised in the shape file. For this reason, in Figure 2 the six articles (Ross et al., 1993; Pérez et al., 2002; Corner et al., 2006; Sequeira et al., 2008; Falconer et al., 2013ab) that had a study area in Scotland were listed under the UK and the three articles (Tsai et al., 2006; Shih et al. 2009; Liang et al. 2010) that had a study area in Taiwan were listed under China. Four studies (Pérez et al., 2003abc, 2005) that focused on Tenerife and one study (Micael et al., 2015) that considered the Azores Archipelago were listed as Spain and Portugal, respectively, as autonomous regions were not delineated in Figure 2.

The geographic spread of studies does not necessarily reflect those areas most in need of GIS-based decision support, e.g. to support site selection, conflict resolution or assess environmental impacts. Over half of the studies considered an area within Asia, with China, India and Vietnam having the most studies (29, 23 and 14 respectively). The high number of studies for these countries may be understandable given their major role in aquaculture production; in 2015 these countries were first, third and fourth, respectively, with regard to the highest aquaculture production by volume (FAO, 2017). However, it is also noticeable that some countries with high production levels (for example Norway and Egypt) were not a key focus for the published scientific studies. Of course, there may be GIS applications and tools that have been developed for these countries, but they may not necessarily have been published in scientific literature or shown up in the database search. However, it must be acknowledged that the focus of scientific studies is not necessarily driven by stakeholder needs, there are other factors that will influence such as funding requirements and scientific interest. Therefore, the results may be skewed by the interests of researchers who may focus on an area or topic, for example Tenerife was a key focus for a number of studies (Pérez et al., 2003abc, 2005).

Most studies reviewed (n = 199, 94%) focused on a sub-national scale, often a waterbody or coastal area. The paucity of studies considering national or international scale could be a reflection of data availability and potential applications. National or international scale assessment is likely to have coarse resolution due to the spatial extent covered. Such assessment is useful for a general overview, assessment of trends or scenarios, large scale planning or for potential development support but more specific spatial assessment for most decision-making purposes would normally have to be at a more local scale with higher resolution. Some studies (e.g. McLeod et al., 2002) employed a multi-stage approach which considered multiple spatial scales, which may be a useful approach for end users.

2.3. Types of study

The articles were sub-divided into nine thematic groups relevant to aquaculture, based on their aims and content (Table 1). More than one theme may have been applicable to some of the studies but to avoid confusion each study was only assigned to the most predominant group. The leading categories were 'Site suitability and site selection', 'Temporal Change' and "Environmental impact", with 73, 52 and 28 studies, respectively, accounting for more than two-thirds of all studies. There were 11 articles that did not fit into any of the designated categories, so they were assigned to a more generic group 'Other'. Between 2000 and 2016 the number of articles and the range of thematic groups increased considerably, and more than half of all studies were published in or after 2012 (Figure 3).

The studies covered a range of different aquaculture systems and species. Figure 4 highlights the different aquaculture systems covered by articles in the three main thematic groups. Shellfish, marine cage and pond aquaculture dominate the site suitability and site selection studies, although in recent years there have been wider applications and interest appears to be developing towards aquatic plants and microalgae. Most temporal change studies focused on pond systems (n = 34, 65% of this Type), and while some of the studies (n = 18, 35% of this

Type) did not distinguish the type of aquaculture system, it is likely that most of these studies also considered pond culture. Ponds and marine cages were the main foci for environmental impact studies, although three studies considered shellfish and there were four studies that did not specify a type of aquaculture.

2.3.1. Site suitability and site selection

The suitability of a site for aquaculture production is of fundamental importance and GIS is ideally suited for assessment (Falconer et al., 2018). It is not surprising therefore that the 'Site suitability and site selection' category relates to largest group of studies (n = 73, 35% of total) reviewed. Site suitability and site selection were also the earliest studies found in the wider dataset, with five articles being published between 1988 and 1995. However, more than half of the site suitability and site selection studies (n = 38, 52% of this Type) were published after 2010 testifying to the continued and ever-increasing use of GIS for this topic. Most site suitability and site selection articles (n = 70, 96% of this Type) considered a sub-national study area, focusing on coasts, catchments or administrative divisions. Only three studies (4% of this Type) considered site suitability at a national level, and no studies considered an international scale across multiple countries.

Most studies found in this category focused on the development of a site selection model, though the type of parameters and number of spatial layers included within the models varied greatly. This is expected as there are no standardised frameworks for developing site selection models using GIS. However, some studies were adaptations of existing models, for example the site selection model developed by Radiarta et al. (2008) was used and adapted by other studies including Liu et al., (2014, 2015) and Aura et al. (2016). New iterations of a model can be useful, particularly as new data, technology and knowledge becomes available. However, updates and adaptations must be clearly stated, and justification is required as to why the original model needed a revision, otherwise there may be confusion. This suggests the need for a common framework for site selection modelling, which includes information for working at different scales and location specific criteria. However, data are often the limiting factor for the application of GIS models for site selection as data may not be available, the quality may be poor or the spatial and temporal resolution not appropriate. In the studies within the site selection and site suitability category, data sources included use of existing and available data, fieldwork measurements and earth observation data.

2.3.2. Temporal change

There were 52 studies (25% of the total) found on temporal change, the earliest was from 2000, but the majority (n = 35, 67%) were published from 2010 onwards. Most (n = 51, 98%) had a study area at a sub-national scale, focusing on a catchment or coastal area. The main type of change considered was general land use variation associated with pond production, followed by studies that specifically focussed on mangrove utilisation mostly associated with shrimp culture. The latter is not surprising since this is one of the main concerns regarding impacts of shrimp aquaculture development (Naylor et al., 2000).

Almost all temporal change studies (n = 50, 96%) used satellite data, although some studies used a combination of aerial photographs or maps in addition to satellite data. Data obtained from Landsat were the most popular with at least 38 (75%) studies using at least one scene from one of the Landsat satellite sensors. The popularity of Landsat is likely due to it being the first, and the longest, earth observation (EO) programme designed to collect data about natural resources so there is an extensive archive covering over 40 years, from the original Landsat-1 to the most recent Landsat-8 mission (Lillesand et al., 2015). Consequently, Landsat data are very useful for monitoring temporal change over many years. Although the resolution varies between the satellite sensors, Landsat is considered a moderate resolution system (when moderate is defined as 4m – 80m) (Lillesand et al., 2015), and this resolution is useful for monitoring changes across catchments or coastal areas. Significantly, the United States Geological Survey (USGS) have made the full data publicly available and downloadable at no cost since 2008 (Lillesand et al., 2015). This may also be a reason for the popularity of Landsat use in temporal change studies for aquaculture; 33 out of the 38 studies which used Landsat were published after 2008. However, this may change in the future with consideration of charges to access Landsat satellite data (Popkin, 2018). Other options include the free and open data from the recently launched Sentinel satellites which are part of the Copernicus programme (Aschbacher, 2017).

2.3.3. Environmental impact

Environmental impact is a key area for regulation and management of aquaculture. GIS can be advantageous as a framework for decision support tools as many aspects of environmental impact have a spatial element. There were 28 studies (13% of the total) grouped in the 'Environmental impact' theme. The earliest study was published in 2001, but more than 60% (n = 17) in this group were published after 2010. All had a sub-national scale, focusing mainly on ponds and marine cages (Figure 4), and a broad range of topics were covered, including waste dispersion, salinization of land and groundwater, and nutrient loading.

Most of the studies in this category differed from one another in nature and it was not possible to generalise their data use and/or methodology. Even when focusing on a similar topic such as waste dispersion from marine cages there were differing approaches. Pérez et al., (2002) combined a spreadsheet-based model with GIS to estimate the distribution of particulate waste from marine fish cage sites, whereas Corner et al. (2006) developed a fully integrated GIS model using a specific software module. However, the dynamic nature of the marine environment can be difficult to model solely in GIS, so Tironi et al. (2010) and Moreno Navas et al. (2011) both employed more complex approaches involving 3D hydrodynamic models, particle tracking and GIS to estimate waste distribution from cage aquaculture and implications for the wider environment. It can be useful to integrate GIS into a wider framework with multiple components in this way, as the strengths and limitations of each can be matched and the overall outcome improved. This is not just advantageous for environmental impact studies as similar approaches were evident in other thematic groups, where studies such as Nocchi and Salleolini (2013) and Ferreira et al (2014, 2015) used a combination of models and software in addition to GIS. However, there is also a risk of increasing complexity which could limit potential applications beyond a specific study area.

2.3.4. Remaining thematic groups

Although site selection, temporal change and environmental impact studies dominate the primary scientific literature, applications have become more diverse in recent years (Figure 3). For example, between 2012 and 2016, six studies (3% of the total) were published on ecosystem services, suggesting the use of GIS to evaluate aquaculture and ecosystem services could be an emerging area of interest and follows the similar increasing trend of the broader ecosystem services discourse noted by Chaudhary et al. (2015). Furthermore, it is apparent from the wide range of studies within the 'Other' category that more thematic groupings could emerge in the future as more studies are published.

3. Use of GIS as tool for aquaculture stakeholders

It is clear that GIS has many advantages for aquaculture stakeholders, notably the ability to process and store a vast range of data sources, resolutions and time-series data (Falconer et al., 2018). Consequently, GIS can be used efficiently and effectively to explore spatial and temporal aspects of aquaculture, linking between biology, physiology, environment, production systems, legal frameworks, socio-economics and infrastructure.

3.1. Availability and need for GIS-based tools

A tool is something that enables a user to perform a task or particular function in order to answer questions. GIS can be used as a tool to explore, analyse and model spatial issues, and it can also be used to develop bespoke, fixed and standalone tools (Longley et al., 2015). While both uses are important for aquaculture planning and management, arguably the former is more useful for academic researchers as this provides the flexibility to explore a research question, while the latter is more beneficial to aquaculture stakeholders as the tool will have been designed for a specific purpose and does not necessarily need advanced technical skills. During a consultation on European aquaculture licensing and regulation, stakeholders requested more such GIS-based tools to assist the decision-making process (Kane et al., 2017).

The assessment of primary scientific literature revealed that most studies used GIS as a tool to investigate a research question or issue, with fewer examples using GIS to develop a tool for use by stakeholders. Where GIS was used for tool development this was rarely developed to a fully usable and functional end-product, though there will be indirect influences on non-academic or commercial applications. Nevertheless, the findings of the primary literature assessment, together with the results of the stakeholder consultation (Kane et al., 2017), suggest there is a gap between scientific research and development for practical, GIS-based end-user tools.

3.2. Considerations when developing a GIS-based tool

3.2.1. Stakeholder needs and tool capabilities

Developing a GIS-based tool can be a challenging and time-consuming task but there are some steps that can make the process more efficient and should lead to better uptake by stakeholders. First and foremost, the developer must determine the overall purpose of the tool and the intended users as this will influence how the tool is structured and how it can and should be operated. It is vital to consider the capabilities of the end user and training requirements as issues can arise through misuse of a GIS tool by individuals operating without the necessary skills or knowledge (Longley et al., 2015). GIS-based tools can be targeted to focus on a specific purpose, so it is important to define the aim, as well as the intended function to allow appropriate use by stakeholders. Part of the process should include a review of existing tools, to ensure any new or improved tools are building on existing approaches or filling gaps and not simply duplicating previous efforts unnecessarily.

Research in other sectors has shown that ease of use, cost-effectiveness, performance and relevance are amongst the most important factors for end users (Hochman and Carberry, 2011; Rose et al., 2016). Stakeholder needs, and the capabilities of technology and developers, should be defined from the start to avoid unrealistic expectations. Throughout the development process, a continuous focus on user needs should ensure the tool is relevant and useful. To facilitate this, it may be useful to implement the design thinking method where developers follow a process which focuses on the needs and perspectives of users (Goodspeed et al., 2016). This approach can be adapted for aquaculture (Table 2). The advantage of design thinking is that it provides a structure and clear agenda for the entire tool development process (Goodspeed et al., 2016). Empathising with users at the start of the project is essential to understanding their needs and requirements. At this stage the developer can also ascertain the technical skills and knowledge of the users. Following the consultation, the developer must define the scope of the tool, before embarking on a creative, brainstorming process where potential ideas are discussed and prioritised. While there may be clear goals and ideas regarding the structure and content, it is important to allow new or different ideas to be explored at this stage as this there could be a simple or innovative solution for a more efficient and useful tool. A prototype should be designed, with stakeholder consultation as part of the process, and then tested with users, allowing time to refine the tool based on feedback. This process will require time, resources and effort from developers and users (Goodspeed et al., 2016), but the investment will usually be rewarded at the end with a tool that addresses the needs of the stakeholders and therefore is more likely to be used.

3.2.2. Data

Data are at the heart of a decision-making tool. However, data collection can be costly and there are always trade-offs between the data that should be collected and the data that can realistically be obtained. In the case of aquaculture, there may be commercial confidentiality associated with data which may affect any analyses or development of a tool, particularly if that tool is designed to be widely available. Online repositories, often backed by national governments and international organisations, can be an extremely valuable data source but there is still a need to consider the data quality and the appropriateness within an application as the data may have originally been produced for a different purpose. Data should always be accompanied by documentation, known as metadata, that describes the dataset and includes key information such as age, ownership, quality and any restrictions for use (Maguire and

Longley, 2005), and there are established standards for this (ISO2014ab). It is important to clearly outline any data restrictions or issues with data quality within the metadata to prevent misuse. In some cases, ethical and legal issues could arise due to errors in the data or if data are used incorrectly within a tool as part of the decision making process, and there are debates regarding who would be accountable, responsible and ultimately liable for such issues (Goodman, 2016). This may be particularly relevant if tools are employed as part of a regulatory process or to make financial decisions and misuse leads to a breach of compliance, unacceptable impacts or monetary losses. Therefore, caveats and disclaimers play an important role, yet it is also necessary to strike a balance as too many warnings will render the data unusable.

Open data provides increased transparency, reduces duplication of efforts and facilitates collaboration (Pfenninger et al., 2017). However, while this is the ideal situation, particularly in an academic setting where it is also often a requirement of funding bodies (Fecher et al., 2015), in reality for applications that will be used by industry, the situation is more complicated and open data may not be achievable. When using data from other sources it is vital to comply with the associated terms and conditions. In many cases datasets are available for educational use or non-commercial applications which could limit their use in industry tools. So there may be a need to reach an agreement, perhaps for a one-off or subscription fee, with the original owner or provider of the data. This is a barrier to many scientific tools becoming commercial realities. For some aquaculture applications, data may be commercially sensitive and there may be security and privacy risks if data is not secured properly (Zissis and Lekkas, 2012). Data providers and/or end users will need strong assurances and guarantees that any confidential information is stored and used in an appropriate manner.

As with any application, if the data are not fit for purpose then, regardless of how simple or sophisticated the tool is, it will be of limited use and the outputs may be misleading. Errors introduced in the data acquisition stage can propagate throughout analyses, affecting the output (Biljecki et al., 2018). When developing a tool, a developer has a choice to either populate a tool with some or all of the necessary data or allow the user to input their own data. In some cases, the former is suitable for a regulatory decision-making environment, but it may lack the flexibility required to investigate alternative scenarios. As with agriculture (Rose et al., 2016), if end users are unable to tailor a tool to their own needs then they may find it irrelevant, but this is something that should be identified during the development phase (Table 2).

3.2.3. Accessibility and longevity

Accessibility and longevity are important factors in the use and acceptability of tools. A tool must be made available in an appropriate format for stakeholders to use, but there are different ways to develop a GIS-based tool for different purposes and the lifespan of a tool may also vary. Some tools have been developed as add-on modules for specific GIS software. For example, Corner et al. (2006) developed a GIS-based waste dispersion model that was developed as a module for the IDRISI GIS software. However, this relies on the user having access to that specific software and there may be compatibility issues with future versions of the software. If GIS based tools have been developed as a commercial product then there is often a support package included or available as an add-on, this can be extremely valuable for end users as usually advice and solutions can be provided for troubleshooting, bug fixing and general enquiries. Although often associated with a fee, the user has the assurance that there is help if required and this increases the overall accessibility of the tool.

Web-based tools can be useful. However, they must be maintained, which may require time and resources beyond the initial lifespan of a project. It is also important to ensure that once a GIS-based tool is made available via the web it is necessary to ensure the content is relevant and up to date, this is particularly important if the tool is freely available and open to all stakeholders. Increasingly, online data portals and web-based services are becoming a popular way to share GIS outputs (Longley et al., 2015) but if they are operated by another organisation the original developer may have limited options for maintenance and over time such platforms may change, or the content may become inaccessible. Bricker et al. (2016) added a GIS layer to an existing web-based GIS tool for aquaculture site selection. However, the links provided are no longer active.

4. Future of GIS and aquaculture

GIS has evolved considerably since the 1980's when it was first used for aquaculture. While once GIS was reserved for technical specialists with access to heavy duty computing power, it is now far more accessible and used for many different purposes by users and developers with varying degrees of expertise (Longley et al., 2015). Most smartphones and tablets now have the capability to operate as a mobile GIS device, moving GIS from the office and out into the field (or farm) and can be an efficient way of collecting spatial data and performing a quick analysis or visualization. This is particularly useful for stakeholders with limited time and resources. Dedicated GIS software are regularly updated with new features and specific modules. In recent years, the rise of open source GIS software such as QGIS has encouraged the development of plugins that can be used for a particular purpose. For aquaculture there is the potential to develop something specific or use broader applications such as QSWAT (Dile et al., 2018), which could offer potential solutions for catchment-based management within a GIS environment. Furthermore, GIS is commonly complemented by other software and programming languages. Python has been used for a number of years and is firmly integrated within the ArcGIS suite enabling quick and efficient data manipulation and automation of routines (Zandbergen, 2014), however R also has growing library of spatial packages and its strong statistical capabilities make it very useful for processing and analysing spatial data (Brunsdon and Comber, 2015).

Potential data sources are also increasing and becoming more diverse. Existing sources of data, such as remote sensing and EO, are more popular and widespread than ever before, and the resolution and frequency of data continues to improve (Palmer et al., 2015; Aschbacher 2017). Novel approaches, such as the use of citizen science, where researchers collaborate with the public, are being used more and more to collect data that would otherwise be too costly or time consuming to obtain by a small team (Brewin et al., 2017; Støttrup et al., 2018). However, this must be carefully managed as there can be issues with engagement, training and data quality (Kosmala et al., 2016). The integration of near and real-time data with GIS can be a powerful way of assessing impacts (Qin et al., 2017) or potential hazards (Lagmay et al., 2017) and allowing action to be taken. However, although technological advances must be welcomed and embraced, care must be taken as there can be unintended consequences from reacting too quickly to real-time spatial information (Miller, 2018). Context is key and in most cases people should use the data and analysis to make the final decision, rather than automate the process.

Increasingly the world is connected via the internet. The Internet of Things (IoT), is a broad term used to refer to the extension of the internet to physical items and ‘smart objects’ which are all connected and exchange data and information continuously (Miorandi et al., 2012; Gubbi et al., 2013). This offers potential for collection of spatial data, automated spatial analysis and real-time decision making (Nourjou and Hashemipour, 2017) that could facilitate aquaculture planning, management and even emergency response. However, it is also important to note that in many parts of the world aquaculture is practiced in rural and often poor communities which remain unconnected to the virtual world. Thus, while IoT offers exciting development for some parts of the sector, there are other farming systems that have more basic requirements and any GIS-based tools would have to take this into consideration.

5. Conclusions and recommendations

The world is facing unprecedented challenges in the face of the growing human population and climate change. Space and resources are already limited and competition amongst users will only continue to increase. Spatial issues must be explored and analysed to ensure aquaculture is planned and managed appropriately. The review of primary scientific literature has shown that GIS can play a valuable role in aquaculture planning and management and the number and types of studies have increased considerably as production has grown.

The most common GIS applications in the present study were related to site suitability and site selection, temporal change and environmental impact. These are certainly key to effective and efficient aquaculture production and increasing environmental sustainability. However, at present there seems to be inconsistent use of GIS technology and its application of data collected for this purpose, resulting in the outcomes and decisions made also being inconsistent and variable in usefulness. Therefore, there are a number of recommendations which can made from the present study outcomes to help address this situation:

Recommendation 1 (Usability of the tool): The use of GIS for spatial planning for aquaculture development is important. However, effort is needed by developers to ensure that the tools developed are relevant to the activity and stakeholders needs, that they are made available in a form useable to the end-user and can be tailored to the end-users needs. This is where a design thinking method can be useful (see Table 2) to account for the What, Why and How the system will be used. This suggests that there could be some methodological development of frameworks to guide different GIS activities and uses.

Recommendation 2 (Data requirements): All studies show that the major limiting factor regarding the use of GIS for aquaculture is data. Data availability, data quality and data suitability affect any application and use in a tool. If the data are not fit for the desired purpose, then the application will be inappropriate and its use as a tool could result in misleading outputs. Therefore, in order to increase the number of GIS-based tools, existing and newly collected data should be evaluated according to the following criteria and used accordingly:

- It must be available and used at an appropriate spatial scale for the decision reached to be meaningful.
- It must be of a suitable quality to fulfil the requirements of the tool and decisions reached.
- It must be up-to-date enough to fulfil the requirements of the tool and decisions reached. For example, online data portals and shared information can quickly go out of date.
- The data provider should ensure that sufficient information is made available for a user to determine if that data is useful.
- The tool developer and/or user has a duty to ensure the information used in the tool is appropriate for the decisions to be taken.

Recommendation 3 (Accessibility to end user): Tools must be made accessible in a format which the end user can or has the ability to employ. This will encourage uptake of the tools for decision making and ensure the decisions are appropriate for a particular situation. For example, it would be inappropriate to use IoT to develop a sophisticated real-time GIS based flood risk model if the community does not have sufficient access to the internet.

Recommendation 4 (Capabilities and training requirements): Capabilities of the end user for use of a tool should be considered to prevent misuse and mis-interpretation of the outcomes. Consideration of training requirements to use any developed tool should be considered at inception. Clearly this is linked to the end-point and technical sophistication of the tool/software and what the end-point of the tool is. Consequently, tools should only be used by end-users with appropriate knowledge to use and apply the tool.

Recommendation 5 (Longevity of the tool): Maintenance of the GIS tool is an important factor to consider at its inception. Sophisticated and well-designed GIS web-tools are of little use if there is no provision made for their maintenance after developed. Circulated software of add-in based tools must also be updated to allow for new underlying software developments and data formats.

In conclusion, it is expected that academic studies in the use of GIS and aquaculture will continue to follow the trend of increasing in number and type. However, further work is needed to bridge the gap between scientific studies and user needs. The tools that are most useful for aquaculture producers may not necessarily require state-of-the-art technology and should instead focus on how to address the user needs, efficiently solve the problem or make the decision in the most cost-effective way. Moreover, the recommendations outlined here can be used to guide the process. Spatial issues must be at the forefront of aquaculture planning and management. Without doubt, studies which focus on pure intellectual challenges and those which are more applied both have a valuable role to play in understanding and analysing the spatial issues associated with aquaculture. This will support the sector to maximise its contribution to food and nutritional requirements, minimise environmental impacts and manage use of resources.

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Appendix I

List of papers that were used in the assessment of primary scientific literature.

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Table 1: Primary scientific literature categorised by thematic group

Type of study	Number of articles
Site suitability and site selection	73
Temporal change	52
Environmental Impact	28
Risk to aquaculture	11
Inventory and mapping	11
Spatial conflict and planning	10
Ecosystem services	6
Animal and human health	5
Livelihoods and socio-economic issues	4
Other	11

Table 2. Adapting design thinking to Aquaculture GIS tools (after Goodspeed et al, 2016).

	Empathize	Define	Ideate	Prototype	Test
What	Observe, listen to and engage with users, to obtain clear knowledge of their needs	Define bottlenecks and problems to be solved	Brainstorm ideas for tool development. Prioritize	Create physical representation of the tool	Develop prototype
Why	Ensure you know users needs	Focus on the problem the tool shall solve	Give all creative ideas a chance	First test and feedback from users	Second test and feedback from users
How	Workshops, interviews	Analyses of interviews, workshop		Create wireframes	Working online prototype to share with test group

Figure legends

Figure 1: Overview of the literature search and identification of articles on GIS and aquaculture for further analysis based on the guidance set by Preferred Reporting Items for Systemic Reviews and Meta-analysis (PRISMA) (Moher et al., 2009)

Figure 2: Number of articles and location of study area. © EuroGeographics for the administrative boundaries.

Figure 3: Number of articles published each year in the thematic groups

Figure 4: Type of aquaculture system featured in site suitability and site selection, temporal change and environmental impact studies

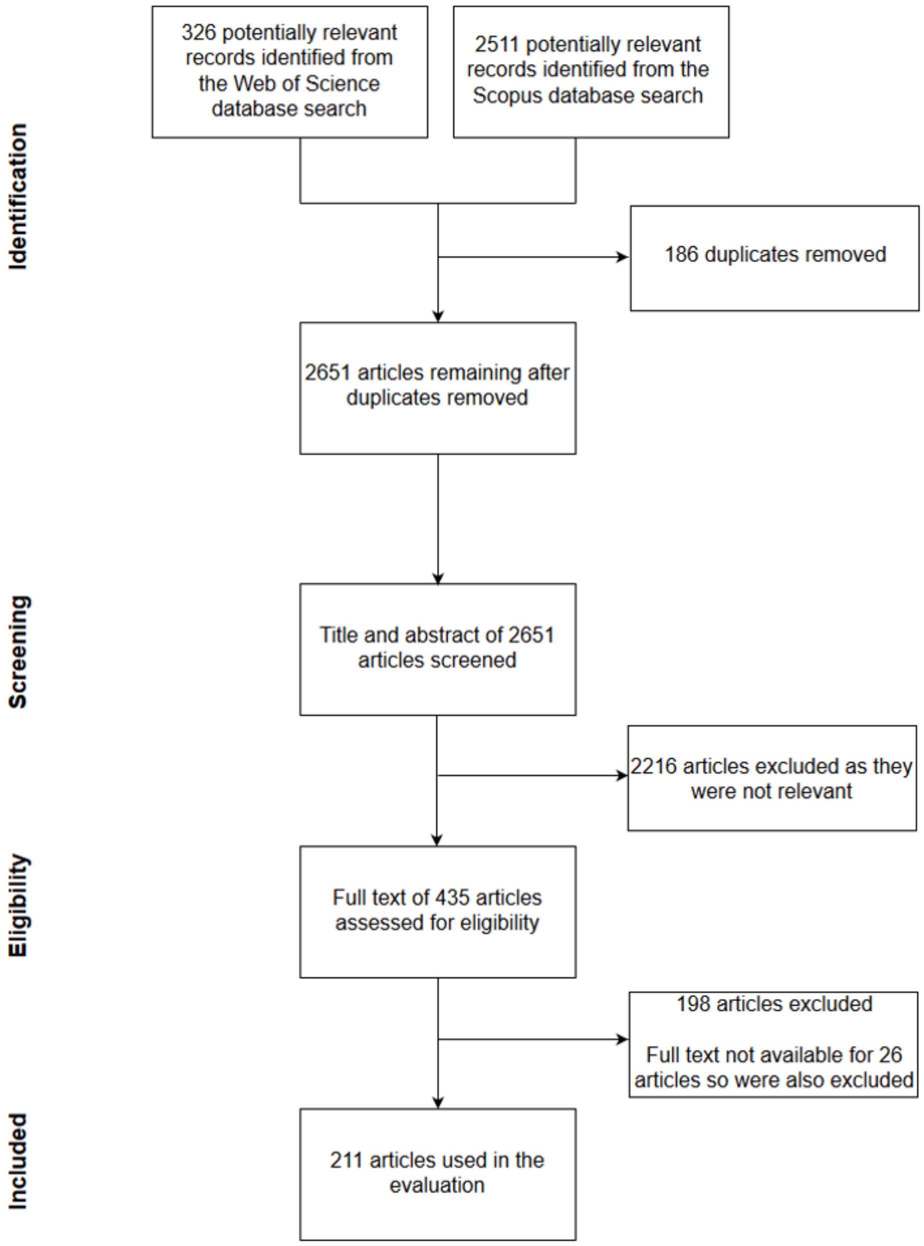

Identification
Screening
Eligibility
Included
326 potentially relevant records identified from the Web of Science database search
2511 potentially relevant records identified from the Scopus database search
186 duplicates removed
2651 articles remaining after duplicates removed
Title and abstract of 2651 articles screened
2216 articles excluded as they were not relevant
Full text of 435 articles assessed for eligibility
198 articles excluded
Full text not available for 26 articles so were also excluded
211 articles used in the evaluation

Figure 1

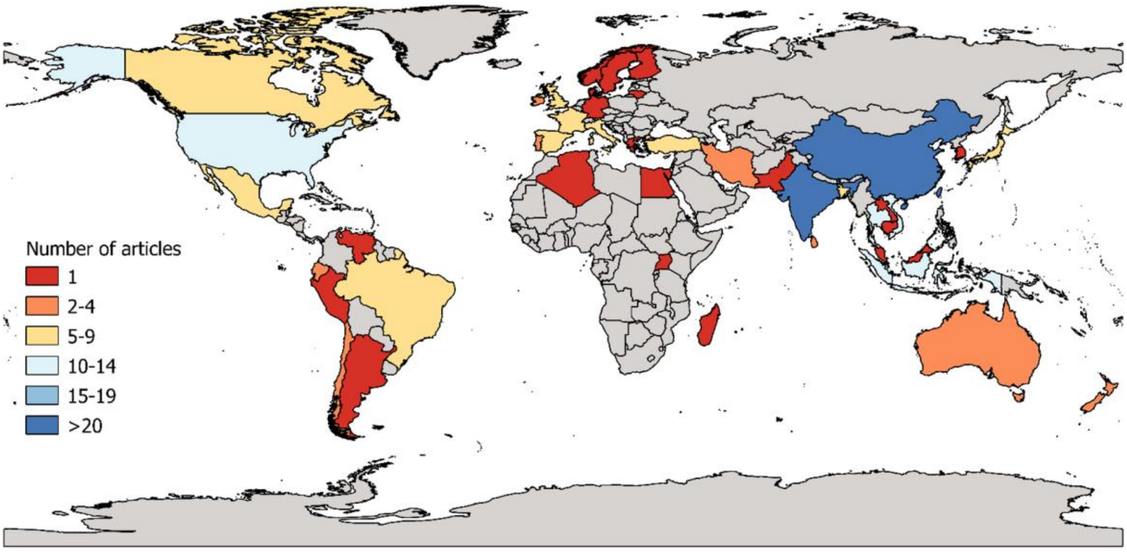
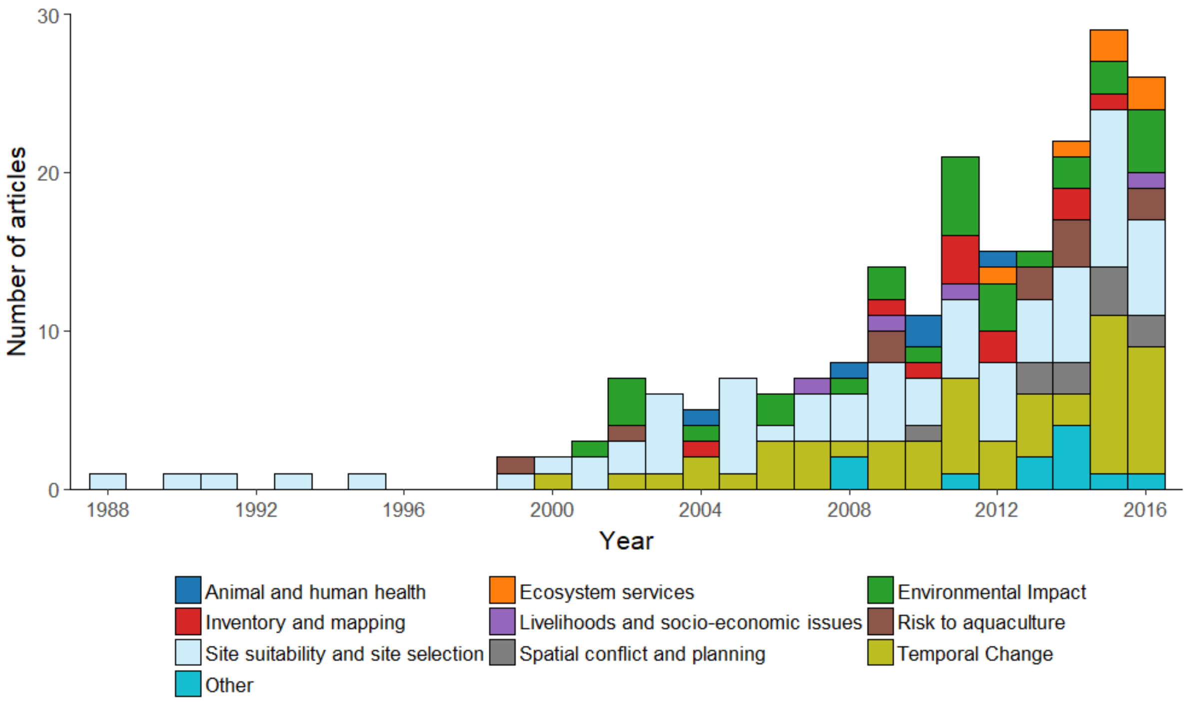


Figure 2



30
20
10
0
Number of articles
1988
1992
1996
2000
2004
2008
2012
2016
Year
Animal and human health
Ecosystem services
Environmental Impact
Inventory and mapping
Livelihoods and socio-economic issues
Risk to aquaculture
Site suitability and site selection
Spatial conflict and planning
Temporal Change
Other

Figure 3

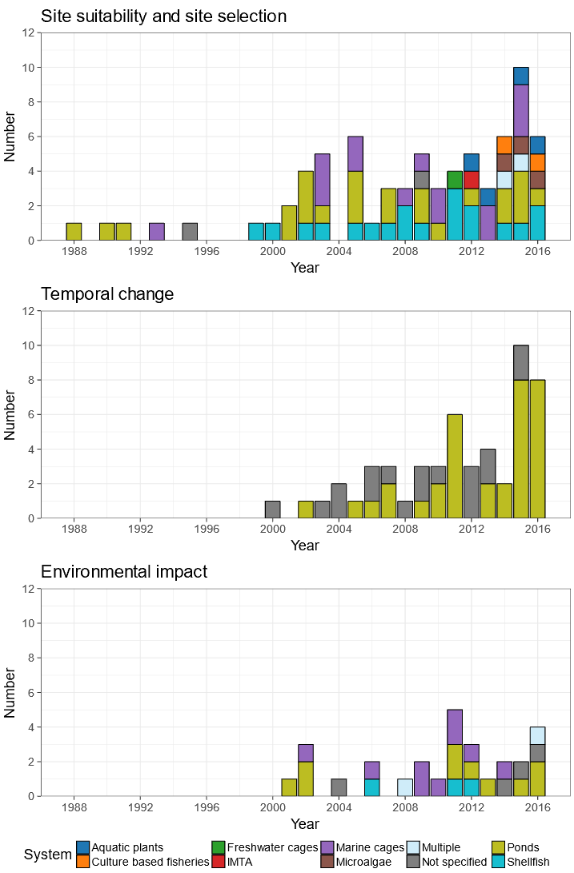

Site suitability and site selection
Temporal change
Environmental impact
Number
Year
0
2
4
6
8
10
12
1988
1992
1996
2000
2004
2008
2012
2016
System
Aquatic plants
Culture based fisheries
Freshwater cages
IMTA
Marine cages
Microalgae
Multiple
Not specified
Ponds
Shellfish

Figure 4