1. Introduction

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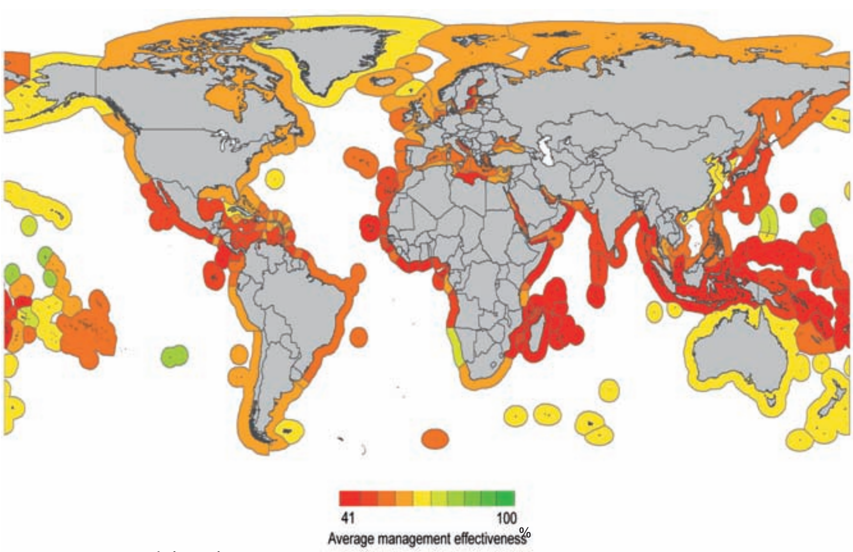
For several decades it has been recognized that the world's fish stocks are becoming increasingly depleted, with the Food and Agriculture Organization of the United Nations (FAO, 2012) recognizing that 57 percent are fully exploited, 30 percent overexploited and 13 percent are not fully exploited. Even a decade ago, Myers and Worm (2003) established that stocks of higher trophic level species were only about 10 percent of their pre-industrial fishing levels, and now in specific areas or fisheries the spawning biomass has been reduced by over 97 percent. Throughout the developed world there is evidence of a rapid growth in fish landings and effort during the early twentieth century, with declining catches occurring after the 1960s. In less developed areas, this rise and fall of fisheries is a more recent phenomenon. Stock overexploitation results not only from too much fishing pressure from highly capitalized fleets, but also from poor fishing practices and management (including illegal fishing), from conflicts in the use of marine space, from political decisions prioritizing short-term socio-economic considerations over longer-term environmental realities, and from various forms of environmental degradation. In less developed areas, fishery problems are compounded by the high demand for fish in protein-restricted circumstances, the lack of alternative employment,

FIGURE 1
Overall effectiveness of fisheries management in the world's exclusive economic zones



Source: Mora *et al.* (2009).

poor governance, and the lack of knowledge and data. Worldwide, the impacts of stock depletions are felt on the unsustainability of remaining stocks, on massive economic waste, increasing social costs and food insecurity. There is now an urgent need for fisheries to be managed more effectively, especially in lower income areas (Mora *et al.*, 2009). Figure 1 provides an indication that none of the fisheries in the world's exclusive economic zones are being managed at more than an 80 percent effectiveness level, with the majority at about 50 percent.

To add to these anthropogenic and institutional problems, fisheries are experiencing pressures that are externally imposed. The rapid world population increase means that food demands are soaring, giving rise not only to uncertainties in supplies but also to price increases and instability. Energy costs have also been rising sharply in response to strains on both demand and supply, and this affects the price of most goods and services, including the direct cost of fishing. The most worrying externally imposed problem, however, is that caused by climate change, with its profound effect on species distributions, ecosystems stability, trophic web interactions, and the very existence of many aquatic ecosystems. Climate change will have other impacts on fisheries through changing weather patterns and sea levels, and it will necessitate rapid and diverse changes in the socio-economics of most fishery activities (FAO, 2008).

It is not only marine fisheries that are undergoing rapid change and uncertainty. Mainly in developing countries, inland fisheries for local consumption have shown significant growth since the 1970s; this contrasts with the situation in developed countries, where catches from recreational fishing have now overtaken commercial inland fish production. However, there are generally large uncertainties on the stock situation for most inland fisheries, and appropriate management of fish stocks is minimal in most areas, especially in developing countries. All stocks in inland waters are particularly vulnerable to increasing environmental pressures and to climate change, which often negatively impacts water quality and quantity. But it is human activity near water courses that prove most detrimental to sustaining optimum freshwater ecosystem conditions, and this highlights the need for an ecosystem approach to the management of freshwaters in all areas.

To counteract the problems and demise associated with capture fisheries, over the second half of the twentieth century there was a significant and almost exponential increase in fish output coming from aquaculture systems, with production providing some 46 percent of fish for worldwide human consumption. About 90 percent of aquaculture production now takes place in the Asia-Pacific region. Recently, various pressures have caused the rate of increase in aquaculture output to slow down, and, if fish supplies from this source are to be maintained, it will be important to produce lower trophic level fish to reduce the fishmeal content of feeds and to promote environmentally sound aquaculture practices and resource management. Of critical importance will be the successful integration of fish production into a wide range of conventional farming practices. These various requisites for successful aquaculture are themselves totally dependent on a good site location, with this applying to both marine and inland farmed production.

Although not all problems of securing adequate future fish supplies are within human control (fish recruitment is also exacerbated by biological and natural physical perturbations), there remains a fundamental necessity to develop improved fishery management measures. This is being addressed through new approaches, such as the ecosystem approach to fisheries or the ecosystem approach to aquaculture, and to more holistic marine spatial planning. Arising from the above discussion, it is the thesis of this technical paper that the majority of the problems currently faced by world fisheries and aquaculture lie in the spatial domain. Thus, there is spatial dis-equilibrium among the factors of production (production functions) that control, regulate or best determine a successful fishery or aquaculture unit. The technical paper describes the main production functions; explains how the distribution of these functions may vary from area to area, and how each function's relative importance to fish production success also varies. Through analyses of the relationships between spatially variable production functions, it is possible to establish optimum input combinations so as to achieve successful production outputs. Fisheries managers will increasingly need to consider the spatial aspects governing output, and this is best done through the use of geographic information systems (GIS).

GIS are essentially spatial analysis software, though for the system to function properly, it is necessary to consider the hardware, data, personnel and procedures that are essential to obtaining useful output from the software. The types of spatial analyses that GIS provides include measurement (linear, aerial, volumetric and temporal), distribution and relationship analyses, network analysis, geostatistical analyses, interpolation, and a wide range of modelling. GIS is now used in a broad spectrum of application areas, including by government, business, academia, industry, military and natural resource management (including fisheries and aquaculture).

Because it is useful to have information on the development stages through which any technology has evolved, the emergence of GIS as a tool for spatial analysis is described in terms of three historical stages. First, early innovations took place between 1960 and 1980 when digital developments in graphical representation and database management allowed for simple mapping output using mainframe computers and line printers or plotters. Output costs during this period were extremely high, so work was limited mainly to government or major institutions or businesses. Second, the era of GIS commercialization spans the years between 1980 and 1995: costs rapidly came down and allowed markets to expand and data became far more abundant, mainly from remote sensing sources. The migration of computing capability from mainframe to micro computers (personal computers) contributed greatly to GIS proliferation, and it was in this period when application areas for GIS expanded, aided by necessary supporting infrastructure developments. At the end of this period, the world market for geospatial systems and services was growing at a rate of 14 percent per year. Finally, the period since 1995 has been an era of mass spatial exploitation. The use of spatial analyses has been recognized in many fields of study. GIS software companies have consolidated to produce some six to eight major proprietary software brands, and a whole infrastructure of support industries and associations has developed, including GIS educational programmes at all levels. Recent developments have been greatly facilitated by the Internet.

What are the reasons for this successful growth of GIS? They are briefly examined under four headings:

- **The growth in computing power.** Over the past 50 years, there has been an unremitting growth in computing power in terms of not only computers themselves, but also in terms of peripheral hardware devices, data storage capacity, associated software, computer graphics capability, and so on. This computing power increase has been at the rate of an order of magnitude every six years.
- **Progress in parallel developments.** GIS forms one specialized part of a complex and integrated array of mainly digital-based technologies; these include the Internet, remote sensing and global positioning systems, software and hardware, geostatistics, visualization, computer-aided design, and digital cartography. Developments in all of these fields have been essential to the success of GIS.
- **The proliferation of data.** The success of GIS is greatly dependent upon the quantity and quality of input data, and this is especially important for activities such as marine fisheries, which take place in extensive 3D aquatic environments. Numerous technical developments have allowed for both an ease of data collection methods, plus significant data cost reductions and greatly enhanced data storage and transfer capabilities.
- **The increasing demand for GIS output.** Demand for output has been fuelled by reduced costs of GIS processing, by a realization of the wide capabilities of GIS, and by the fact that so many problems are rooted in the spatial domain. Demand has also been spurred by a proliferation of GIS books, conferences, courses and exhibitions.

Because of the complex milieu in which these activities function, early uses of GIS for fisheries or aquaculture purposes were slow to materialize. Complexity is mainly in terms of data gathering, the mapping of moving objects, the 3D nature of aquatic space, and the generally fragmented nature of the organization of fisheries management or research. The first applications of GIS appeared in the mid-1980s, with most early work being led by FAO and aiming at aquaculture location, e.g. Kapetsky, McGregor and Nanne (1987). During the 1990s, GIS applications to fisheries and aquaculture proliferated into thematic areas such as atlases, mapping of habitats and marine productivity, fisheries management, aquaculture location and human impacts on fishery environments. About half of GIS work was directed towards marine fishery subjects, with the balance between inland fisheries and aquaculture. During this period, the first books were published (by FAO): Geographical information systems and remote sensing in inland fisheries and aquaculture (Meaden and Kapetsky, 1991) and Geographical information systems: applications to marine fisheries (Meaden and Do Chi, 1996). And towards the end of the 1990s, the first GIS conferences aimed specifically at fisheries and aquaculture were organized. In the past ten years, there has been considerable further expansion in GIS activity, with the emphasis being on quantitative and qualitative expansion in the work, and with far more sophisticated work being attempted. This is especially true in respect to sophisticated modelling and geostatistical analyses. The promotion of fisheries and aquaculture GIS through activities at FAO has been a major impetus to the recent proliferation of activity in this area.

Chapter 1 concludes with stating the aims of this publication. These aims are basically to outline the ways in which GIS can contribute to resolving many of the problems associated with fisheries and aquaculture, i.e. by taking an approach that assumes that most problems can be perceived as lying in the spatial domain and are thus conducive to GIS applications through relevant mapping and analysis functions. A secondary aim is to update and consolidate the earlier 1990s FAO publications mentioned above.

In preparing a technical paper that impinges on a complex mixture of themes and topics, there is inevitably a problem in arranging a logical sequence of the material. Although a consensus has been reached on the arrangement of chapters, some readers might find it necessary to "skip around" the document in the order that it makes best sense to them. Figure 2 shows the progression of stages through a GIS project and the human influences affecting these process stages. The left-hand column divides all the human inputs into internal (from within the group or organization) and external inputs (outside sources that may influence the GIS process stages). The main body of the right-hand flow diagram shows the linkages among successive stages that will typically be performed during the completion of any individual GIS-based project. It is important to note the feedback loop, which essentially means that the final information output from the GIS can either: (i) be directed towards any of the human inputs so that they are better informed on spatial-based matters relating to fisheries or aquaculture; and (ii) inform any further GIS work, e.g. perhaps as a result of models developed or any methods used. All of the process stages are covered by this technical paper.

FIGURE 2
Progression of stages in a GIS project and the human influences affecting these process stages