1. Introduction

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1.1 SPATIAL CHALLENGES CONFRONTING FISHERIES AND AQUACULTURE

For several decades it has been increasingly recognized that the world's fisheries[1] are threatened by overexploitation and other mainly human-induced problems (Caddy, Carocci and Coppola, 1998; Pauly *et al.*, 2002; Mullon, Freon and Cury, 2005; Clark, 2007). More and more fish stocks are noted as being depleted or threatened and, indeed, in the latest report on the state of the world's fisheries and aquaculture, the Food and Agriculture Organization of the United Nations (FAO) reported that 87 percent of the world fish stocks for which assessment information is available are either fully exploited (57 percent) or overexploited (30 percent), and 13 percent are not fully exploited. Most fisheries thus require effective and precautionary management (FAO, 2012a). Bodiguel, Greboval and Maguire (2009), also working for FAO, preface their recent publication with "Over the last 20 years, the marine fishery resources of the world have been increasingly subjected to overexploitation, detrimental fishing practices and environmental degradation. The phenomenon now affects a majority of fisheries worldwide, with very severe consequences in terms of resource unsustainability, massive economic waste, increasing social cost and food insecurity." (p. vii). In a seminal paper, Myers and Worm (2003) estimate that populations of higher trophic level large predatory fish are only about 10 percent of their preindustrial fishing levels and that this loss, mainly attributed to fishing pressure, is having a serious affect on the stability of ecosystems.[2] And a recently published Green Paper from the European Union (European Union, 2009) reveals that no progress had been made in halting the decline of stocks in European waters during the last decade, and now 88 percent of their stocks are overfished, 30 percent are outside safe biological limits, 93 percent of cod are caught before maturity, and "European fisheries are eroding their own ecological and economic basis." (p. 6).

These stark facts are only a small example of the deluge of publications that collectively portray the increasingly dire circumstances faced by the world's fisheries. Graphical formats also illustrate fisheries demise. Figure 1.1 illustrates a typical longer-term (1889–2007) scenario of fish landings and fishing power[3] for trawlers operating from the United Kingdom of Great Britain and Northern Ireland, a major commercial fishing area. Figure 1.1 (a) shows that landings of demersal fish slowly rose during the early twentieth century as fishing power increased. They peaked during the 1940s through the 1960s (excluding the Second World War period); since then, there has been a rapid decline, and landings for England and Wales trawlers are now only ten percent of those recorded at their peak[4]. Figure 1.1 (b) shows that the effort from sail-powered fishing smacks increased (grey circles) until the 1930s, after which the fishing

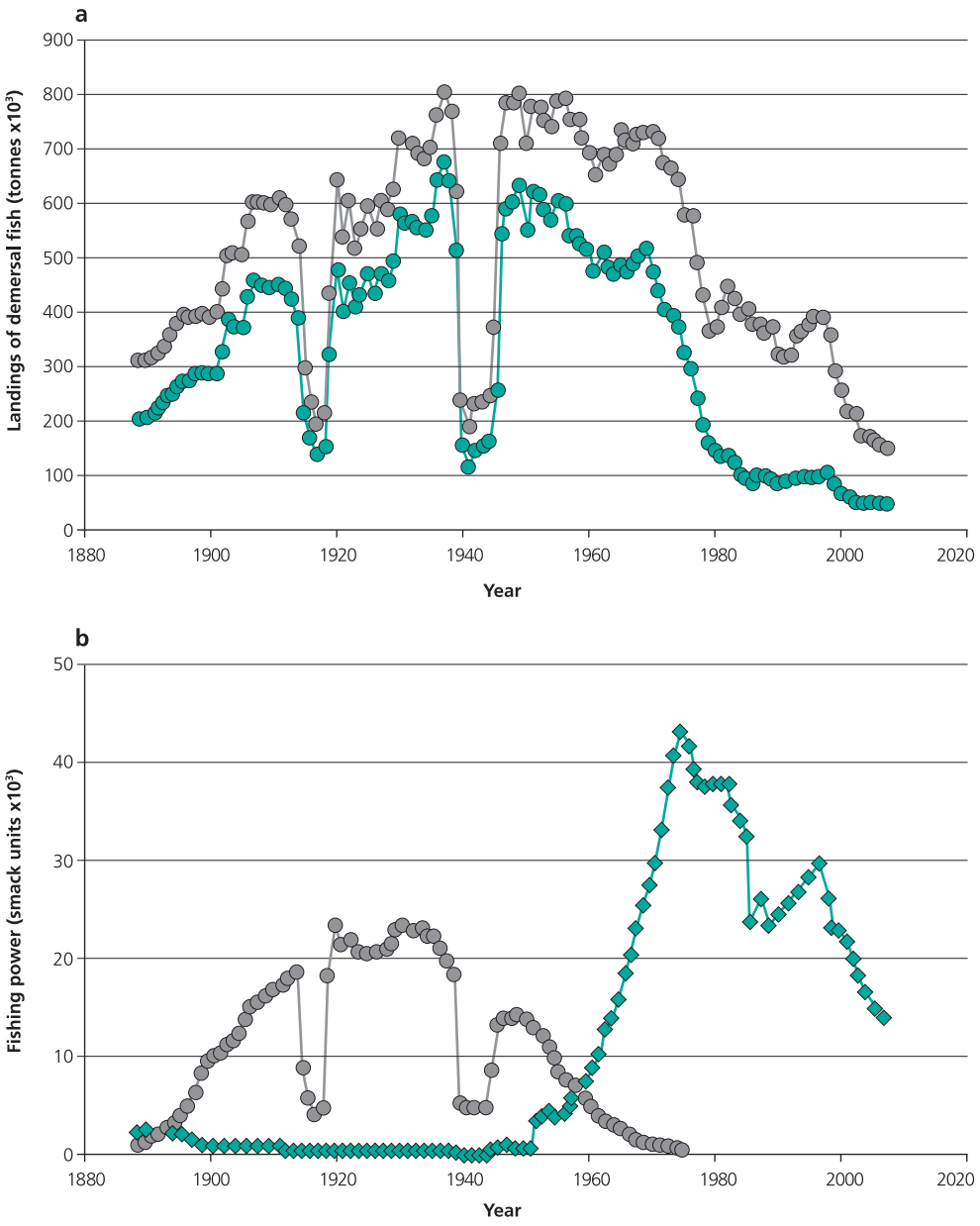
1 Unless otherwise stated, the term "fishery" in this technical paper will refer to both marine and inland fisheries.

2 Loss of higher trophic fish is caused not only by excessive catches of these fish per se, but also by overfishing of lower trophic species, which, therefore, represents a net export of energy that can no longer be used at higher trophic levels (Coll *et al.*, 2008).

3 Fishing power is a standardized indicator of the power (energy) put into fishing; in this case converted to the equivalent of the late nineteenth-century sail-powered fishing smacks.

4 Landings per unit of power for some commercial species of the United Kingdom of Great Britain and Northern Ireland; for example, haddock are now only 1 percent of what they were a century ago (Thurstan, Brockington and Roberts, 2010).

FIGURE 1.1
Change in landings and fishing power for the United Kingdom of Great Britain and Northern Ireland, and England and Wales of demersal fish from 1889 to 2007



Source: Thurstan, Brockington and Roberts (2010).

Note: Grey circles in Figure 1.1 (a) represent the United Kingdom of Great Britain and Northern Ireland landings; green diamonds are England and Wales landings.

power was rapidly replaced by motorized trawlers (green diamonds). These vessels reached their peak in the late 1970s, and then their numbers steadily declined.[5] These are typical production (landings) or fishing power (or effort) graphs that could be replicated formost developed economies. However, at the world scale, the World Bank (2009) has indicated that the global fleet capacity increased by a factor of six between 1970 and 2005, a period during which the global harvesting productivity decreased by

[5] Note the effect of fishing subsidies given by the European Union during the 1990s that caused fishing power to increase.

the same amount. In association with this rise and fall of the fisheries, there have been long-term declines in the spawning stock biomass of nearly all commercial species, and a study by Jennings and Blanchard (2004) estimates that the current biomass of large fish in the North Sea is 97–99 percent lower than it would be for an unexploited stock and Rose (2004) shows that the situation is even worse for the Newfoundland cod fisheries.

Most of these inferred problems are associated with capture fisheries under the jurisdiction of developed countries, especially those in North America, Europe and East Asia, as these are areas where economic resources have been applied to fisheries, such that resource extraction levels exceed sustainable harvesting levels. Additionally, these areas frequently experience conflicts for use of the marine resource space, water quality issues may be problematic, fisheries management may function in a less than satisfactory way[6], political compromises are such that satisfying short-term national socio-economic needs are prioritized over longer-term environmental realities, there may be little knowledge of the level of illegal fishing activities,[7] and fisheries have mostly been managed on a single-species basis rather than as part of a holistic marine ecosystem.

However, because fisheries production and consumption increasingly operate as an international activity, then problems that may have emanated from developed world fisheries are now manifested at the global scale and are severely impacting fisheries in developing countries (Christensen, Aiken and Villanueva, 2007). Recent examples of factors contributing to the demise of fisheries in less-developed areas are summarized in Box 1.1 (Bodiguel, Greboval and Maguire, 2009). The factors given here are broad categories and thus each includes many subcategories of problems. For instance, a "strong demand for limited resources" leads to high prices for fish caught and, therefore, an incentive to invest in more fishing effort that in turn leads to overfishing and, consequently, reduced biomass availability.

BOX 1.1
Factors contributing to the unsustainability of fisheries in less-developed areas

- Strong demand for limited resources
- Poor governance
- Complexity and lack of knowledge and data
- Failure of institutions and policies
- Inappropriate incentives
- Interaction with other sectors and with the environment
- Open access to fish resources
- Poverty and lack of alternatives to fishing

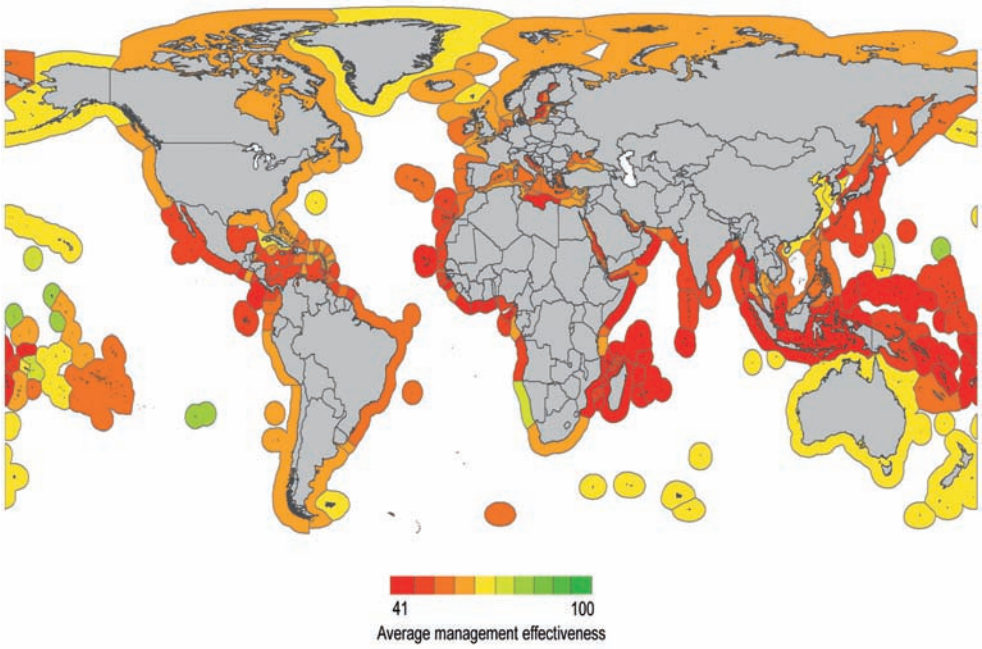
Source: Modified from Bodiguel, Greboval and Maguire (2009).

[6] Examples of poor or inappropriate management include: lax or insufficient legal enforcement powers; poor catch recording including under-reporting; excessive discarding in order to attain legal quotas; over-generous subsidies to support fisheries growth; insufficient incentives for fishers to decommission vessels or to quit the industry; insufficient fishing effort/capacity reductions; inflexible management procedures; use of inappropriate fishing gears; and a lack of cooperation between members of regional fisheries management organizations.

[7] In a recent paper (Agnew *et al.*, 2009), it is estimated that between 11 and 26 million tonnes of fish caught annually are illegally fished or are unrecorded. This level of illegal exploitation severely hampers efforts to sustainably managed capture fisheries.

In many cases, maximizing short-term profits is more important than sustaining long-term exploitation.[8] Interestingly, however, fisheries were often a profitable sector but "the income the sector generated is not allocated to the institutions needed to promote sustainability (fisheries research, management, monitoring or control)." (p. 6). Figure 1.2 gives a general indication at the world scale on the effectiveness of fisheries management for each exclusive economic zone (EEZ)[9] (Mora *et al.*, 2009), and it can be seen that none of the world's fisheries are being managed at more than an 80 percent effectiveness level, with the majority at about 50 percent. There is also a clear link between income levels and management effectiveness, with better management, for example, in relatively prosperous areas such as Oceania, North America, northern Europe and less efficient management in central America, much of equatorial Africa and southeast Asia.

FIGURE 1.2
Overall effectiveness of fisheries management in the world's exclusive economic zones



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

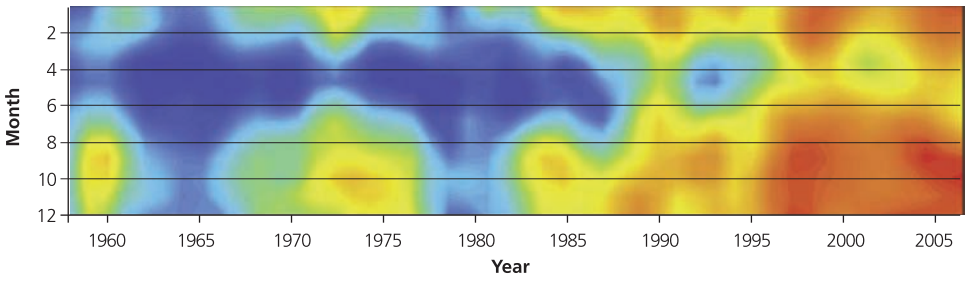
To add to these basically anthropogenic and/or institutional problems, it is likely that fisheries are experiencing problems from sources that are not within their direct control, i.e. so-called external factors. These include matters such as climate change,

[8] In almost all fishery areas studied, Bodiguel, Greboval and Maguire (2009) noted that the demand for fish "was not controlled through appropriate management of fishing capacities." (p. 2) and, indeed, the authors noted that fisheries were often treated as a "transient economic sector", that policies and laws were out of date, that fishery institutions were incapable of coping with substantive problems, that management units were not properly constituted, and that "management was still essentially based on the sector's bioecological component, to the detriment of the other components of sustainability." (p. 3).

[9] This map is based on scores for scientific robustness, policy-making transparency, implementation capability, fishing capacity, subsidies, and access to foreign fishing for each of the surveyed areas.

with its diverse physical, social and economic consequences,[10] plus rising energy costs, rapid population increases and rising food prices. Climate change will rapidly and profoundly affect marine and other aquatic ecosystems as these ecosystems attempt to adjust to varying thermal regimes (Brander, 2007; Cheung *et al.*, 2009a,b), with some organisms being able to make adjustments more easily than others, and with some coastal ecosystems such as salt marshes, lagoons, mangroves, deltas and coral reefs being "squeezed".[11] Figure 1.3 illustrates how the dominance of a warm-water plankton species over a cold-water species has occurred on a monthly and yearly basis in the North Sea, and work by Payne *et al.* (2009) notes how the change in planktonic composition is having an effect on North Sea herring recruitment. Additionally, under climate change, shorter-term weather patterns will be altered and in many places become more extreme, and increasing marine acidity will make life in the sea more difficult for many species. Changes in fish and their associated ecosystems caused by climate change will necessitate rapid and diverse changes in the socio-economics of most fishery activities (FAO, 2008; Cochrane *et al.*, 2009). Other social and economic externalities imposed on fisheries, although readily comprehended, may affect fisheries in exceeding wide and complex arrays.

FIGURE 1.3
A simple ratio between a warm-water plankton species (*Calanus helgolandicus*) and a cold-water species (*Calanus finmarchicus*) per month from 1958 to 2005 in the North Sea



Note: Red values indicate a dominance of the warm-water species and blue values the dominance of the cold-water species.

Source: Adapted from Edwards *et al.* (2007).

Marine fisheries provide nearly 90 percent of all captured fish. The other 10 percent come from inland fisheries. This latter sector has shown slow but continuous growth since at least the 1970s (FAO, 2009b), although some of the growth is due to improved data collection and record-keeping. At least 95 percent of inland fisheries production comes from developing countries, and in developed countries catches from recreational fishing have now overtaken commercial inland fishing production. At the world scale, the fish stock situation for inland fisheries is quite complex, partly because the fishery activity and the records for this are fragmented and thus there is little real knowledge of the overall status of the fisheries (Welcomme, 2011). The stock dynamics are significantly controlled by environmental processes, principally climate-induced

[10] Allison *et al.* (2009) note the huge economic vulnerability that will be incurred by many developing countries because of the affect that climate change will have on their capture fisheries. The main countries affected will be Bangladesh, Cambodia, Colombia, Guinea, Malawi, Pakistan, Peru, Senegal, Uganda and Yemen. Their vulnerability will be due to the combined effect of predicted warming, the relative importance of fisheries to national economies and diets, and limited societal capacity to adapt to potential impacts and opportunities.

[11] Meaning that ecosystems are unable to adjust rapidly enough or that there is no space left for them to move into.

floods and droughts, plus high variations in nutrient inputs with their consequent effects on freshwater productivity. In conjunction with natural environmental perturbations, there are major anthropogenic impacts, including species introductions, pollution (mainly from sewage and agricultural runoff), multi-use of inland waters, sedimentation, habitat disturbance and degradation, all of which reduce the resilience of the stock. Climate change will have a severe impact on natural distributions of all freshwater species (Fisher and Rahel, 2004b).[12] Suitable habitat for each life stage in inland waters is dwindling rapidly, so it has become increasingly clear that inland fisheries particularly require an ecosystem approach to their management, especially in larger catchment areas, and that more effective governance and management is required in most inland fishery areas.

Given the sustained demand for fish as a high-quality protein (Delgado *et al.*, 2003; Wijkstrom, 2003) and given that production from marine and inland fisheries has reached a plateau, then the only source of increased fish production must come from aquaculture. Worldwide, the rate of growth in aquaculture output has been high at about 7 percent per year from the 1950s to 1980s and over 11 percent since then (Delgado *et al.*, 2003), with aquaculture now supplying some 46 percent of fish for human consumption (FAO, 2010a) and with 90 percent of production being concentrated in the Asia-Pacific Region (FAO, 2009b). However, this growth is slowing down and there are concerns regarding the ability of aquaculture to provide for future fish protein needs, certainly at costs that can be met by poorer consumers.

Naylor *et al.* (2000) identify the following four production priorities if aquaculture is to successfully fill at least part of the growing fish products deficit:

- expansion of the farming of low trophic level fish;
- reduction of fishmeal and fish oil inputs into feed;
- development of integrated farming systems;
- promotion of environmentally sound aquaculture practices and resource management.

The last point encapsulates the absolute priority for the aquaculture industry as a whole, but the achievement of this is fraught with challenges.

Kapetsky and Aguilar-Manjarrez (2004) have pointed to the criticality of site selection if aquaculture is to be successful. In many cases, aquaculture is only one of many farm practices, so it may be competing for production space. Yet, its inputs criteria are far more complex than most other farm crops and, generally, the activity demands production space that is both highly desirable and is in very limited supply.[13] Therefore, it may be increasingly difficult to finance, identify and secure specific sites or locations for terrestrial-based aquaculture activities, and poor location choice can have disastrous consequences in terms of stock losses related to pollution or disease. Location problems are exacerbated by generally uncertain future water supplies, extreme weather events, increased incidence of poor water quality and sea level rise (Brander, 2007). Marine-based aquaculture production is likely to be limited by the price and/or availability of suitable broodstock, seed, fishmeal and fish oil inputs, and by exacting physical controls such as shelter, water quality and water depth. On top of these problems, there are social, educational (knowledge), political and planning (regulatory) and market constraints to aquaculture expansion. This comprehensive range of controls that may limit aquaculture expansion points to the need for an ecosystem approach to aquaculture, and there are strong signs that this has been recognized (Perez-Sanchez and Muir, 2003; Kam, Prein and Day, 2007). Despite all the challenges, it is likely that aquaculture will continue to grow in response to the

[12] Fisher and Rahel (2004b) show that with a 3 °C rise in temperature there will be a 50 percent loss in the range of trout in the eight Rocky Mountains states of the United States of America, and this reduced range will be far more fragmented than at present.

[13] Meaden and Kapetsky (1991) detail the complexity and diversity of aquaculture space needs.

demand for fish and seafood. Currently, its need for broodstock, seed and feeds slows development, but once this dependence has been reduced the industry will start to benefit from gains similar to those made by the livestock industry (FAO, 2009a).

The above broadly outlines the problems currently facing the world's fisheries, but it should be noted that not all of the problems are self-inflicted by human activities. All biological and physical systems are in a state of continual flux. Chance physical events such as hurricanes, tsunamis, volcanic eruptions and temperature abnormalities may affect natural ecosystems in infinite ways, thereby affecting the state of equilibrium within any natural ecosystem. Trophic chains or food webs may become temporarily unbalanced with populations of some organisms either greatly benefitting or negatively suffering. And, apart from chance events, there are shorter- and longer-term natural processes occurring, which either cause gradual regime shifts, or which can trigger so-called tipping points leading to sudden and major regime change. Therefore, from the fishery perspective, recruitment – regardless of human intervention – will continue to be variable, with individual species populations or ecosystems components being very difficult to forecast or indeed determine.

In sum, with a few exceptions, fisheries worldwide are in considerable trouble and any problems can be exacerbated by natural, physical and biological perturbations. It is clear that the levels of exploitation of marine biological resources generally far exceed levels that can be sustainably maintained.

It is also clear that, because these problems are not being adequately resolved, many existing management practices and legal instruments controlling fisheries[14] must be strengthened and additional management measures need to be applied. This demise in the situation regarding fish stocks has played a significant role in promoting the need for new approaches to both fisheries and aquaculture management. These new approaches have been termed an "ecosystem approach to fisheries" (EAF) (FAO Fisheries Department, 2003; Garcia and Cochrane, 2005; Carocci *et al.*, 2009) and an "ecosystem approach to aquaculture" (EAA) (Soto, Aguilar-Manjarrez and Hishamunda, 2008; FAO, 2010b; Aguilar-Manjarrez, Kapetsky and Soto, 2010), both of which will be later examined in some detail.

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. The problems themselves arise out of disequilibrium in the spatial arrangement of the production functions that best determine a successful inland or marine fishery, or indeed, an aquaculture production facility[15]. For example, it can easily be perceived that the variable population of a species can be mapped over an area, and the resulting distribution may be related in some way to other natural variables that might influence this distribution such as water depth, salinity, temperature, chlorophyll, bottom sediments types and plankton distributions, or to human activities such as fishing effort, pollution, use of specific gear, species market prices and management systems. Similarly, the variable production from aquaculture must relate to those factors of production that control aquaculture success and thus output such as water quality and quantity, temperatures, market availability, soil quality and land costs. Through analyses, it will be possible to establish optimum relationships between species and their controlling variables (production functions). With this knowledge, the causes of less than optimum species populations can be identified, and further temporal analyses could show changes in species distributions and could account for the causes

[14] Legal instruments include: the United Nations Convention on the Law of the Sea; the United Nations Fish Stocks Agreement; the FAO Compliance Agreement; the international plans of action on fishing capacity, illegal and unreported and unregulated fishing; the FAO Code of Conduct for Responsible Fisheries; Management Plans for Action; and the World Summit on Sustainable Development.

[15] The meaning of "production functions" is additionally covered in Section 3.2.

of these changes. What is being inferred here is that problems of spatial disequilibrium[16] are not only very common but they are also very susceptible to spatial analysis. Thus, what this technical paper is introducing within a fisheries and aquaculture context may be conceived as "spatial thinking", a topic that has been cogently expanded by Valavanis (2002). Broadly, spatial thinking is concerned with five groups of geographic questions: (i) location and extent; (ii) distribution and pattern or shape; (iii) spatial association; (iv) spatial interaction; and (v) spatial change. Fishery managers, if they wish to maximize spatial equilibrium (with all production functions being in a sustainable balance), will need to learn to think spatially and to perform spatial analyses – this is where geographic information systems (GIS) tools can assist them considerably.

1.2 WHAT ARE GEOGRAPHIC INFORMATION SYSTEMS?

For those who may not be fully conversant with the concepts encapsulated by GIS, it is worth exploring these briefly in terms of definitions, components and capabilities. This will be done in a broad sense because only the briefest of this background knowledge is essential to those working in fisheries and because there are many general sources of information both in the literature (Bernhardsen, 2002; Lo and Yeung, 2002; DeMers, 2005; Heywood, Cornelius and Carver, 2006; DeMers, 2009b; Longley, *et al.*, 2011) and on the Internet:

- Environmental Systems Research Institute (ESRI): http://gis.com/content/what-gis;
- United States Geological Survey (USGS): http://edc2.usgs.gov/pubslists/gis_poster/gis_poster_front14x9.pdf;
- StrateGIS-projektet: http://webby.lst.se/strategis/english/12_queries_about_gis.htm;
- Wikipedia: http://en.wikipedia.org/wiki/Geographic_information_system.

The term "geographic information systems" may be identical or closely related to a number of other terms, such as "geographical information systems", "geospatial systems" and "geographical information science"; collectively, these terms may be thought of as forming part of "spatial science" or "geoscience" or "geotechnology".[17] However, "GIS" as the acronym for geographic information systems successfully encapsulates what this technical paper is concerned with. There are many definitions of GIS and the precise definition may depend on who is giving it, the context in which it is being used, when the definition was made, and the degree of detail being provided. However, it is generally agreed that GIS are computer-based systems whose incorporated software are capable of using georeferenced data for a range of spatial analyses and outputs. "In short, GIS add value to spatial data. By allowing data to be organized and viewed efficiently, by integrating them with other data, by analysis and by the creation of new data that can be operated on, GIS creates useful information to help decision-making." (Heywood, Cornelius and Carver, 2006, p. 18). Geographic information systems are thus a special class of information systems, one that incorporates spatial considerations. It is possible to subcategorize GIS into more specific information systems such as traffic management, environmental information, soil information, facilities management, market analysis and fisheries management information systems.

From this brief definition, it may be clear that GIS can be divided into a number of essential components:

- **People.** GIS cannot operate in isolation from the organizational context and there must be people to plan, implement and operate the system, as well as to make decisions based on the output. The implementation of GIS, including aspects of guidance and support, is discussed in Chapter 4.

[16] "Spatial disequilibrium" means that the occurrence of a feature or a process on the earth's surface is out of balance in a manner that is unsustainable and, therefore, future problems are certain to occur.

[17] GIS will also be an essential ingredient in the issues of "spatial planning", EAA and EAF, which are discussed later in this technical paper.

- **Data.** For most GIS operatives, data have now become the most important element to GIS, a fact largely based on their high costs relative to other operating costs. Today, a vast array of data is available from varied and diffuse sources. The requisite data for any specific project must be carefully identified and acquired, and the quality of these data will determine the usefulness of the final GIS output. Data sourcing is discussed in Chapter 3.
- **Hardware.** A range of hardware exists for transforming data into digital formats, which must be stored, manipulated and processed by computers before output can be obtained via plotters, printers and screens. This is described in more detail in Chapter 2.
- **Software.** GIS has the potential to utilize a range of software for carrying out a variety of tasks, most of which provide the essential instructions and other linkages between the data and the hardware. Further details are given in Chapter 2.
- **Procedures.** Analysis requires well-defined, consistent methods to produce accurate, reproducible results.

For some readers, it is useful to briefly describe what a GIS is in terms of its technical and operational characteristics. Box 1.2 describes the operational characteristics that would describe most modern GISs when thought of as a functioning technical system. It should be mentioned, however, that a GIS, perhaps being used for fisheries purposes, can function at what might be conceived as a far more basic level than that described in Box 1.2.

BOX 1.2
The operational characteristics of a modern GIS

The components of a modern GIS, including its operational characteristics, can be envisaged as follows:

- It is part of a computer network rather than a stand-alone computer and it is configured with advanced processing capability and high memory storage. It must have strong connectivity links for data acquisition and for working as part of a network.
- As well as internal software, it has connections to external (distributed) software allowing for increased functionality with multiple processors, computer clusters and data storage systems.
- It utilizes Internet access to data and technical resources available on the Web and for distributing relevant parts of GIS output.
- It is developed using industry standards for computer systems, software, databases and external communications.
- It generally contains a range of off-the-shelf software allowing it to perform a wide range of data processing and spatially based functions.
- It uses data stored locally on its own hard drive(s), and data drawn from local area net works, as well as data obtained from data warehouses through the Internet.
- It is capable of using various data structures and it can integrate spatial data with other forms of georeferenced data in a totally integrated manner.
- It is able to present the results of information retrieval and analysis using multimedia technologies that may include sound, graphics and animation.
- It is tightly linked to other software applications such as statistical analyses and visualization, which enhances its functionality, as well as spreadsheets and word processing for input and output tasks.
- It supports multi-user information needs ranging from simple information queries and browsing to sophisticated spatial problem solving.
- In many cases it uses open source GIS software, which, at least for now, may offer some advantages for GIS users over more proprietary solutions.

Source: Updated from Lo and Yeung (2002).

What type of questions or procedures will GIS address? GIS software has been designed to address a wide range of spatially related questions or procedures; below are some examples in order that the reader may appreciate the diverse functionality[18]. In one sense, the headings are rather arbitrary because any single category of functionality may incorporate two or more functions.

- **Measurement.** The knowledge of distance or the spatial (aerial) extent or volume of a feature or incident will be basic but important and, using proximity analysis, GIS can establish the distance of objects relative to a theme or to other objects. Any units of measurement can be deployed, including statistical measurements such as sum, mean, mode and standard deviation.
- **Distributions and relationships.** Spatial distributions of objects may be either random and regular or clustered, and GIS have the functionality, usually via the use of the nearest neighbour analysis, to describe distributions in these terms. Using contiguity analysis, they can also calculate the relationship between differing distributions across a surface, i.e. spatial autocorrelation,
- **Network analysis.** This analysis applies to linear features such as transport routes, rivers, pipelines and cable networks. Analyses can establish least costs routes, shortest path routes, degree of connectivity, etc. Measurement in network analyses can be in terms of monetary units, distance, time, etc.
- **Temporal analysis.** Spatial changes can be in absolute terms or defined overtime. Thus, it is valuable to know, for instance, the varying rates of growth of an urban area over equal consecutive time periods, or to identify the proportional changes in land use for a given area over time. The long-term collection of remotely sensed data has greatly expedited time series analyses.
- **Modelling.** This is a wide heading that frequently includes "what if" scenarios, or models are developed to show what a likely distribution of an object might be given its known distribution in a sample area, and this can be done for past, present or future scenarios. Optimum location analysis is a modelling procedure that attempts to optimize the location for any activity based on known inputs of the principal production functions. Digital terrain modelling allows for the inclusion of the height dimension for GIS analyses of slopes, aspect, contours and volumes.
- Interpolation. This is simply the generation of missing values based on a set of known values within a study area. For instance, if a series of spot heights (altitudes) are known, then it is possible to interpolate contour lines for the same area. Interpolation can be applied to a wide range of measured values.

GIS are now used extensively in a wide range of applications. According to Lo and Yeung (2002), major areas of GIS applications can be grouped into six categories, as indicated in Box 1.3.

Chapters 8 to 10 include case studies showing how GIS might be used for different tasks in relation to fishery projects, including relevance to both the EAF and the EAA, and Valavanis (2002; p. 14–15) provides a detailed list of the types of marine spatial questions that GIS can address. In order to execute any of these functions, the GIS software must contain instructions to perform numerous individual commands. Some of these are what could be called general "housekeeping" tools, i.e. they are non-spatial and are designed to get the data into some optimum structure (editing, cutting, adding, ordering, importing, adapting, arithmetic operations, etc.), while other commands will perform basic GIS spatial functions (e.g. buffering, reclassifying, overlay and density estimations).

[18] See Chapter 7 for more detail on GIS functionality.

BOX 1.3
Major application areas for GIS

Academic	Research in humanities, science, engineering, etc. Education – universities, colleges, schools
Business	Banking and insurance Retail and market analysis Real estate and estate management Telecommunications
Government	National, state and local level – topographic mapping, census analyses, planning and development Law enforcement – crime analyses, police deployment Health care and medical research International development
Industry	Transportation – route selection, vehicle tracking, goods distribution Utilities services – water, gas, electricity network management
Military	Training Command and control Intelligence
Natural resources (forestry and fishery)	Resource inventory, harvest planning, wildlife management, conservation Environmental management

1.3 THE EMERGENCE OF GIS AS A SPATIAL TOOL

For anyone embarking on the use of GIS, it is of interest to know something of the temporal developments in this area. Although "geographic information" in the form of maps, gazetteers, inventories of local resources, texts, etc., has been around for many centuries, GIS as interpreted today is the system based on the electronics associated with digital computing. As such, GIS could only evolve from work done during the 1950s to develop the required computing systems. It is useful to first describe historical developments in GIS under headings assigned to recognizable growth periods and then to examine the reasons and conditions that allowed for the growth in GIS.

1.3.1 A brief history of GIS

The historical progression in GIS can be conveniently described in three temporal stages. These stages only look at progress made that is directly associated with GIS, i.e. factors associated with parallel developments are examined in Section 1.3.2.

Early innovations (1960–1980)

From the late 1950s, work had progressed on using computers to produce graphical output and to develop database management systems. Once these developments had been accomplished, GIS became a possibility. The first recognized GIS was the Canada Geographic Information System (CGIS) produced for the Canadian government, this being a system to address land and resource management in that spatially extensive and resource rich country (Tomlinson, Calkins and Marble, 1976). This early innovation period was characterized by a large number of individual research projects and applications that emerged in response to specific needs (examples are shown in Box 1.4). Because of the high costs involved, nearly all research was carried out by government institutions, largely universities, using mainframe computers. Developments were based on proprietary software and were applications driven, i.e.

the software was custom developed to suit specific project needs. Most of the GIS output was in mapping and measurement formats with relatively little spatial analysis being accomplished, and the main application areas included defence, land and resource management, urban planning and census analyses. Towards the end of this period, with the advent of remote sensing capabilities, data started to become available in quantities that were essential to larger-scale GIS work.

Era of commercialization (1980–1995)

With a great deal of research having been accomplished by the 1970s, private companies then began to make their first moves into GIS. These were generally led by individuals who could see the large economic potential that would exist for spatial analysis products, especially through the production and sale of software tools that offered a packaged range having varied functionality. Examples of the early GIS software products that were hosted on minicomputers (workstations) were ESRI's ARCINFO in 1982, INFOMAP by Synercom, and CARIS produced by Universal Systems. By the late 1980s, the advent of microcomputers[19] allowed for considerable cost savings, and other GIS then produced included MapInfo, SPANS, Intergraph, PC-ArcInfo, plus various products from European software houses (see Section 2.3 for more details). Part of the reason for this upsurge in software commercialization was the strong progress that was then being made in developments that are parallel to GIS, and which are essential for its success (see Section 1.3.2). Most GIS applications were still being made to traditional areas of forest and land management, urban planning and by

BOX 1.4
Examples of early GIS innovation projects

Examples of seminal work to develop GIS between 1960 and 1980 include a range of projects aimed at a variety of aspects associated largely with map production (see Foresman, 1998, or Lo and Yeung, 2002, for more details):

- Geographical Information Retrieval and Analysis System (GIRAS) was developed in the mid-1960s by the United States Geological Survey to handle and analyse land-use data
- Local Authority Management Information System (LAMIS) was developed in the United Kingdom of Great Britain and Northern Ireland for land-use control.
- The first raster-based GIS (an automated mapping application called SYMAP) was created at the Harvard Laboratory for Computer Graphics in the United States of America in 1966.
- ODESSEY was produced as the first vector-based GIS by Harvard researchers in 1977. Other spatial software developments in the late 1960s by Harvard include GRID, SYMVU and CALFORM.
- A land-management system called the Minnesota Land Management Information System (MLMIS) was developed in the late 1960s by the University of Minnesota, United States of America.
- The Experimental Cartography Unit (ECU) at the Royal College of Art in London, United Kingdom, developed high-quality computer mapping in the early 1960s.
- To support the United States of America population census of 1970, Dual Independent Map Encoding (DIME), a data structure and street address database, was developed in 1965.
- The University of Edinburgh, United Kingdom, produced the Geographic Information Mapping and Manipulations System (GIMMS) as a high-quality, vector-mapping system in the early 1970s.

The GIS History Project, launched in 1996, provides interesting details on a wide range of historical developments in GIS. See Mark *et al.* (1997).

[19] The fore-runner of today's personal computer.

the utilities. By the late 1980s, applications were being adopted by areas beyond the highly developed regions, especially in poorer developing countries where GIS had the potential to expedite decision-making. By the end of this development period, it would be true to say that GIS had become a mature technology in terms of both hardware and software, plus the supporting infrastructure that a complex information technology (IT) product needs, such as marketing structures, exhibitions, journals, conferences, ancillary equipment, books, data suppliers and consultants. By the late 1990s, the world market for geospatial systems and services was approximately GBP 3 billion (i.e. about US$5 billion) (Wilson, 1999) and growth, at least until the early 1990s, was reported as being about 14 percent per year (Frost and Sullivan, 1994).

Era of mass exploitation (1995–present)

Lo and Yeung (2002) note that a major facet of this current era is the development of the geographic information infrastructure. For example, in the United States of America, a National Spatial Data Infrastructure was established in 1994 with a remit to enhance technological, political, standards and human resource aspects of GIS through acquiring, processing, sharing, distributing and improving the utilization of geographic data. Similar initiatives have been made in many countries with the result that the profile of spatial data and of GIS has been significantly raised. Lo and Yeung (2002; p. 9) note "GIS has popularized the use of geographic information by empowering individuals and organizations to use such information in areas that earlier generations of GIS users could never have thought of." Although the main cause of the recent explosive growth in GIS has been greater access to data, this itself has been enhanced by developments in a range of parallel fields (see Section 1.3.2 and Box 1.5). Berry (2007) has described these fields as collectively forming the subject area of "geotechnology".[20] Of special importance has been the ability to deliver data via the World Wide Web. Other recent important developments contributing to the mass use of GIS include: a huge reduction in the relative costs of doing GIS work; the implementation of a range of standards into the various aspects of GIS; the fact that GIS can be performed on all hardware platforms; developments in geostatistical modelling; and recent developments in interactive GIS. GIS is now an indispensable tool for use in dozens of applications areas (Box 1.3). Fisher (2010; p. 5) indicates that it is likely that "there are now millions of the general public using geotechnology through the worldwide web".

1.3.2 Reasons for the growth in GIS

It has been shown how growth in GIS has been progressing for approximately half a century and that this growth has been rapid and accelerating. Fairly recently, the United States Department of Labor has recognized geotechnology as one of the three most important emerging and evolving fields of the twenty-first century, i.e. together with nanotechnology and biotechnology (Gewin, 2004). What are the reasons for this growth and importance? Answers to this question can best be outlined under four general headings (described below), although the important factor of cost reductions can be included under all headings.

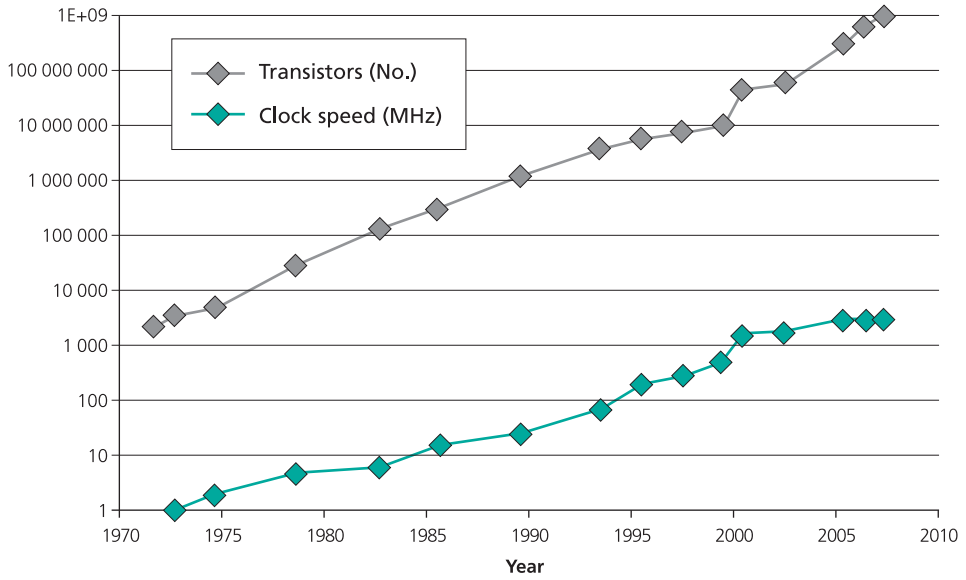
The growth in computing power

Although this section could include not only the increasing power of computers per se but also the increasing power and sophistication of peripheral hardware devices, space prohibits a look at the growth in capability of the latter. However, it is important to point out that the growth in computing power is inextricably linked with rapid developments in computer subsystems such as operating systems, computer graphics, database management systems and graphical user interface design. Additionally, because

[20] Along with Global Positioning Systems and remote sensing, GIS can be considered a major pillar of geotechnology.

GIS functionality is varied and relatively complex, the huge growth in computing power has been a considerable spur to enabling the technology to be available to a widening user group. Detailed information on specific developments in computer technology can be found in Bernhardsen (2002), Megrey and Moksness (2009) and on Wikipedia (http://en.wikipedia.org/wiki/History_of_computing_hardware); and year-by-year progress (from 1939 to 1994) can be gleaned from the Computer History Museum (www.computerhistory.org/timeline/?gclid=CLHshef5pZsCFV8B4wod9nG5EA). Although the cost of a computer has seemingly remained the same for at least 30 years, what is now obtained for every unit of cost is considerably more than was secured in the past. Indeed, even 20 years ago, Rhind (1990) calculated that the cost of computing power had decreased by an order of magnitude every six years over the previous 30 years, and there is no indication that this rate of advancement has changed much since then. So the converse to this is that we are now getting an order of magnitude more computing power every six years; or the US$2 000 PC or Apple Macintosh computer of today will do what a US$2 000 000 computer was capable of doing 20 years ago. Figure 1.4 provides evidence of this huge increase in computer power. It can be seen that exponential progress is being achieved both in terms of computing computational power, as indicated by the number of transistors in the central processing unit (CPU), and computer clock speed (both shown logarithmically). However, there is now evidence that progress is slowing down as manufacturing technology appears to be reaching its limits in terms of how many transistors can be placed on a silicon chip, and particularly on how fast their clocks can run.[21]

FIGURE 1.4
Changes in computing capacity as noted by the number of transistors in the central processing unit and computer clock speeds



Source: Megrey and Moksness (2009).

Apart from computing processor advances, there have been substantial improvements in hard drive technology and in other storage media. A leading maker of hard drives (Seagate) estimates that its drive capacity increases at approximately 60 percent per year, with accompanying increases in density capacity.[22] Multiple terabyte (1 000 GB) drives

[21] Megrey and Moksness (2009) note that there are limits to making circuitry smaller and in managing electrical movements and heat through the circuits.

[22] Modern drives now pack as much as 75 GB of data onto a single 3.5 inch platter.

are already available and standard laptops may have up to 200 GB drives. Drive speed is also greatly increasing, with 7 200 revolutions per minute (RPM) being standard on mainstream hard drives. These capacity increases are being achieved on smaller drives. There are some challenges to continually improve this technology in terms of systems reliability, mainly because the rate of technological change is hard to keep up with. In 1990, a typical gigabyte of storage cost about US$20 000, whereas today it is less than US$1. CD–ROMs have continued to be an important medium for data delivery and storage, but the ubiquitous "memory stick" (pen drive) is often preferred. These sticks are now able to store at least 64 GB at extremely low costs.

Other areas of computing progress are in graphics and display technology and in portable computing. Most computer users are familiar with the now ubiquitous flat screens, but few users might appreciate the enormous technological advances that have been necessary in order to produce them (see Megrey and Moksness, 2009, for details). Because flat screens allow significant room saving, it is becoming more common for users to have two or three screens, and this mode of operation can result in significant productivity benefits (Russell and Wong, 2005). Laptop computers have proliferated in their use and range of model specifications. The affordability of these machines has greatly improved, and extremely versatile notebooks can be purchased from around US$300. The distinction between desktop computing and the use of portable computers has rapidly blurred, and many notebooks are now used as "docking stations" whereby they are linked up to computing networks for specific purposes. The use of other computing hardware is discussed in Sections 2.2.1 and 3.5.1.

Progress made in parallel developments

From this analysis, it is clear that GIS forms one specialized part of a complex array of mainly digital-based technologies. Indeed, GIS is only able to function as a result of developments undertaken in a large number of separate fields of research – these are so-called parallel developments. Box 1.5 provides a brief description of the main parallel developments. Although space forbids a detailed look at the progress made within each of these important fields, some of the fields will be briefly covered in this technical paper. While it is clear that developments are mostly in the IT field, some such as visualization and geostatistics[23] stem from apparently unrelated disciplines. As with computing, the main driver of progress in these fields are cost reductions allied to the vast range of digital applications developments.

[23] Geostatistics refers to the use of algebraic formulae and calculations that are aerially (spatially) related and are applied to spatio-temporal data sets. This use is typically accommodated via the use of software such as GIS.

BOX 1.5
Parallel developments that link to GIS

For optimal operation, it is essential that GIS does not function in isolation. Its development to date, and the milieu in which it functions, is heavily dependent upon an array of associated disciplines, developments or capabilities. These include:

- The Internet – This is required for information and for data downloads, and increasingly for interactive GIS functionality.
- Remote sensing and global positioning systems – Satellite and aerial remotely sensed data and information possibly provide the largest source of data and of locational accuracy for GIS.
- Environmental modelling – Output from models provide a source of data and modelling itself is performed using GIS as a platform.
- Software developments – Not only are there many varied GIS-based software packages but linkages between GIS and other software functionality are essential for many system tasks.
- Hardware – As well as forming the computer-based platform for GIS operations, numerous other pieces of hardware may form part of a complete GIS, e.g. scanners, plotters, digitizers, data loggers and sonar.
- Visualization – Mapping output has to be optimized in perceptual terms if the output is to be easily understood. There is an increasing range of visualization considerations such as animations, time series data, 3D, graphs and multimedia, and there are additional visualization opportunities such as via Google Maps and Google Earth.
- Geostatistics – Much of the output from fisheries GIS depends upon the application of geostatistics to model various projections or distributions, e.g. estimating fish stocks or the relationship between fish species and a wide range of environmental variables.
- Computer-aided design (CAD) and graphics – This represents an area having similar input/output requisites to GIS and thus it has contributed significantly to its methodology.
- Digital cartography – While most cartography is not concerned with analysis per se, the output from digital cartography may share exact requirements to those of GIS.
- Photogrammetry – This is the technique of measuring objects from photographs, electronic imagery, videos, satellite images, etc. These provide important sources of spatial information.

Source: Adapted from Meaden (2009).

The proliferation of data

Access to high-quality data lies at the core of any successful GIS. As GIS has developed as an IT applications area, the relative importance of data has greatly increased, not only with regard to the fundamental role it plays in the success of any project but also in terms of the relative proportion of total project cost inputs that data represents.[24] For some areas of GIS, and fisheries GIS is an excellent example, data of sufficient quality can be expensive (and thus important). This lies in the fact that data gathered from a 3D marine environment incur additional cost considerations compared with most terrestrial data, i.e. in terms of the necessity to utilize survey or other vessels and to gather data on moving objects that are often difficult to access in terms of depth and mobility.

Data suitable for mapping, and thus for GIS, were traditionally in hard copy format in the form of maps or tabular data sets. These data were far from ubiquitous and the non-spatial attribute data were frequently insufficiently georeferenced, and/or they were only collected for specific surveys or projects. During this era of paper-based data collection, which has now largely disappeared, clearly all data had to be digitized if they were to be used for GIS. There are still many paper-based data sets or maps that can be of use and the means of digitizing this material is briefly

[24] Longley *et al.* (2001) estimate that data costs can be as high as 80 percent of total GIS project costs.

described in Sections 2.2.1 and 5.2.1. However, during the last four decades, there has been an incremental shift towards the direct collection of data in a digital format and some of the numerous ways of doing this, e.g. via the use of data loggers, global positioning systems (GPS) and remote sensing, are described in Chapters 2, 3 and 5. This automation of data collection has resulted in an exponential increase and proliferation of data.

But it is not only the ability of gathering or collecting digital data that has led to their proliferation. These data have to be stored. The ability to store vast quantities of data has undergone a complete revolution both in terms of the amount that can be stored and the miniaturization of storage devices, including the cost per unit of data stored. Data storage media – until quite recently confined to tape drives, floppy disks and hard drives – can now additionally be stored via removable optical media such as CD–ROMs and DVDs, or flash drives such as USB memory sticks (pen drives), and offline means such as portable hard drives (http://en.wikipedia.org/wiki/Computer_storage). There are data compression means that allow for space saving on all storage media. Allied to this increased storage capability, there is also the need to keep a much better record of what is being stored and this is achieved through improved metadata recording (see Section 3.5). The ability to store huge quantities of data has had a profound effect on GIS possibilities.

Once data have been stored, they need to be sourced, accessed, transferred or distributed. Here, again, the range of means by which this has improved has greatly aided in the proliferation of data for GIS. As well as the portable storage media mentioned above, by far the largest data transfer and distributing agent has been the Internet. Access to the World Wide Web has grown, and still is growing exponentially, allowing for instant delivery of data from a vast number of sources. Providers of GIS data over the Internet use geo-portals, and these data outlets are now very widely used by both public and private sector suppliers, an action that has greatly encouraged the growth of GIS (de Smith, Goodchild and Longley, 2006). The use of search engines such as Google can greatly expedite the search for appropriate data and geo-portals.

The increasing demand for GIS output

With the huge increases in computing power and the associated reduction in costs, plus improvements in parallel developments and the proliferation of data, it is not surprising that GIS has grown at a phenomenal rate, especially during the era of so-called "mass exploitation". But it is also the growth in demand that has partly been responsible for the improvements in these factors that are fuelling demand – from the GIS perspective, it is a "win-win" situation. However, there are other factors that are also contributing to demand growth. Just as in fisheries, it is increasingly realized that many of society's social, economic and environmental problems have a strong spatial dimension, and the problems are, therefore, susceptible to analyses by means of GIS. This realization has been spawned through a far greater awareness of GIS and its potential. This awareness has permeated from a core range of self-perpetuating activities and causes. Initial successes for GIS have, for instance, created a demand for knowledge about GIS in the form of books and journals. Whereas 25 years ago the first books on GIS were beginning to appear,[25] a recent search on www.amazon.com (accessed 10 December 2012) under "books" using the search command "geographic information systems" produced a list of over 17 000 GIS-related books. The fact that 67 of these books are listed, but have yet to be published, indicates a strong potential market. However, a growth in specialist GIS journals has failed to materialize because, as a technology, GIS

[25] The first general textbook on GIS was by Burrough (1986).

development is mostly confined to journals on software development or related areas, and as an applications tool, mention of GIS occurs in journals dedicated to the specific applications areas of, for example, forestry, fisheries or urban planning.

Apart from books and journals, trade magazines, conferences and specialist GIS groups or societies also promote GIS (see also Section 4.8). ESRI provides numerous periodicals that can be subscribed free of charge (www.esri.com/subscribe). Moreover, ESRI Free Online Library (http://training.esri.com/campus/library/index.cfm) covers the literature of geographic information systems, science and technology. It indexes journals, conference proceedings, books and reports from the origins of GIS to the present. There are currently 129 295 entries in the bibliography with 156 listed for "aquaculture" and 708 listed for "fisheries" (as of 10 December 2012).

Educational courses also raise awareness of GIS. Given the complexity of the GIS subject area, most of these courses are still confined to further or higher education levels. Whereas two decades ago these courses were by and large non-existent, today most, if not all, university geography departments include GIS as a separate course or module, often at the master's degree level. This availability of trained GIS personnel has greatly aided in the proliferation of GIS applications areas (Box 1.3), i.e. the market for GIS functionality and output has expanded rapidly. This expansion has been greatly assisted by those factors mentioned earlier, such as IT cost reductions and developments in parallel technologies, and collectively these aids to progress have ensured that the final products (output) being achieved by GIS are often of exceptionally high standards and thus of exceptional use in the decision-making process.

1.4 EARLY DEVELOPMENTS IN THE USE OF GIS FOR FISHERIES AND AQUACULTURE PURPOSES

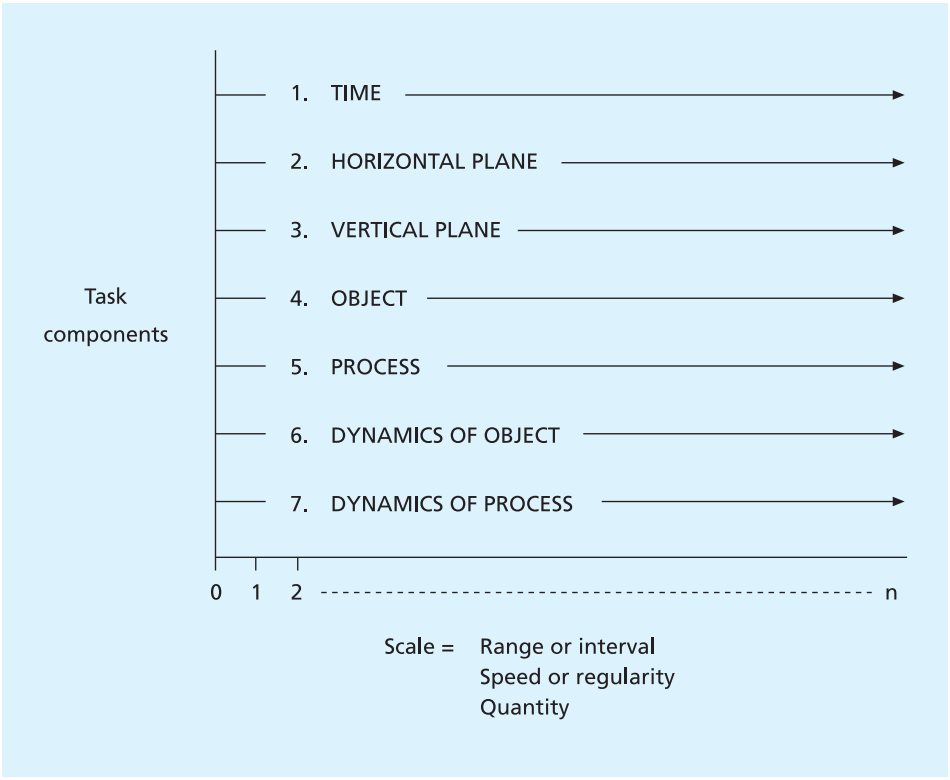
The use of GIS for any fisheries purpose was slow to materialize, this largely being a function of the paucity of marine data and of the complex milieu that is the aquatic or marine environment. Meaden (2000) has previously shown that this complex milieu can be conceived in terms of the "task components" that need to be considered when undertaking any fisheries-related GIS work (Figure 1.5). Thus, terrestrial GIS is mainly concerned with components 1, 2 and 4, whereas most fisheries GIS must also be concerned with 3, 5, 6 and 7. This is because fisheries take place in a 2.5D[26] or 3D spatial environment, an environment comprising of large-scale bodies of water exhibiting differential 4D movements, within which most of the objects are moving independently. These variable movements affect spatial distributions, which in turn mean that the periodicity and resolution of mapping becomes a difficult but essential issue. The marine environment, therefore, provides a fundamental problem to any GIS-based work.

A further factor delaying the growth in fisheries GIS arises from the organizational structure of fisheries per se, especially the fragmented nature of the activities. Thus, fisheries research and management tends to take place in an array of types of "institutions" such as universities, fishery management authorities, consultants and research institutions. These are scattered worldwide, often in peripheral, coastal locations, and many institutions are either not conversant with GIS as a management or decision-making tool, or they are too small to support such activities. GIS publications relating to fisheries tend not to appear in the more established literature – they are more frequently in the form of governmental reports or in other "grey literature" resources.

It is possible to detect that the actions by FAO were probably the first moves into fisheries-related GIS. The report on a workshop held in Rome in 1984 (FAO, 1985) to show how remote sensing could help in progressing aquaculture or inland fisheries

[26] A 2.5D dimension is where the vertical dimension is considered, but only in relation to objects that are on the ground or on the sea floor.

FIGURE 1.5
Task components of a fisheries-based GIS



Source: Meaden (2000).

included papers showing how shrimp farm locations could be identified, how algal growth could be monitored and how inventories of intertidal zones could be compiled, with each of these studies showing how mapping could be derived from remotely sensed satellite data. In 1985, Caddy and Garcia (1986), working at FAO, presented their ideas on the importance of using a range of mapping techniques as management tools in solving fisheries-related problems, and Kapetsky, McGregor and Nanne (1987) produced an FAO technical paper describing how GIS could be utilized for identifying sites for shrimp farms in Costa Rica. By 1991, FAO had commissioned and published the first technical paper on fisheries GIS (Meaden and Kapetsky, 1991). Until the late 1980s, almost all publications on fisheries GIS were related either to simple habitat mapping or to the use of GIS for optimizing potential aquaculture sites, tasks where the variables controlling the production activity are largely static and terrestrially based. During this period, remote sensing was an extremely important source of data on a variety of parameters (Johannessen *et al*, 1989; Simpson, 1992), and where appropriate data were difficult to obtain the authors showed ingenuity in securing an array of "proxy" data.[27]

[27] This refers to data that can form a reasonable substitute for missing data or it can infer what pattern a distribution might take, e.g. air temperatures can be a reasonable proxy for water temperatures, or the growth of particular species of plants can give a clue to soil acidity.

TABLE 1.1
Examples of fisheries-related GIS work produced during the 1990s

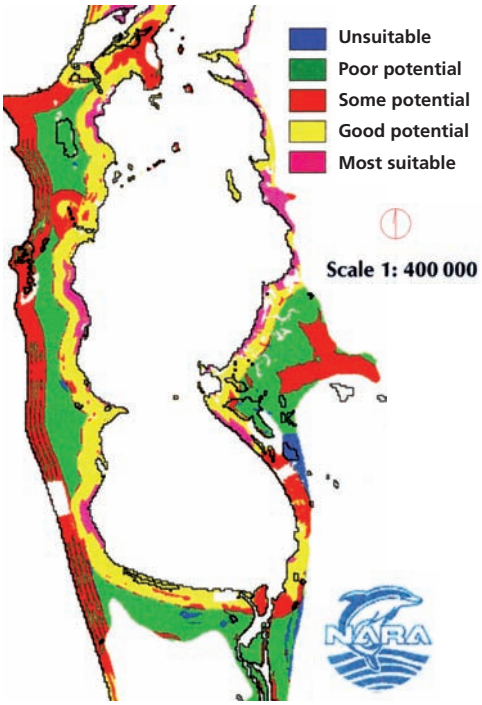
Fisheries theme or topic	Examples of studies
Mapping and atlases	Selvik *et al*. (1993); Ostrowski (1994); Ramster (1994); Carocci and Majkowski (1996); Ramos, Sobrino and Jiménez (1996)
Habitat Mapping (riverine and marine)	Gordon (1994); Liebig (1994); Somers and Long (1994); O'Brien-White and Thomason (1995); Rubec (1996); Castillo, Barbieri and Gonzalez (1996); Keleher and Rahel (1996); Long and Skewes (1996); Rogers and Bergersen (1996); Sotheran, Foster-Smith and Davies (1997); Rubec *et al*. (1998)
Marine productivity mapping	Trathan *et al*. (1993); Caddy, Refk and Do Chi (1995); Sakurai, *et al*. (1998)
Fisheries management	Meaille and Wald (1990); Legault (1992); Meaden (1994); Long, Skewes and Pointer (1994); Jordan, Greenhawk and Smith (1995); Meaden (1996); Al-A'ali and Bakiri (1996); Kemp and Meaden (1996); Smith and Lalwani (1996)
Human impacts on fishing environments	Wood and Ferguson (1995); Irwin and Noble (1996); Porter *et al*. (1997)
Aquaculture location and activities	Ali, Ross and Beveridge (1991); Paw *et al*. (1992); Paw, Robles and Alojado (1993); Ross, Mendoza and Beveridge (1993); Aguilar-Manjarrez and Ross (1994); Aguilar-Manjarrez and Ross (1995a); McGowan, Nealon and Brown 1995); Habbane, El-Sahb and Dubois (1997)
General systems and GIS	Swartzman, Huang and Kaluzny (1992); Li and Saxena (1993); Kapetsky (1994); Do Chi and Taconet (1994); Taconet (1995); Le Corre (1995); Durand, Loubersac and Masse (1998)

By the early 1990s, the range of fisheries applications using GIS was expanding. Space prohibits a detailed look at this expansion, but Table 1.1 gives an indication of the main fields into which fisheries GIS was now moving, including illustrations of studies, and Meaden (2001) provides a summary of the main fisheries GIS work accomplished before the beginning of the millennium. It should be stressed that much of the work was cross-disciplinary, though an analysis by Meaden (2001) of 216 fisheries GIS publications made between 1985 and 1999 showed that 49 percent were directed towards marine fisheries, 20 percent to inland fisheries, 16 percent to aquaculture and 15 percent to coastal fisheries. Whereas at the start of the decade much of the work had been little more than mapping or site selection, by the end of the 1990s there was an impressive variety of publications undertaken in terms of species, habitats, regions, scale, objectives, etc., and in terms of the GIS functionalities being deployed. Publications were mainly in the form of symposium, workshop or conference proceedings (40 percent), journal articles (25 percent), government reports (16 percent) and others (19 percent). By the end of the millennium, GIS work in fisheries-related areas had taken off. Figure 1.6, from an investigation by Meaden (1999) into suitable sites for shrimp farming in west central Sri Lanka,[28] illustrates typical output from this period. Construction of this map required data inputs from distributions of 14 production

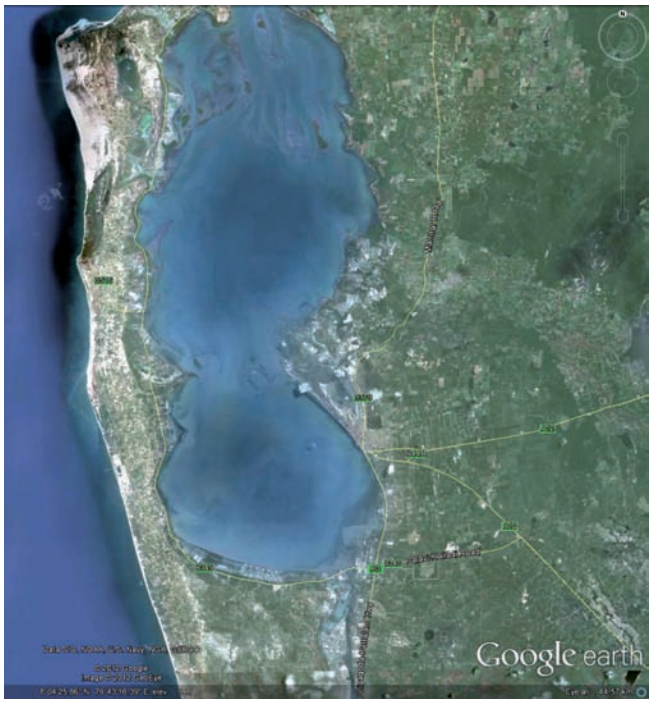
[28] Note the "hierarchy of suitability" scale used in Figure 1.6. This scale was used because western Sri Lanka is an area where some input data could not be adequately quantified. Areas in white on the map show the Indian Ocean to the west, or terrestrial areas over 5 m in altitude to the east, and a number of lakes and lagoons.

variables,[29] each of which was "scored" as to its relative importance for shrimp farming. While some data were readily available from the national mapping agency, others had to be derived from the use of proxy data, and remote sensing imagery was of major value. It can be inferred from Figure 1.6 that both overlay and buffering procedures were used, and the legend indicates that only relative "values" of site suitability for shrimp farming can be given. It is of interest to note that a recent search of Google satellite imagery for this mapped area clearly shows that extensive shrimp farms have now become established in many of the "most suitable" areas, especially those along the eastern shores of the Puttalam Lagoon (the large inlet at the middle right of the map).

FIGURE 1.6
Illustration of typical GIS output from the late 1990s showing suitable areas for shrimp culture in central, west Sri Lanka



Source: Meaden (1999).



Location: 8°5'6.72"N; 79°46'14.15"E

Source: Data SIO, NOAA, U.S. Navy, NGA, GEBCO
© 2012 Google
Image © 2012 GeoEye
(accessed 10 December 2012).

Since the start of the millennium, the use of GIS for fisheries has continued to expand, so much that the array of uses would greatly exceed the capacity to report them here (Fisher and Rahel, 2004a; Meaden, 2009). The summary here of recent developments in fisheries GIS is, therefore, kept to a minimum because factors such as data acquisition, GIS training and support, software developments and sources are examined later in specialized chapters. Additionally, Chapters 8, 9 and 10 review in some detail the current status of GIS as applied to aquaculture, inland and marine fisheries, respectively. An important main feature of fisheries GIS that has emerged in the past decade is the holding of triennial symposia on "GIS and spatial analyses in fishery and aquatic

[29] Selected variables were: water quality; water salinity; access to saline water; elevation below 5 m; access to road transport; access to electricity; distance from other shrimp farms; human population density; protected areas; conflicting water users; soil structure; soil pH; availability of fresh water and availability of shelter (from wind).

sciences". These symposia began in 1999, and the fifth and most recent in the series was held in Wellington, New Zealand, in August 2011. This series is undoubtedly the major international showcase for developments in fisheries GIS, and proceedings for each symposia are published, e.g. Nishida and Caton (2010).[30] As well as the symposia, there are other fisheries and/or marine workshops and conferences that often hold specialized sessions on GIS, for example, those run by the American Fisheries Society, ESRI and the National Oceanic and Atmospheric Administration (NOAA) Coastal Services Center.

1.5 THE AIMS AND THE STRUCTURE OF THIS TECHNICAL PAPER

The importance of taking a spatial perspective on fisheries and aquaculture management and on using a spatial analysis tool (GIS) as a means of helping to solve management problems has been stated in some detail. So it is the aim of this technical paper to explain in a concise yet easily interpreted manner exactly how the use of GIS might achieve solutions to the major fishery problems of today. With the management of fisheries and aquaculture moving towards the adoption of an ecosystems approach, i.e. whereby a very wide range of biological, physical and socio-economic considerations all contribute to optimizing sustainable fish production scenarios, then the range of spatial considerations is greatly extended. This being the case, the tool offered by GIS becomes even more important. Another aim of this technical paper is to bring up-to-date information on this rapidly changing subject area to a wide audience. The original FAO fisheries technical papers on applications of GIS to fisheries and aquaculture (Meaden and Kapetsky, 1991[31]; Meaden and Do Chi, 1996[32]) were written many years ago. Thus, in respect to the rapid progress in computing environments, these technical papers were in need of updating. It is hoped that the material that follows will allow a widespread audience to gain access to this useful technology.

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 1.7 attempts to show 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.

After the relatively detailed introduction in this chapter, which is intentionally designed to furnish readers with a wide array of background information on GIS, Chapter 2 looks at both the hardware items that may be employed directly to secure effective functioning of GIS, and it looks at this functioning in terms of the range of options for software acquisition and its use. Chapter 3 examines the broad and important "inputs" side that is fundamental to all GIS, i.e. that of data characteristics, quality and sourcing.

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[30] The symposia are organized by the Fishery-Aquatic GIS Research Group based in Saitama, Japan, and details of their most recent programme can be found at www.esl.co.jp/Sympo/5th/Final%20announcement.pdf .

[31] Available at www.fao.org/DOCREP/003/T0446E/T0446E00.HTM.

[32] Available at www.fao.org/DOCREP/003/W0615E/W0615E00.HTM.

Readers will appreciate that, because this is a wide area to cover, the main intention is to "get you started", i.e. to illustrate some main characteristics of spatial data for GIS, to examine the types of data that may be needed for a fisheries or aquaculture GIS, and to look at avenues that might be explored in the search for data and data sources. Armed with knowledge on the essential ingredients of GIS (i.e. hardware, software and data), then any prospective GIS user might wish to "get started". Arguably, the most important subject area for ensuring success in GIS work are considerations relating to the GIS implementation process, and these are reviewed in Chapter 4 in tandem with the support, training and guidance factors necessary for the continuing successful operation of GIS. Having secured a potentially functioning GIS, experience has shown that any data acquired may be in an array of different formats; some will already be in a digital form while other data may be in various hard copy formats. All data must be converted to digital formats and they should be structured so as to conform with the needs of spatial modelling. These data preparation concerns are detailed in Chapter 5. A special and very important data source for GIS is that collected by remote sensing systems. This is covered in Chapter 6, which also touches on the topics of image analysis and how the vast volumes of remotely sensed data may be accessed and integrated into GIS. Chapter 7 covers the wide subject of GIS functionality: What is it that GIS tools actually do? After an explanation of the important data processing and manipulation functions that make the data fit for specific purposes, details are given on a range of GIS analytical techniques that may be useful in the areas of fisheries and aquaculture. By this stage of the technical paper, readers should have a sound insight into what GIS is all about, so Chapters 8, 9 and 10 illustrate, mainly via a range of case studies, some uses of GIS for aquaculture, inland and marine fisheries research or management. Chapter 11 reviews the likely future trends and/or issues in fisheries or aquaculture that GIS might suitably address, and Chapter 12 discusses the various challenges to working with GIS for fishery purposes, and suggestions are given as to how these challenges might best be overcome (or at least be recognized). After a brief conclusion (Chapter 13), an extensive glossary and references are provided as an appendix.

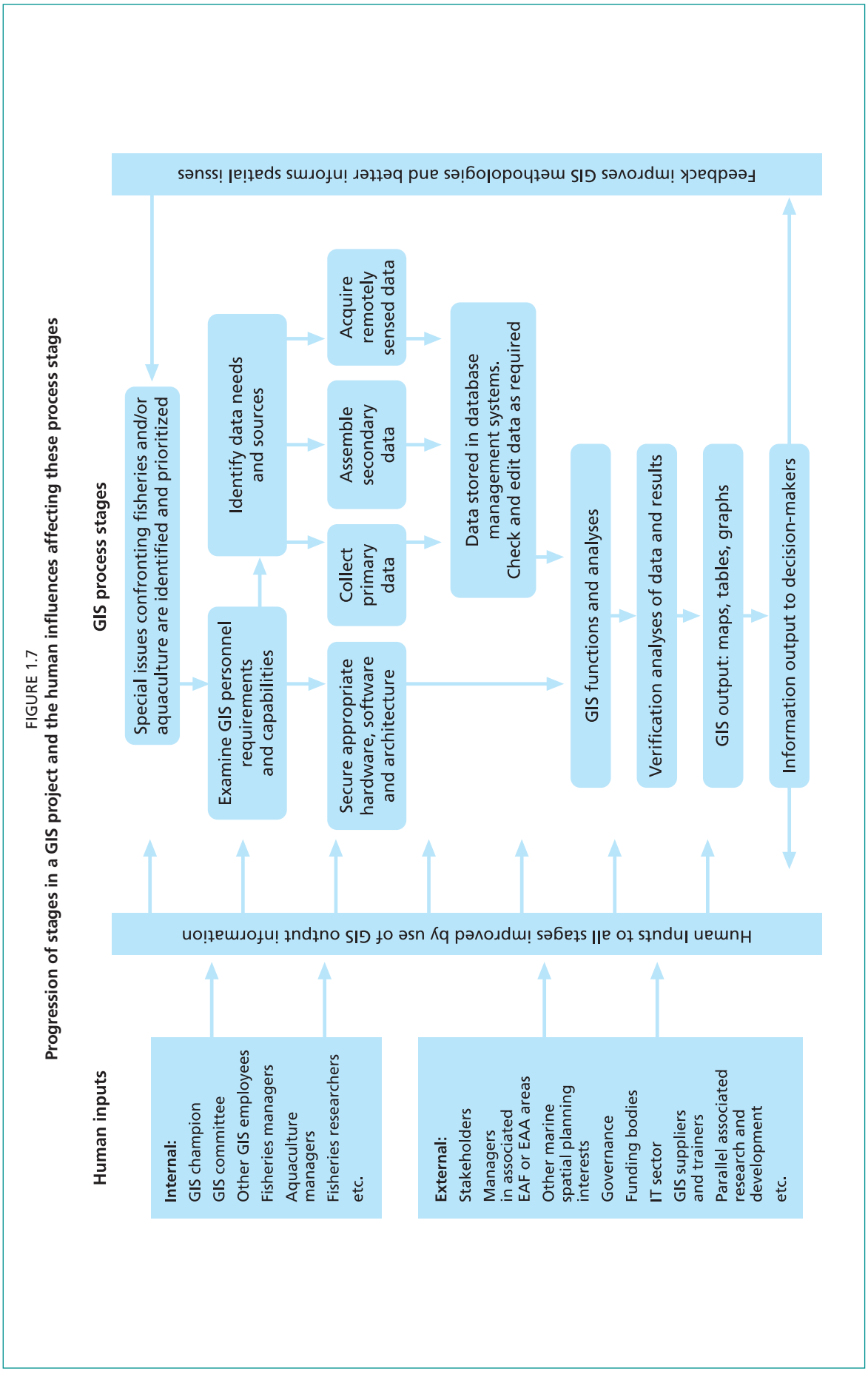

FIGURE 1.7
Progression of stages in a GIS project and the human influences affecting these process stages