Advances in geographic information systems and remote sensing for fisheries and aquaculture

Summary version

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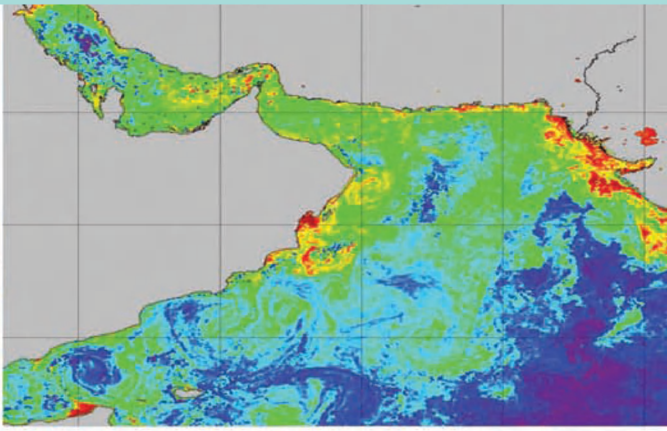

Cover photos:
Clockwise from top left: Double-rigged shrimp trawler with cod end of one net about to be opened (courtesy of Robert K. Brigham, NOAA's Fisheries Collection); Chlorophyll concentrations in the Gulf of Oman region (courtesy of ACRI-ST InfoceanDesk environment monitoring service from EU FP7 and ESA MyOcean GlobColour Products, ESA ENVISAT MERIS data, NASA MODIS and SeaWiFS data); Uur River in Mongolia (courtesy of Zeb Hogan); Gilthead seabream cages, Lavagna, Ligurian Sea, Italy (courtesy of Aqua sarl and Francesco Cardia).

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Summary version

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Preparation of this document

A challenge to geographic information systems (GIS) and remote sensing work on fisheries or aquaculture concerns geographic cognition and spatial awareness. There is a lack of appreciation that many or perhaps most of the problems concerning fisheries and/or aquaculture may be rooted in spatial differentiation, thus fisheries managers and others may often not appreciate the importance of the geographic perspective. It is because of this lack of appreciation that there is the need to train people in the use of GIS and remote sensing. The recent emergence of "marine spatial planning" is an exact reaction to this lack of realization about the importance of spatial issues. As a consequence, this technical paper was prepared to provide policy-makers and senior managers, who have to deal with their national fisheries and aquaculture sectors, with an overview of GIS and remote sensing tools to help them lead to more sustainable fisheries and aquaculture. This document will also be of relevance to aquaculture operators, industry organizations, non-governmental organizations and other groups interested in understanding GIS and remote sensing and their influences on master plans, industry regulation and the management of aquatic resources.

The FAO Fisheries and Aquaculture Resources Use and Conservation Division has been active in promoting the use of GIS and remote sensing in fisheries and aquaculture for many years. Promotional activities have been carried out by means of technical publications, training courses and workshops as well as the FAO GISFish Web site also created for this purpose.

The need for technical papers for understanding and applying GIS and remote sensing in fisheries and aquaculture was recognized in the 1990s; in fact, the Food and Agriculture Organization of the United Nations (FAO) commissioned and published the first technical papers on the subject: *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). The present technical paper aims to update these papers.

Abstract

Marine fisheries around the world remain seriously threatened from fishing overcapacity plus a range of environmental problems. As a result, the rising demand for fish products is largely being supported from increased aquaculture output. Changes in the sourcing of fish will continue to cause significant spatially variable effects on the marine and other aquatic environments, effects that are best managed through the application of geographic information systems (GIS) and remote sensing methods. Furthermore, changes need to take into account wider approaches to addressing aquatic problems, i.e. via marine spatial planning and/or ecosystem approaches to both fisheries and to aquaculture. This publication is an essential guide to understanding the role of spatial analysis in the sustainable development and management of fisheries and aquaculture. The publication is an easy-to-understand publication that emphasizes the fundamental skills and processes associated with geographic information systems (GIS) and remote sensing. The first chapter initially puts the array of spatially related problems into perspective and discusses the earlier applications of GIS and remote sensing. Chapters, 2, 3 and 4 outline what are considered to be the basics on which GIS can function, i.e. hardware and software; spatial data; and how GIS systems themselves are best implemented. Chapter 5 looks at preparing the data for GIS use and Chapter 6 explores what remote sensing consists of and the main purposes for its use. Chapter 7 discusses the functional tools and techniques offered by typical GIS software packages. Chapters 8, 9 and 10 examine respectively, the current issues and status, including extensive case studies, of the application of GIS and remote sensing to aquaculture, to inland fisheries and to marine fisheries. The final two chapters examine the emerging thematic issues that will be faced by fisheries and aquaculture in the near future, and then provides useful clues as to how challenges in accomplishing GIS work might best be overcome. The paper concludes with a series of recommendations underlining the paramount need to recognize that it is mainly through the application of a spatial perspective and approach that problems in fisheries and aquaculture will be better addressed. This technical paper is an update of previous FAO publications.

This publication is organized in two parts to inform readers who may be at varying levels of familiarity with GIS and remote sensing. One part is a summary and is addressed to administrators and managers, while the other is the full document and is intended for professionals in technical fields and for university students and teachers. The latter part is available on a CD–ROM accompanying the printed part of this publication.

Meaden, G.J. & Aguilar-Manjarrez, J., eds. 2013. *Advances in geographic information systems and remote sensing for fisheries and aquaculture.* Summary version. FAO Fisheries and Aquaculture Technical Paper No. 552. Rome, FAO. 98 pp. Includes a CD–ROM containing the full document (425 pp.).

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Abbreviations and acronyms

ASFA	Aquatic Sciences and Fisheries Abstracts (FAO)
AUV	autonomous underwater vehicles
CHARM	Channel Habitat Atlas for Resource Management
COAs	conservation opportunity areas
DEM	digital elevation model
DMBS	database management systems
EAA	ecosystems approach to aquaculture
EAF	ecosystems approach to fisheries
EMR	electromagnetic radiation
ERS	Earth Resources Satellite (from ESA)
ESRI	Environmental Systems Research Institute
FAO	Food and Agriculture Organization of the United Nations
FOSS	free or open source software
GIS	geographic information system
GISFish	Global gateway to geographic information systems, remote sensing and mapping for fisheries and aquaculture
GPS	global positioning systems
IFREMER	Institut Français de Recherche pour l'Exploitation de la Mer
ISO	International Organization for Standardization
IT	information technology
LAN	local area network
LiDAR	light detection and ranging
MERIS	Medium Resolution Imaging Spectrometer
MODIS	Moderate Resolution Imaging Spectroradiometer
MPA	marine protected area
NASO	National Aquaculture Sector Overview
PDA	personal digital assistant
SAR	synthetic aperture radar
SMOS	Soil Moisture and Ocean Salinity
SPEAR	Sustainable options for People, catchment and Aquatic Resources
SPOT	Système Pour l'Observation de la Terre
TIN	triangulated irregular network
TOREDAS	Traceable and Operational Resource and Environment Data Acquisition System
UNESCO	United Nations Educational, Scientific and Cultural Organization
USB	Universal Serial Bus
UTM	Universal Transverse Mercator
WAN	wide area network

Foreword

Global ecosystems are under enormous pressure. The pressure comes mainly from the increasing human population, which is attempting to extract resources at an accelerating rate from a planet that is finite. The pressure on fishery resources is manifested in a variety of ways, including: (i) reduced access to, and availability of, land and water (especially freshwater); (ii) overfishing of commercial fish stocks; (iii) degradation of fish habitats; (iv) pollution and deoxygenation of waters; (v) increasing competition for the use of the aquatic space; and (vi) changes in atmospheric processes, such as climate change and its consequences.

The FAO Fisheries and Aquaculture Department is charged with the important responsibility of tackling these issues. Its principle "mission" is to "promote policies and strategies aimed at sustainable and responsible development of fisheries and aquaculture in inland and marine waters." More specifically, within the Fisheries and Aquaculture Resources Use and Conservation Division (FIR), the Aquaculture Branch (FIRA) is responsible for "programmes and activities related to development and management of marine, coastal and inland aquaculture, with regards to technical, socio-economic and environmental aspects, and conservation of aquatic ecosystems, including biodiversity", and the Marine and Inland Fisheries Branch (FIRF) is "responsible for all programmes and activities related to management and conservation of fishery resources, including mainstreaming biodiversity and ecosystem concerns in fisheries management through an ecosystem approach to fisheries". Readers of this technical paper will see that its subject matter goes right to the heart of both of these remits.

In order to directly address the serious aquatic issues described above, how is it best possible for FAO to meet its responsibilities? Although each of the issues has to be dealt with in an individual way, a detailed look at the full range of issues reveals that spatial problems are an important commonality.

The use of spatial planning tools such as Geographic information systems (GIS) and remote sensing for fisheries and aquaculture can greatly help in the identification, analysis and possible allocation of specific geographical areas to be used for fisheries and aquaculture, particularly in those countries that have limited natural resources that are in high demand by competing users. Spatial tools can also simplify the process of zoning and site selection for aquaculture and can match other demands on the marine space. These tools, therefore, become important considerations in bridging the future supply and demand gaps in fishery products. And now that planning, management and research in the marine and other aquatic spaces is dominated by "ecosystem approach" considerations, and with the need to better consider other users of marine space through "marine spatial planning", it is certain that GIS will prove to be an indispensable tool. GIS and remote sensing technologies are invaluable technologies to support sustainable aquaculture expansion and intensification as well as sustainable fisheries.

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1. Introduction

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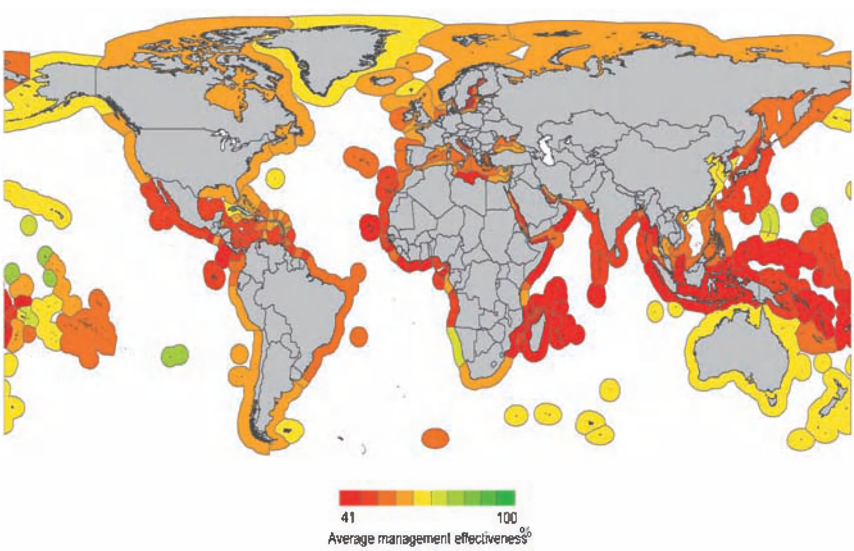
For several decades it has been recognized that the world's fish stocks are becoming increasingly depleted, with the Food and Agriculture Organization of the United Nations (FAO, 2012) recognizing that 57 percent are fully exploited, 30 percent overexploited and 13 percent are not fully exploited. Even 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:

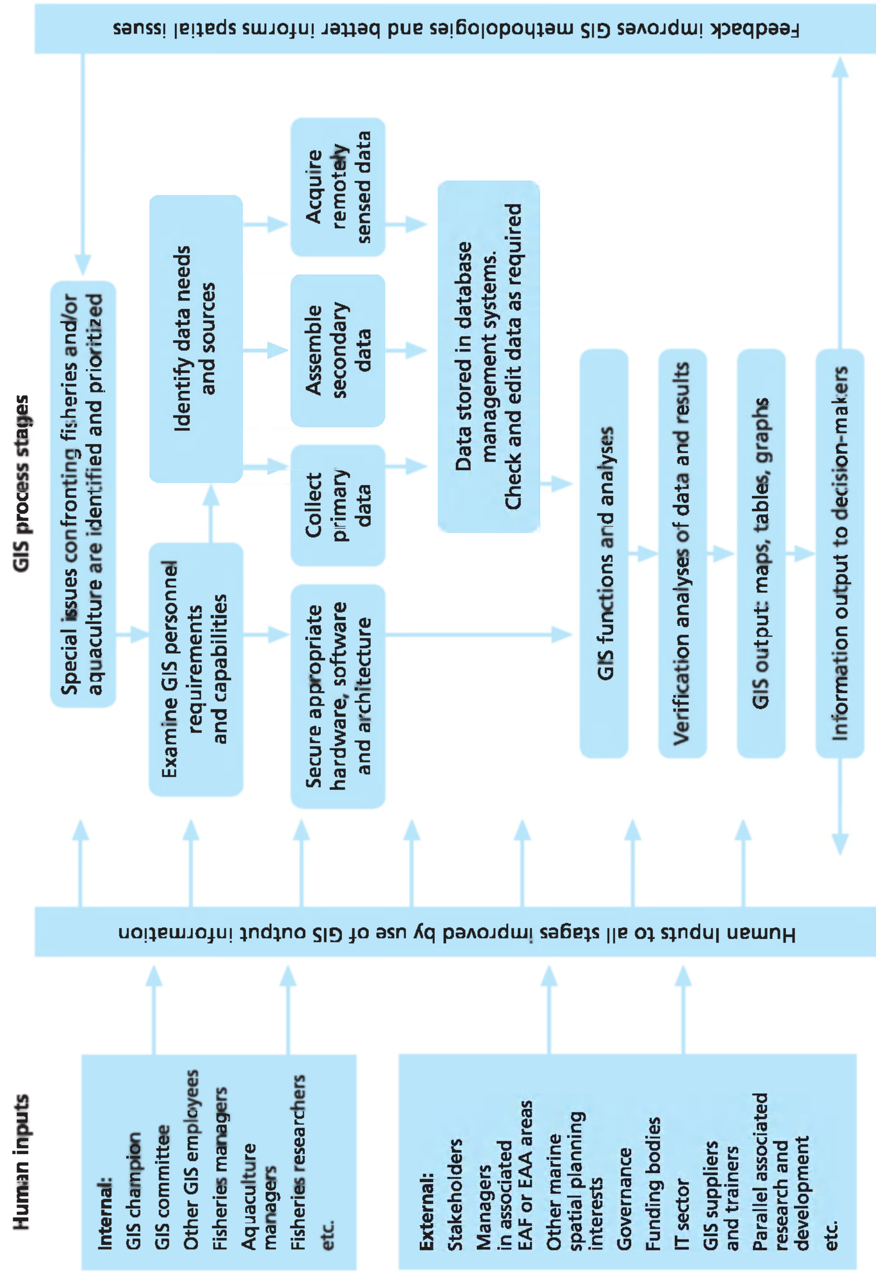
- **The growth in computing power.** Over the past 50 years, there has been an unremitting growth in computing power in terms of not only computers themselves, but also in terms of peripheral hardware devices, data storage capacity, associated software, computer graphics capability, and so on. This computing 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



2. GIS hardware and software for fisheries and aquaculture

G.J. Meaden (FAO consultant, Canterbury, United Kingdom)

While it is recognized that many individuals or groups wishing to utilize GIS for fisheries management or research will do so using existing information technology (IT), it is important that a broad general knowledge exists on the wide range of possible system components. In this chapter, attention is directed towards the essential hardware and software needed to support GIS operations, and these infrastructure components are discussed under suitable headings. As the IT sector continues to make rapid advances, it is recognized that much of the information in this chapter may soon become outdated, certainly in terms of cost and performance. However, rapid advances will "produce significant gains in work productivity, increase our basic understanding of natural systems, help fisheries professionals detect patterns and develop working hypotheses, provide tools to rationally manage scarce natural resources, increase our ability to organize, retrieve and document data and data resources, and in general encourage clear thinking and more thoughtful analysis of fisheries problems." Megrey and Moksness (2009, p. 2). Although the choices with respect to the hardware used for GIS are very wide, they are relatively easy to make in that precise definitions already exist in terms of equipment function and capability. In contrast, the choices regarding software tend to be more complex. This is because software can be almost infinitely adapted so as to obtain any desired output, with this being achieved through multiple GIS packages, tools, cost variations, functional range and user preferences in terms of the required quality of the output. One software option that is only briefly explored is that of doing all or most GIS work via the use of Web-based GIS software. At present, this is still a relatively complex route to obtaining required functionality, with users being restricted to what is available online and users may not have sufficient bandwidth for efficient Internet delivery. However, this is a route to GIS that needs to be explored over the coming decade, and information is provided for investigating this option.

Necessary hardware components of a GIS system can be conveniently discussed under the three headings of: (i) hardware for inputs of required digital data; (ii) hardware for data processing and storage; and (iii) hardware for obtaining GIS output. The hardware required for capturing the essential digital data consists of four main types, one of which (data loggers) is discussed in the following chapter, as it comprises a range of general digital collection devices that are best considered under the heading of data collection methods. The first main hardware type is computing systems designed for data collection. These comprise a range of handheld "tablet" or "palmtop" computers that are frequently "ruggedized" for use in adverse physical conditions. This equipment is typically multifunctional, in that it not only serves data gathering purposes but the data can also be processed and used directly in other software packages including GIS. Internet connections may also be readily available. The second type of data input hardware is scanners. These are devices that capture data through the use of a photosensitive head, with the captured data being stored as regular rows of "pixels" having values according to light or colour intensities recorded. Scanners vary greatly in size (typically being able to scan from A4 to A0 sizes); in their method of scanning (with either the photosensitive head moving or the scanned sheet moving in front of this head); and in the degree of detail recorded. Scanned images may be useful either as the "backdrop" or as superimposed imagery, or as the on-screen image for digitizing. The final type of data input hardware is digitizers. These are essentially devices that allow for the digital capture of graphic lines on a map along with their geo-coordinates and their meaning. Digitizers vary from small "tablet" size to very large table size. They work on the basis of the user following, via the use of a cursor, desired lines on a map, which is mounted on the tablet or table. The cursor is continually clicked and the location of these clicks is recorded in the computer to which the cursor is linked. Today, most digitizing is done "on screen", whereby the cursor follows a scanned image on the computer screen instead of using a stand-alone digitizer.

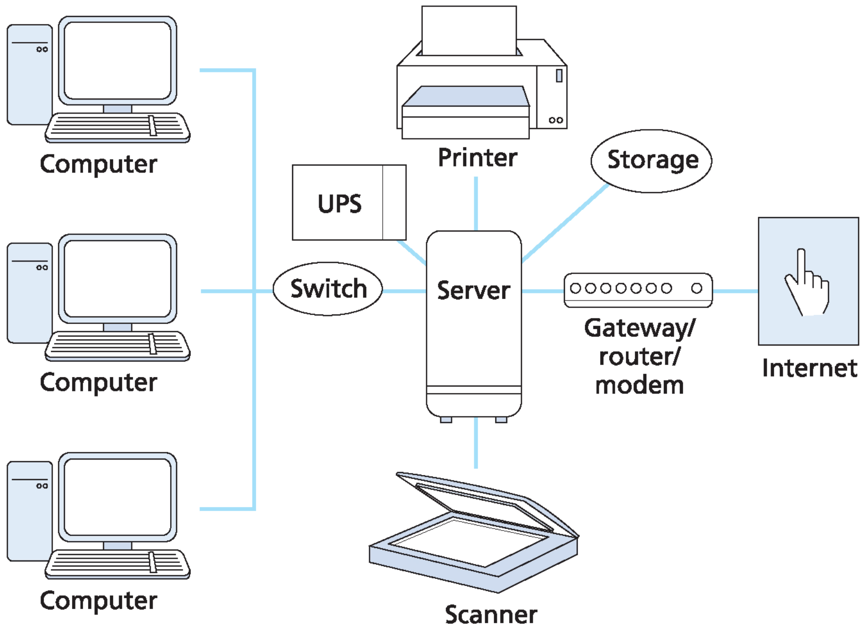
The main hardware devices for processing and storage of digital data are computers. The huge advances in all facets of computing, including cost reductions, have been discussed in Chapter 1, so here it is only necessary to outline some specifics of computers relating directly to GIS use. Today, GIS work is mostly performed on desktop computers, though a small amount of "higher-end" or data-intensive processing might be carried out on large mainframe computers. However, there is an increasing move towards using so-called mobile devices, such as laptops, tablets, palmtops, notebooks and personal digital assistants. In many cases, work in the field might be accomplished by these mobile devices, with the work being transferred to a desktop computer for higher-end processing. For GIS work, it is particularly important that desktop computers are of a high capacity in terms of storage, screen size and processing capabilities, as data and performance requirements for graphically related mapping might be very large. More details on computer specifications are given in the full technical paper, as are details regarding linked peripheral considerations (operating systems, keyboards, USB ports and other attachments). Although all computers have internal digital storage capabilities, there is a range of other data storage devices such as external hard drives, optical disk drives, memory sticks and linked file servers, most of which can be used as secure back-up storage. Two other important items of hardware that are discussed are uninterruptable power supply, which is necessary in case of power disruptions, and wireless routers or modems, which allow access to the Internet and thus to external communications.

Although GIS output comes in several forms (maps, text, tables and multimedia) and can be delivered via disks, the screen, the Internet and in hard copy, direct output from hardware can either be for temporary "ephemeral" use (soft copy) or of a permanent (hard copy) nature. The computer screen is the output medium for ephemeral images. These images can be deleted, added to, altered, sent to another computer or filed. Filed images can be saved on any of the storage devices listed above, using various file formats, and then retrieved for future use, e.g. pasted into other files or used for multimedia purposes or transmission via the Internet where they might enhance selected Web sites. Permanent hard copy output is produced via a wide range of plotters and printers. Plotters essentially produce output by drawing lines on paper or film to make up an image. They typically vary in size from A4 to A0 and are limited to six or eight colours. Compared with printers, output will be very slow, and for this reason their use is rapidly declining. Printers come in several varieties, the most important being inkjet and laser, and they too produce output of varying size. Some of the advantages over plotters are the huge range of colours that are available, the speed of output, and the fact that their high-resolution potential (measured in dots per inch) can enable high-quality output.

The hardware combination required for successful GIS work can vary greatly, and the actual configuration of the hardware assembled is termed the system architecture. The architecture finally assembled will be a function of the hardware that may be inherited, the capital outlay available, the purposes of the GIS, the size of the organization doing the work, plus knowledge of what is available and any personal preferences. As an organization takes on more complex work, the configuration of hardware is likely to become extended. At its minimum, the architecture will comprise a personal area network, which might consist of IT basics such as a computer, screen, keyboard, printer and perhaps a scanner, plus the necessary linkage hardware for getting access to the Internet. The next level of architecture might be a local area network (LAN). Figure 3 gives some idea of a LAN configuration, though there could be almost infinite variations to this basic model in terms of actual devices and hardware capacity. As well as the hardware mentioned above, there is likely to be a central server that feeds data and software to individual computers, and also has extensive data storage capacity, an uninterruptable power supply and high-speed access to the Internet. At the highest level of architecture, a wide area network (WAN) contains the ability to link many and varied LANs at perhaps a national or international level. For fisheries GIS work, this may be important because work will often be progressing in scattered and perhaps isolated institutions. Over a period of years it is likely that many institutions will slowly be migrating towards WAN functionality.

Turning to GIS software considerations, it is important to mention that the discussion is restricted only to software that might be of direct use and not to any of the other software that may conveniently and usefully be linked to GIS, i.e. operating systems, databases, spreadsheets, graphics, digitizing and remote sensing software. Discussion is also restricted to software that is readily available in the marketplace, and thus options of developing or writing new purposeful software are not discussed. The software discussed can be conceived as either proprietary, specialist marine, or as free and open source software. Proprietary software is software that is readily available, usually from international software companies, and that has been developed to perform a large number of GIS analyses and functions.

FIGURE 3
Main components and linkages in a LAN computer architecture



There are perhaps a dozen major GIS packages, and this technical paper provides further details on five main products: ArvView (ESRI); Idrisi (Clark Labs); MapInfo (Pitney Bowes); GeoMedia (Intergraph); and Manifold (CDA International). All the main packages perform a similar range of basic GIS functions, though they may vary greatly in their costs, total functional range, their usability, licensing arrangements, add-on modules, the extra services or support provided, and user agreements. The visual output will also vary greatly. None of the proprietary GIS packages have been developed specifically for fisheries or aquaculture work, though all of them can be suitably deployed for this. There has been a strong tendency for certain GIS software to become dominant and this dominance is reinforced when training is carried out using these specific packages; thus, most trained labour is only available having specific GIS software experience

Most GIS software has been developed for various forms of terrestrial use, and the software serves this function well. It has been, however, more difficult to develop specialist marine or marine fisheries GIS because the market has never been large and because the marine environment is more complex for most mapping and spatial analyses purposes. This contrasts with the use of GIS for inland aquaculture, where the activity is another type of terrestrial land use. Despite the challenges of developing GIS for fisheries purposes, this technical paper describes many small-scale initiatives to develop software applications that are capable of carrying out assorted marine and/or fisheries spatial analyses. Recently, there have been some attempts at developing specialized multifunctional fisheries-related GIS software packages, and two of these are described. The first of these (Mappamondo GIS) has a reasonable GIS functional range, making it useful for a range of selected spatial analyses, but the second (Marine Explorer) could be defined as a comprehensive marine fisheries GIS. The full functional capabilities of this package are described and briefly discussed.

A significant part of this chapter on hardware and software is devoted to an analysis of a sector of the software market that is probably underutilized, certainly with respect to its use in fisheries and aquaculture. This refers to the use of free and open source (FOSS) GIS software. Conventional software is too easily taken for granted because it may have been extensively promoted and marketed or used in training or educational institutions. However, dependence on known software can deprive users of the flexibility to adopt an open-minded approach to resolving spatial problems. There are now a wide range of ad hoc applications, many of which are based on FOSS software. The emergence of FOSS can be viewed as part of a wider movement towards making freely available a much larger range of computing software, and this is particularly advantageous for GIS users who are on a limited budget. Most open source software comes with the rights to using the source computer coding, meaning that the software can be manipulated, changed or extended for use under any particular circumstance. A large community of users has developed around the FOSS ideals, and there are support groups, specialist conferences, libraries of applications, etc., which may be based around particular programming languages, thematic applications, types of user organizations, or based in particular geographic areas. Other developments in the FOSS arena include the establishment of the Open Source Geospatial Foundation to oversee the interests of FOSS developments and the creation of internationally recognized operating standards for the software. Users who might wish to take advantages of the cost savings offered through FOSS will have to consider whether this use outweighs possible negative factors associated with the fragmented nature of the FOSS community, the need for fairly advanced operating skills, and the fact that it might be necessary to cope with the use of many potentially diverse software applications. This technical paper outlines all the main advantages and disadvantages of pursuing the FOSS route to GIS work, provides details on a selection of the major FOSS GIS packages, and gives cautionary guidance on the selection of specific FOSS software.

3. Spatial data for fisheries and aquaculture: characteristics, quality and data sources

G.J. Meaden (FAO consultant, Canterbury, United Kingdom)

It has frequently been suggested that the most important component to successful GIS operations is data and that the data will usually be the most costly input into individual GIS projects. It should, therefore, be a fundamental aim for all GIS operatives to secure high-quality data because without this the output from project work may lack reliability and decision-makers will not have confidence in using the information produced. This chapter seeks to give guidance towards achieving appropriate data needs. With respect to data for marine fisheries projects, they can be difficult to obtain given the major expenses in gathering data at sea and the sheer volume of data required, i.e. given that marine environments may be very expansive and that they have both horizontal and vertical dimensions. Additionally, the mobility of all aquatic environments imposes greater temporal constraints on the validity of the data collected. Until the late 1980s, virtually all data collected was in hard copy format, but since then rapid technological progress has occurred so that today almost all data gathering is via electronic instruments, meaning that data are usually in a format suitable for direct GIS use. References are made in this chapter to hard copy data collection techniques and formats because there is a legacy of older data that may need to be digitally converted and because there are still circumstances where data collection is more conveniently accomplished using traditional methods.

The use of GIS for any fisheries or aquaculture project will almost certainly be a response to a desire to improve the likely success of these activities. Success for any production activity can be measured in terms of four basic criteria: (i) economic; (ii) social; (iii) physical or biological; and (iv) sustainability. It is important to point out that when the forerunner to this technical paper was published (Meaden and Kapetsky, 1991), the criterion for success was economic (in terms of profit maximization), but it is now recognized that this criterion has entirely changed, such that success is now based on concepts surrounding sustainability, with this being achieved through either an ecosystem approach to fisheries (EAF) or through an ecosystem approach to aquaculture (EAA) (FAO, 2003; Carocci *et al.*, 2009; FAO, 2010a; Aguilar-Manjarrez, Kapetsky and Soto, 2010). This change may have a profound effect on the types of data collected as the data have to mainly support sustainability rather than economic objectives.

Personnel organizing and/or managing GIS projects will need to give detailed considerations as to what data are best required for project success, including factors such as the spatial area for the project and the scale and resolution or detail at which the study is carried out. The technical paper provides advice on all main questions that need to be asked of any data to be collected.

For their success, all production activities are controlled by the availability of "production functions", i.e. those factors or variables that, in combination, influence the success of any production activity. Some production functions will be "one-off" considerations such as the initial land purchased for aquaculture ponds, while others will be akin to operating costs as their consideration may be continual, e.g. access to markets or target fish species to catch. Production functions may be highly variable in an area, such as soil quality, bottom-sediment types or population density, while others may be highly uniform, such as sea

BOX 1
The main spatially variable production functions influencing marine cage culture

Here the aim is to consider off-the-coast or offshore mariculture.

- Distance from shore (ports) – This is important in respect to frequent observation, feeding, stocking and harvesting activities.
- Water depth – Sea cages must be tethered and deep water presents a challenge.
- Water temperature – Species will have developed preferred temperatures and temperature tolerance ranges.
- Availability of shelter – Cages in open waters are vulnerable to storm conditions that can cause cages to break free or break up with subsequent stock losses.
- Distance from competing water activities – It is essential to avoid siting cages in busy sea areas or areas liable to pollution.
- Water quality – Many near-coastal sites may suffer from various forms or sources of pollution, e.g. oil leakages, sewage outfalls or sources of disease. Dissolved oxygen levels are also important.
- Turbidity and suspended solids – Some species have preferences for clearer waters.
- Interactions of farm sites with immediate environments – Cage sites need to take account of local biodiversity, waste deposition and benthos issues.
- Distance from other cage farms – Because of disease problems, cages should be located in relatively isolated and well-dispersed locations.
- Prevailing wave heights – Where long fetches prevail (usually around open oceans), prevailing waves may be too high for conventional cages, though completely submerged cages may be possible.
- Availability of inputs – The location of marine cages should be chosen with respect to important inputs such as extension services, veterinarians and feed suppliers.
- Predators – In some areas, predation from cages is a problem.
- Visual impacts – Cage locations should not be visually intrusive.

water temperature or salinity. Production function deficiencies can be increasingly overcome, such as providing electrical energy inputs through the use of mobile generators or the supply of any oxygen deficiency through artificial oxygenation. Each production function will be of variable importance to production success, so it is important that the functions can be ranked or measured in some way. Once this is done, then some measure of weighting can be given to each production function, i.e. as part of the GIS processing procedures. The technical paper describes the main production functions controlling the success of inland aquaculture, marine fisheries and marine cage culture (Box 1). The functions controlling marine fisheries are far more varied than those influencing aquaculture because fisheries are highly variable in terms of the methods used, species targeted, scale of the activity and degree of technology used. It would also be true to say that the thematic range of GIS projects applied to marine fisheries is wider than the range currently applied to aquaculture. Once the production functions have been clearly identified, then it is the spatial data that best describes the disposition of each of these functions that will be needed as source data for any GIS work.

If data are to be of use in a GIS, they must have certain minimum requirements. Because many of these requirements are general to all computing, e.g. data should be in a uniform format, follow classification rules, have an accepted measure of accuracy, then requirements are not discussed here. Other requirements are much more specific to GIS work and they include: (i) having a temporal facet so that the user knows what the data relates to – this has implications for when data might need updating and when comparisons might be made between specified times or time periods; (ii) relating to a thematic area or to some accepted classification system. Data classifications may be very general, e.g. "marine", "fisheries" or "aquaculture", or they may be more specific, e.g. "mature cod", "mature plaice", "mature whiting",, and there can be any subclassification hierarchy within themes; (iii) data having a quantitative facet involving some kind of count or measurement – this will involve considerations of precision and accuracy; and (iv) considerations on the scale and resolution applicable to any GIS project. The scale of the project means considering the area to be covered and therefore where the boundaries are so that data needs can be properly assigned. It is often sensible to make the GIS project area coincide with national or regional boundaries, i.e. simply because data are often collected with respect to named political areas. Resolution implies a consideration of what can be shown on a map relative to the area being mapped, and this will have large implications with respect to the volumes of data that need to be collected.

The most important facet of data that are being collected and used for GIS work is the spatial facet, i.e. exactly where is the data referring to? This locational data may be referring to features that can be drawn on maps as points, lines or polygons, and the data gathered must accurately have a georeference for all objects or events that are of interest to a project. Georeferenced data are typically recorded in terms of latitude and longitude or by using some form of Cartesian coordinate system. Latitudes and longitudes are recorded either in degrees, minutes and seconds or in decimal degrees. While this information is useful, it suffers from the fact that longitudinal lines on maps all converge at the North and South Poles and thus distances between lines of longitude vary with distance from the poles. Cartesian coordinates try to overcome this problem by covering the mapped area with a regular grid of horizontal and vertical parallel lines, with these lines usually being based on the internationally recognized Universal Transverse Mercator (UTM) projection system and its unique alphanumeric referencing system. However, this georeferencing method also suffers because it is impossible to impose a true grid of parallel lines over what is a spherical object (the Earth). For mapping smaller areas, the distortion is very little, but at the world scale the UTM map projection greatly exaggerates areal and horizontal distances that are nearer to the poles. Whatever mapping projection or georeferencing system is used, it is important to use the same system for all mapping within a single project. The spatial data used for mapping can also be in the form of named areas or a descriptive code. These coded data are mainly used when doing GIS work involving polygons, i.e. spatial areas that might be named counties, land-use zones, geology types, for example. The technical paper provides various worked examples that explain georeferencing requirements and methods in more detail.

Before examining the collection of data for GIS, it is important to be familiar with considerations regarding data quality, as this largely determines the reliability of the final output from any GIS. The main factor influencing data quality is the resources of money, time and effort that can be put into data collection. However, data quality is largely scale dependent. Thus, if data were being collected for a small-scale (large area) project, then the use of the same data for a large-scale project would almost certainly be inappropriate because the resolution of the data would be insufficient for accurate mapping at the larger scale. Consideration must also be given to:- (i) the accuracy of data used and to their precision (how precisely has a measurement been recorded); (ii) standardizing the methods used for data collection; (iii) the use of appropriate classification systems and thematic categories; (iv) the timeliness of the data; and (v) possible sources of error in any data collected. In order to try to improve the quality of data, especially for GIS use, various attempts have been made to establish so-called “data standards”. These are mainly internationally recognized standards managed by the International Organization for Standardization (ISO), though there are also geographic standards pertaining to individual countries or organizations. Standards set by ISO and others mainly relate to any data products produced, to the format and manner in which data are transferred, to data quality standards, and to metadata standards (the recording of information about any data collected).

The actual data to be collected are conventionally categorized as being in one of two classes: (i) primary data, which are “raw” (unprocessed) data that are directly collected for a specific project; and (ii) secondary data, which are data that have been previously collected, usually for totally unrelated projects. The collection of primary data entails considerations of the availability of time, funding, trained personnel and any equipment needed, as well as whether there is existing secondary data that might be used. It will also be necessary to establish a sampling strategy. This is because it will almost certainly be impossible to collect all data and therefore considerations of what will be a representative sample are important, including how best to define the sampling strategy so as to achieve statistically significant results. At its most basic level, primary data may be collected using a range of methods involving no equipment. These methods include: (i) direct sketch mapping, e.g. fishers might be asked to sketch in on a local map areas where they prefer to fish for particular species; (ii) face-to-face interviewing, which may be useful for obtaining socio-economic information on fisher group activities; (iii) questionnaires, which can usefully be carried out by mail, telephone or face-to-face on any subject; and (iv) filling in pre-printed forms. All data collected in the ways described here will have to be converted into digital formats for storage and use in a GIS.

A vast range of equipment exists that allows for primary data collection, and nowadays nearly all of the data can be directly captured in digital formats that are easily structured for direct GIS use. The equipment can be best described in an approximate hierarchy going from basic or simple to highly complex. At the simplest level, there is a range of electronic "read-out" equipment that comprises small devices, frequently handheld, for measuring a variety of parameters, including water temperature, light intensity, water flow rates, pH levels, or the size and weight of objects. These devices vary in their complexity and utility according to their accuracy, ability to store data, ease of use, range of functions, etc., and their cost usually reflects this diversity. At a slightly more sophisticated level, there are digital cameras. They have the ability to accurately record in a convenient visual format any localized scene or layout of objects of interest, and they are useful in recording temporal rates of change, e.g. the shrinkage rates of glaciers or river water levels. Cameras can also be aircraft mounted to give direct overhead (mapping) imagery.

Data loggers and personal digital assistants (PDAs) – the next level of equipment –have a greater range of functionality. Data loggers typically allow for a wide range of data to be captured and stored on any thematic area of interest. They are generally battery powered, portable and equipped with a microprocessor, plus internal memory for data storage, and they may have various sensors. They may be either handheld or utilized in situ, perhaps in a river to capture water-flow rates, or they may be attached to free floating or tethered buoys in the sea, or installed on board autonomous underwater vehicles (AUVs). They can usually be directly interfaced with computers for the downloading of data. PDAs may best be conceived as handheld computing and communication devices: they have access to the Internet, a small colour screen, cell phone capability and Wi-Fi connectivity. They deploy touch-screen technology and can be loaded with a wide range of software. In many senses, PDAs replicate the functionality of desktop computers, though their small screen size is far from optimum for GIS use. However, technological progress in the field of PDAs is so rapid that it is difficult to conceive of their possibilities within even the next decade.

At a much higher level of sophistication are global positioning systems (GPS) and acoustic sonar devices. GPS are highly sophisticated because they rely on complex satellite systems. However, here, the interest is in their ability to precisely ascertain a wide range of information all of which can be given an exact georeference. Thus, for any location given in latitude/longitude or as UTM coordinates, etc., details can be captured on a thematic object or event, plus any associated attributes such as altimetry, speed or direction of travel, and local time. Having instant access to georeferenced data is a huge advantage when gathering data for GIS purposes. GPS may, additionally, be either handheld or they may be incorporated into other technology such as vehicle navigation, vessel monitoring, cell phones and even digital watches and cameras. Finally, acoustic sonar devices are especially relevant to fisheries GIS because this radar-based technology allows for the real-time capture of a variety of underwater data, including the location of fish shoals and sea-bottom topography and substrates. The technology is usually deployed as attachments to the hull of vessels, but it may be incorporated into AUVs or onto the headrope of large trawlnets. The data received from acoustic sonar use are in the form of echolocations, whose patterns are translated into identifiable features by trained users, and which can form the basis of much underwater mapping.

Data collection methods and data sources for secondary data have both undergone fundamental changes over the past few decades. Changes have involved the types of data sources, the form that data takes, delivery mechanisms for data, and the breadth and volume of data available. The move away from largely fragmented paper-based data sourcing to more centralized digital data sourcing means that almost none of the data sources or the media and formats used 20 years ago are now relevant. It is likely that 95 percent of fisheries or aquaculture-related data are now available in digital format, though there remains important "historical" mapping and tabular data that awaits digitizing when the need occurs. Most useful secondary data are stored in databases on powerful server computers awaiting delivery when required via the Internet, though delivery may also be via CD–ROM or DVDs. There are a vast number of fisheries and aquaculture secondary data sources supplying anything from highly generalized small-scale data to highly specialized large-scale data. The sources are best located via online searching, but the technical paper provides details on some of the main fisheries and aquaculture access portals and on sources of data on selected themes in inland fisheries, i.e. as examples of the types of secondary data available. For GIS-related work in inland fisheries or aquaculture, a major source of secondary data will be from the national mapping or hydrographic agencies in any specific country, whose addresses can be obtained by online searching. A problem to obtaining much secondary data is that the data may be costly, especially if they are in a digital format, and there may also be copyright rules that apply. GIS users seeking mapping may find that some larger private companies may allow free access to mapping, e.g. Google Earth's satellite imagery and the Environmental Systems Research Institute (ESRI) provide a range of ready-to-use, high-quality data for GIS visualization and analysis. A number of cautionary questions that need addressing with respect to obtaining secondary data are, for example: (i) How old is the data?; (ii) Does the data come with usage rules attached?; (iii) What is the scale or resolution of the data?; (iv) Might there be cheaper sources of data required?; and (v) Does the data provide exactly what the project needs? Secondary data for capture fisheries purposes are generally more scarce than the data for aquaculture. This is because most fisheries data have been gathered on very specific parameters, for specific projects covering relatively small spatial areas. Such data may also be hard to locate. This means that GIS projects may concentrate only on spatial areas or themes where it is known that sufficient data exists, or that projects aims are only defined in terms of what data are known to be available.

Suitable data for GIS projects may sometimes be difficult to locate or acquire. A means of coping with this can frequently be found through the use of proxy data; this is data that may not be directly related to the exact data required but can nevertheless be a substitute for the real data. For instance, if water temperature data cannot be easily acquired, then data on air temperatures for an area of interest usually shows a high correlation with water temperatures, and Aguilar-Manjarrez and Nath (1998) showed how soil suitability for the siting of fish ponds in Africa could be inferred from using proxy data obtained from a 1995 FAO-UNESCO Soil Map of the World. Sometimes two proxy data sets can be combined in order to gain a realistic required map; for example, to obtain a land price or value map, using GIS capabilities it might be sensible to combine a map of population density with a soil quality map. This is based on the fact that population density and soil quality are strong indicators of the demand for, and thus cost of, land. In the marine or freshwater realms, existing aquatic habitats often act as a close proxy of the likely fish species to be found, though in these realms the strength of any relationship would be far more generalized and less certain. Notwithstanding this uncertainty, much recent GIS work has utilized proxy data to establish habitat suitability or essential habitats for aquatic species.

4. Implementation of GIS

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Now that background information has been given on the potential usefulness of GIS in fisheries or aquaculture research or management and on the potential hardware, software and data requirements, readers should be in a position to assess whether this IT system is likely to suit their future needs. If the decision is made to further investigate GIS capability, then the means of doing this is explained in this chapter. A full discussion is given here on the range of implementation decisions that are essential to the successful functioning of any GIS. It is important to mention that in the past many organizations made unsuccessful attempts at implementing GIS, and research has concluded that the lack of success was due to failures to:

- identify and involve all users when considering needs for the GIS;
- match GIS needs with the right hardware and software;
- identify the full range and extent of capital and operating costs;
- conduct a pilot study that would ascertain full operational requirements;
- operate the GIS within the right department, one that has geographical skills; and
- provide sufficient training, background support and hands-on GIS experience.

In addition, the adoption of a new and possibly complex technology such as GIS might have repercussions on existing working practices, including changes to work priorities, workflow patterns, product outputs, training needs, budgetary considerations, management priorities, and work and space allocation. Implementation of IT technology such as GIS needs to follow a recognized, though variable, set of procedures that are well described in sources listed in the full technical paper and these procedures will form the basis for the rest of this chapter.

Initiation of GIS as a valuable fisheries or aquaculture research or management tool is likely to come from an external source, perhaps a trade magazine, an exhibition stand or conference attendance, through networking with others in fisheries research or management, or perhaps as a recommendation from a consultant or a GIS software house. Whatever the source, there is likely to have been an individual within the organization who has perceived the likely benefits that GIS can provide and who has taken steps to recommend this. This person is frequently referred to as a “champion” because he or she is keen to “champion” a worthy cause – in this case GIS. It is clear that the champion has already recognized the full potential of GIS; he or she is likely to have discussed it with colleagues, and then the ideas would have been made known to those at decision-making levels. It may appear to readers that this is not the GIS initiation process that has occurred within their organization, i.e. they may simply have had GIS use imposed upon them. This may not be a desirable situation, though it depends on how the imposition was made. It is vital that the introduction of new technology is undertaken with care, i.e. as it will inevitably involve disruptive changes in working practices. In order to best facilitate working practice changes, management should identify a suitable "champion", i.e. the person to nurture the future development of GIS within the organization.

Once the possibility of using GIS has been "championed", the feasibility of GIS adoption needs to be determined, i.e. is the use of GIS likely to be a sensible route to take. This feasibility will vary greatly between organizations according to such factors as needs, familiarity with IT, management skills and other resources available, plus the extent to which GIS will aid in meeting the organization's objectives. Four useful ways of conducting a feasibility study are through: (i) A GIS committee that may have been established precisely to work out the viability of GIS; (ii) questionnaires or interviews to determine the views of relevant people within an organization on the likely value of GIS; (iii) holding workshops or demonstrations that explore the idea of GIS adoption; and (iv) through use of an external consultant who can ascertain the likely needs and affordability of a GIS. Any combination of these approaches might be taken, and it would be useful for all GIS participants to update their familiarity with relevant aspects of GIS. The technical paper provides a list of questions that need to be asked in any feasibility study, and, based upon the answers, it might be recommended to proceed further with GIS adoption; or perhaps to seek alternative arrangements such as contracting out work to a specialist GIS contractor; or to share GIS work with another sympathetic co-user; or to abandon GIS plans for the present.

A final but important exploratory step to take on the route to possible GIS adoption is that of a cost–benefit analysis. This involves an exercise that attempts to balance the total costs of acquiring the system against the benefits that will be gained from deploying a GIS, that is, do the advantages of adoption outweigh the disadvantages? It is important to mention that costs and/or benefits may not be solely calculated in financial terms; some are likely to be measured in more nebulous values that largely relate to gaining information for better decision-making. In fact, with respect to any GIS implementation decision, it is likely that intangible costs or benefits will be more important than tangible, making the adoption decision possibly more difficult. Other problems are that benefits of GIS may take a long time to accrue, so initial costs will far outweigh benefits, and that cost–benefit ratios vary considerably between different GIS projects. Examples of costs and benefits are provided in the technical paper. It is suggested that the actual analysis should be carried out by an external organization or consultant, if only because these agents will be best placed to explain the results to senior management.

If it is agreed that GIS adoption is feasible and that likely benefits outweigh likely costs, then GIS implementation can move to a system design stage. The outcome of this will be a "GIS system design" document that provides answers to the feasibility questions and that demonstrates the conceptual design of the complete GIS, including the likely hardware, software, system architecture, personnel needs, main data sources and management requirements. This is, therefore, a comprehensive guide to management showing that all implementation considerations have been covered. Compilation of this document is likely to be a major task, one that is likely to involve external advice and contributions. Only in cases where it is considered best to develop GIS capability as a slow incremental growth from an existing small-scale facility will the system design document be minimal in scope and content. Additional guidance is given in the technical paper to system design, especially to the requisite sectional headings for such a document.

If the decision is made to proceed with GIS implementation, there are frequently standard procurement and installation procedures that organizations are obliged to follow. In practice, it is often the case that an implementation plan is drawn up as part of the "system design" document described above, though additional information might now be considered, including any timing for the installation plus other organizational matters such as support and training needs, system maintenance and security arrangements. The implementation plan might be devised by a "GIS committee", which might be in place to oversee overall GIS developments, and which might expect advice from management and from external consultants. The technical paper provides examples of implementation plans that could be useful for supplying content headings, plus a checklist of important issues when actually implementing a GIS and a guide to the varying staff roles of groups or individuals who might be involved. The implementation itself may follow one of four main models:

- An "in-house" development using a slow-growth approach whereby the GIS is incrementally built up over an extended period, allowing easy adaptations to occur.
- An "in-house" development using a "big-bang" approach whereby the GIS is developed in a non-working environment, with the date announced beforehand indicating when the GIS will become operational and thus ready to use.
- All GIS work is contracted out, which is often a good policy if the amount of future GIS work is thought to be minimal.
- The purchase of a "turnkey system" whereby all work on developing the system is carried out by an external GIS supplier, and the complete tested system is delivered for immediate use at a preselected date.

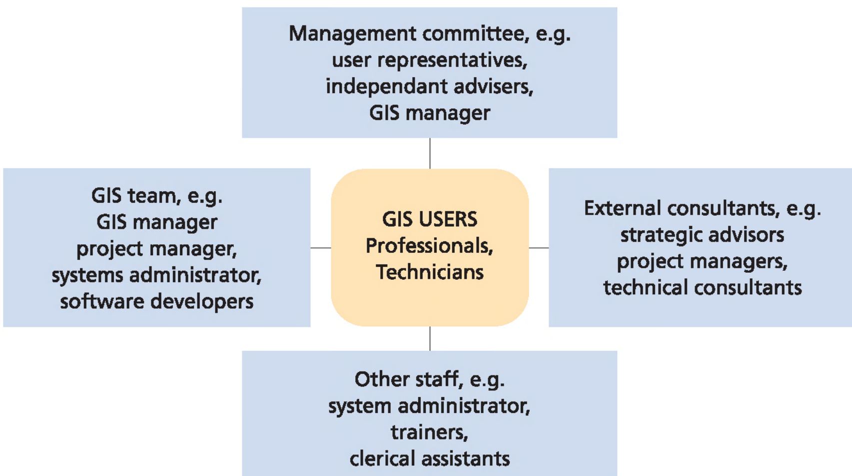
The last of these implementation models might require a tendering process for which there are probably official organizational policies and procedures. From the beginning, it will be important that the implementation has management approval and that it will be in the hands of a competent individual. Any implementation plan will need to be prepared for flexibility in the sense that many changes are likely to occur during the development and adoption period. During the possible long and difficult implementation process, personnel involved will need to be aware that there are likely to be effects on the organization, some of which may be profound, including institutional restructuring, job insecurity, rationalization and possible redundancies.

Once the GIS has been implemented (installed), there are a number of immediate concerns and procedures that must be in place to ensure that the system will work proficiently. Initially, it is useful to subject the system to a few small "pilot" projects designed to test a range of system functionality. These tests should include not only GIS output but also items of hardware, data access, formatting and structure, and that staff are aware of their roles. This work should be overseen by the GIS committee and at least some members of management. It is almost certain that this pilot work will reveal challenges that need addressing, and a good implementation plan will have allowed for this, probably under "contingency planning". Because it is likely that the first few months of GIS operation will produce many technical problems and/or adjustments, it is essential that reliable contacts are available for a range of possible emergencies or system failures.

It is impossible to conceive that any GIS work will be successful without enthusiastic support from either the GIS champion and at least someone at management level. Longley *et al.* (2005) identify the following management support areas that are critical to successful GIS outcomes: (i) customer support in terms of both "upstream" or "downstream" GIS work; (ii) operations support in terms of system administration, maintenance, security, technology acquisitions, etc.; (iii) data management support to ensure that access is available to the best data possible; (iv) applications development and support to ensure that future software needs are enabled; (v) project management to oversee all important decisions with

FIGURE 4

Varying staff roles of groups who might be involved in GIS implementation



Note: Figure 4 could apply to most types of GIS adoption approach, although only a large organization is likely to have all of these groups.

respect to GIS progress; and (vi) human resources support to maintain harmonious working relationships among people having a wide range of competencies and experience. Figure 4 illustrates the wide range of staff both within and external to the organization who might be involved in the adoption of GIS.

In a more direct or specific sense, there are a number of other supervisory tasks that are of major importance and that are most likely to be performed by the "GIS champion". These comprise:

- **Working patterns and task allocation.** Where a fisheries or aquaculture GIS is operating at a small-scale, with perhaps only one or two people, there are rarely work allocation decisions because it is likely any worker will be in a position to master most tasks or to come to an agreement on task allocation according to skills, time availability, etc. In larger GIS groupings, it may be essential to have a leader who is reasonably multifunctional, but who also manages workflow, liaises with customers, supervises data processing and writes-up reports. Other workers would typically take on specific roles. Maintaining a constant workflow is often a difficult task, one that takes on significant planning, especially because it must be combined with numerous unknown contingencies, e.g. hardware breakdown, staff sickness, emergency work or staff redeployment. It is common to build in a 25 percent time contingency when estimating project timing.
- **System safekeeping and security.** Data security is a vital ingredient in most computing environments, and the costs or consequences of a security breakdown can be large in terms of data losses, time wasted, leakages of information, and in monetary terms. Causes of problems include electrical failures, insufficient data back-up, deliberate illegal activities, unintentional data deletions and system operational faults. To safeguard the system, measures should be put into place, such as regular password changes, use of back-up power supplies, the regular back-up of data and files, and perhaps limited access to certain files.
- **System maintenance.** Like most other practical systems, GIS needs to be maintained in optimum working order, and system maintenance refers to sustaining the ability of the system to function as required. It is normal for any organization to build system maintenance routines into the GIS work schedule. The approach to maintenance may be reactive, whereby the GIS team knows exactly what to do or how to cope with any system emergency, or it may be proactive, where procedures are in place allowing for regular servicing or maintenance of equipment plus the provision of software upgrades. Data are also in constant need of maintenance in terms of their quality, timeliness, seeking additional sources and metadata upkeep, plus maintaining data storage capacity.
- **Coping with organizational change.** The introduction of GIS will almost inevitably bring about change within the organization, and Heywood, Cornelius and Carver (2006) report the following changes that may occur following GIS introduction: (i) changes in job descriptions as employees are

obliged to take on different roles; (ii) levels of responsibility will be affected, which may negatively influence some employees; (iii) the functioning of GIS often positively acts to break down barriers within an organization; (iv) GIS can foster increased contacts with the wider external IT community; (v) relationships between groups or departments within an organization may strengthen as GIS takes on an expanded role; and (vi) if GIS really "takes off", then sometimes the inevitable internal restructuring can have positive or negative repercussions. The technical paper sets out principles for introducing new technology into an organization.

With respect to the discussion on GIS implementation, the stage is now reached where GIS may have been adopted, is fully installed and is able to function as required. But the account cannot finish here because the GIS system must be expected to continue to function into the indefinite future. In order that this happens, attention now turns to the range of support and training that is available and necessary. Support and training is examined in terms of its needs, its main sources, the mediums for delivery and the range available. The concern here is mostly with GIS-related support and training, but it may also be important to keep up to date with major developments occurring in the fisheries or aquaculture fields. The technical paper gives numerous leads to the wide variety of support and training that are available.

Instruction and exercise manuals are the first major source of support. Most manuals are originally supplied as hard copy or as CD–ROMs, though they can often be downloaded from software houses or other sources. Manuals are aimed at providing both the instructions on the use of GIS and for resolving problems that users might experience while attempting specific functions. Under this heading, four main categories of manuals are identified:

- GIS hardware and software manuals that provide instructions on how the hardware or software can be used. Sometimes this information is available via a "Help" facility within the software, or online instructions are given from the providers showing where help is available.
- Some GIS software providers have developed a range of "illustrative manuals" that provide case studies on a range of ways in which their software can be used. Sometimes similar exemplar material is available from Internet sites that specialize in particular thematic areas.
- More specifically, some GIS software houses provide exercise or tutorial manuals allowing users to work through exercises on various areas of GIS functionality or analysis.
- A few GIS manuals and exercise manuals have appeared specifically covering marine-, fisheries- or aquaculture-related topics. Examples of "how to use GIS software" for fisheries or aquaculture work are given, i.e. rather than more general information "about" fisheries or aquaculture GIS.

A second major source of support is "hands-on" practical training. Degree-level courses are not discussed here because there are now a large number of full- and part-time courses available and they can readily be found by using Web-based searches. With the boom in GIS over the last two decades, the range of hands-on courses has greatly increased, such that all aspects of practical GIS are covered. However, most of these courses relate to the general use of GIS, i.e. rather than being fisheries or aquaculture specific, for which there is still insufficient general demand. When enrolling on training courses, participants need to be careful of the level at which they are pitched. Practical training is available either on a face-to-face basis or by "distance learning", which usually involves online tuition. Face-to-face provision is normally only available in major cities, so courses are often "residential" (i.e. the attendee on a training course may have to stay for a period of time in a city and thus incur accommodation costs). These courses have an advantage in that a high degree of individual attention may be obtained, though they may have the disadvantages of being both expensive and the fact that too much knowledge is imparted over a short time, making the retention of material difficult.

As well as instruction and training manuals, there is a range of other published material, which makes up the third source of support. This material may be available in either hard copy or digital formats, and it can be briefly described under three headings:

- **General GIS books.** Unlike the situation two decades ago when only about a dozen GIS books were available, today such books are numbered in the thousands, and the subject matter of these books has moved from general GIS towards being topic specific in terms of application or methodological areas. A range of introductory texts is recommended in the technical paper and all GIS users should be generally familiar with this level of content.
- **Fisheries or aquaculture GIS publications.** These are far more specialized publications, but they are very relevant to workers in these areas. The technical paper lists all 20 of such publications published during the last decade.
- **Journals and trade magazines.** These periodicals originate from a variety of sources, though most are produced by academic publishers or software houses. Unfortunately, many are rather technical, as they are often aimed at promoting new progress in GIS development. There are no specific "fisheries and/or aquaculture GIS" journals or magazines, though a list is given of major magazines in which GIS information pertaining to aquaculture may be published.

A fourth route to support and training can be attained through attending conferences, workshops or exhibitions. This is a more verbal or visual method of support, one that includes a great deal of flexibility and thus attractive for many GIS participants. Unfortunately, events specific to fisheries and/or aquaculture GIS are rare, but there are many general GIS events that can prove useful, though most of these only take place in developed countries. Conferences, workshops and exhibitions all allow opportunities for networking and thus the exchange of knowledge and ideas. The technical paper provides information on Web sites that describe a range of GIS conferences, and details are provided on a major series of fisheries and aquaculture symposia organized by the Fishery-Aquatic GIS Research Group, based in Saitama, Japan.

The final source of support and training concerns the various persons or groups who specifically aim to offer advice either freely or on a paid basis. This miscellaneous group comprises: (i) consultancy services, where expert advice can be purchased on a range of GIS-based issues, though these would rarely be directly related to fisheries and/or aquaculture; (ii) user support groups who operate freely over the Internet and who specialize either in discussions in groups or forums on particular subject areas or who specialize in particular GIS software; (iii) software houses that might offer a range of support, including time-limited advice that accompanies many software licences, sponsored user groups, and various training materials that they publish; (iv) professional organizations that operate in many countries and that aim to promote GIS via conferences, publications and reports, consultancy and advice to governments. Joining such a professional body can be advantageous from career, influence and participation viewpoints.

5. Preparing data for GIS use

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Once data for GIS use have been collected via any of the methods described in Chapter 3, the data will need to undergo a number of preparatory stages before they can be effectively used. Exactly what needs doing depends upon the format in which data have been collected. Some data may be in a usable form as digital data that only needs delivering via the Internet or CD–ROM; some data may be stored on a data collection device; and other data may be in hard copy form as paper maps, tables or lists. Some GIS workers contend that getting data suitably edited and formatted may be the most important task of any GIS project. The qualitative assembling and pre-processing of data is the primary theme of this chapter, though the chapter also describes how data are best modelled and structured for GIS use, data storage, database functioning and metadata. Having data stored in the correct format for any GIS software is fundamental to all operations. Thus, there will be strict rules on matters such as how a georeference should be stated, the range of values that are permissible, the number of decimal places to be recorded and the coding that can be recognized. Some GIS handle several data formats and there are now applications that switch data between formats.

The primary preparatory data need is that of getting data into the system in a digital format. The first method for doing this, via the use of a scanner and digitizer, has been described in Chapter 2. Here, it is simply necessary to note that good data presentation from the scanning process is best achieved through the use of high-quality maps and through careful geo-registering of maps, plus accurate recording of associated information on colour, attribute, line thickness, etc. Successful digitizing, either via a table or via the "on-screen" method, is only achieved with careful attention to detail and accuracy in the line following process, i.e. to avoid duplicated lines or lines that do not properly complete polygons. The results from the digitizing process should be stored in individual thematic files, such as for coastlines, railways, rivers and streams and bathymetry. As well as scanning and digitizing, hard copy tabular data can be input manually through the creation of files (typically in database or spreadsheet formats) using computer keyboard entry. To be of use in any GIS, manually entered data must have suitable georeferences or coded references to place names, zip codes, land use, etc. The final method of data entry is through the direct transfer of digital data via CD–ROMs, DVDs, memory sticks, data loggers or the Internet. Because much of these data will not have been collected with any specific GIS project in mind, care must be taken with respect to their date and resolution and to the classification categories or data formats used, among other things. There might also be a problem with respect to the size of data files, especially if using sonar or remote sensing data, so adequate data storage capacity must be available.

Once the required digital data have been assembled, it will be essential to validate the data for correctness and for being up to date. Any mistakes or changes that are necessary can then be made through various editing processes after which the data can be suitably organized and stored. Maintaining up-to-date edited data can be a costly and time-consuming task, this being a function of numerous sources of error such as inexact digitizing, unsuitable formatting, incorrect data recording and uncertainties in data classification. Most GIS have their own editing function tools. There are two main types of editing:

- **Graphical editing.** This refers to making corrections to any points, lines or polygons (graphical entities) on a digital map. The need for graphical editing mainly arises from incorrect digitizing, and typical errors are described in the technical paper. Most GIS software contains tools that help identify errors and then edit any digitizing errors.
- **Non-graphical editing.** Here, the concern is with correcting the attribute data that corresponds to mapped features, e.g. place names or feature types. Sources of errors mainly include incorrect feature classifications or poor keyboard entry. Non-graphical errors are more difficult to detect and it may be impossible to check every feature. However, Heywood, Cornelius and Carver (2006) show that data can often be verified by seeking out impossible or extreme values, by looking for inconsistencies, and by using scattergrams or trend surface analyses to identify data anomalies.

Editing will be a continual GIS prerequisite because new data sets are always being added and existing data sets will undergo many revisions. The need for data validation and editing will be especially important to fisheries GIS work because the nature of many spatial distributions in aquatic environments is both temporary and volatile.

For maximum efficiency, all data collected must be appropriately stored, organized, managed and shared, and this is accomplished via the use of files, databases and database management systems (DBMS). Files are the basic form of data storage used in any computing environment. A file is usually a single collection of records about a certain theme, and it may cover a certain time period and a specific location or area. Files themselves may take several forms, such as text, tables, imagery or shapefiles, and the data might have been entered onto a spreadsheet or into a database or stored within a file format that is specific to a particular GIS. Within any file, all data must be consistently stored using the same format throughout. A collection of files is usually referred to as a database, and this may cover a wider set of themes or areas than individual files. For use in a GIS, it is essential that all the data (held in files within the database) can be linked to some form of georeference, i.e. either geo-coordinates or names given to particular areas. This latter georeference is called a "unique identifier". A single database may be very large and may cover numerous related themes, plus all the attributes related to each theme, e.g. perhaps a lake fisheries database would have files on physical characteristics of the lake, species in the lake, management policies for the lake, land use around the lake edge, etc., with each file storing information on the different attributes pertaining to each theme. Databases are important to GIS software because they provide structure to the stored data allowing the data to be manipulated in a multitude of ways. Within a GIS or IT department, a series of databases may be held on one computer, although larger departments may have specialist server computers that supply data to all users having access rights.

In order to attain wide functionality, collections of databases within a workplace are managed by the DBMS. In a sense, it is the DBMS that lies at the core of GIS capability. DBMS software provide the ability to load, access, modify and maintain data, plus a range of security, back-up and administrative tasks; most GIS software now contain their own internal DBMS. But unlike most DBMS, GIS must be capable of handling spatial demands of the data, allowing the GIS to be manipulated, to be queried or searched, and generally to maximize the efficiency in which the data can be utilized for carrying out the whole range of GIS tasks. Although the DBMS can be structured in a variety of ways, the so-called relational DBMS model has become the favoured model for GIS use. The technical paper provides details on the working requisites of this DBMS model and provides a worked example of how files can be joined and manipulated using relational DBMS techniques.

For users of large quantities of data, it becomes increasingly important to keep a record about all of their data sets. This record is known as the metadata, a collection of which may form a metadatabase. Metadata include a range of essential facts about the data sets, including information on data quality, data ownership, themes or variables included, coordinate systems used, data exchange formats, codings used for attributes, and organizations producing the data. Having information on these factors ensures that data can be used with confidence, and it will provide clues as to when data may need updating. Many database managers will not add data sets to their databases if the sets do not come with their own metadata.

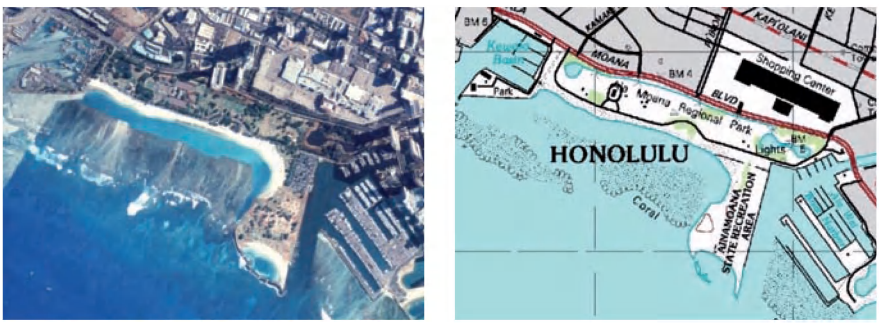
With data now being stored and ready for use, attention turns to how best to show the real world in a mapping format, i.e. it is important that all features of the real world that need to be mapped for any given GIS project be displayed in a meaningful way. To achieve this, it will be necessary to identify classes of features, e.g. buildings, roads, land uses and sediment types, and for each class and subcategory it will be necessary to make a decision on how features might best be displayed in a mapped form. This cartographic classification will require much generalization, that is, the simplification of the real world by omitting unimportant features, by simplifying real-world shapes, and by the features classification process itself (see Chapter 7). The aim of this real-world modelling process is to achieve a set of symbols that best and most accurately create a visually pleasing, intuitive or understandable mapped representation for the area of interest, plus the means of portraying the non-graphical entities on the maps (place names or features types). Figure 5 illustrates how real-world features (as detected from a remotely sensed image) might be represented as mapped data. It will be clear that the way in which features are displayed on a map will be scale dependent, i.e. at a small-scale (large area) towns might simply be shown as a dot, whereas at a large scale (small area) a town will consist of roads, buildings, green spaces, etc. A close inspection of the graphical symbols that depict features in any mapped area show that they can all be classed as being either points, lines or polygons, and, through the use of some kind of georeferencing, these are convenient formats in which information about map features can be stored in a database, such that any feature can then be digitally mapped. GIS software has the capacity to use the graphical data to produce maps that are either structured in the vector data format or in the raster data format.

The vector data format relies on having the exact geo-coordinates for every point, line or polygon needing to be mapped. To map any point, single x and y coordinates are necessary so that the GIS can accurately position the point in relation to a mapped project area. Straight lines can be drawn by knowing the start and end coordinates for the line, after which the GIS simply joins these two points. Curved lines are either drawn by knowing the coordinates of numerous coordinates around the curve and then joining them up, or they can be drawn by using an algorithm embedded in the software that relies on the use of selected coordinates around a curve to plot the likely position of the curve. Polygons are just lines that start and end at the same geo-coordinate, i.e. to completely enclose a mapped area. The technical paper describes in more detail various specialized vector file formats. The vector format is particularly suited to drawing accurate linear versions of maps and it also allows the GIS to perform specific calculations efficiently based upon linear lengths or areas.

The raster data format relies on the mapped area being comprised of equal size cells (or pixels). These cells are usually square shaped, but theoretically they could be rectangles, equilateral triangles or hexagons. Individual cells in a raster format may be identified by sequential alpha and/or numeric figures for the

FIGURE 5
Real world spatial features represented as geospatial (mapped) data

Realworld space **Spatial representation**



Source: Feinholz and Walker (2007).

columns (x axis) and for the rows (y axis). Raster mapping information is built up in layers, each representing a different theme such as land use, sediment type and water temperature. Each raster cell is allocated a single code (or value) based on the predominant feature or class occupying that cell. The coding given to each cell might be in terms of a numerical value, a weighting, a coding allocated to a colour, a reflectance value, etc. The dimension of cells is important to working in a raster format because larger cells occupy larger portions of the real-world surface, and they therefore produce a cruder or more generalized map; conversely, smaller cell sizes produce more accurate maps, but they require more data storage space. The use of very small pixels allows maps to be produced that look the same as vector drawn maps. Because of the large amount of data storage associated with the raster format, there are various methods for data compression that are described in the technical paper. In the past, it was important to select to work in either vector or raster format, but today most GIS can convert between working in either of the formats.

Two other data models are important to GIS use, and they are concerned with the structuring of data for: (i) 2.5D terrain modelling; and (ii) network models. Terrain modelling in 2.5D incorporates the x, y and z axes, but with the z axis only referring to the ground height above mean sea level (or an agreed datum line) or the water depth below a datum line. Terrain modelling itself is conventionally subclassified into one of two data formats according to whether they are using vector or raster formats, i.e. either triangulated irregular networks (TINs) that use the vector format or digital elevation models (DEMs) that use the raster format. It can be envisaged that the ability to incorporate the z axis into fisheries GIS work considerably broadens the potential for spatial analyses, i.e. because fisheries and mariculture function almost entirely in a 3D environment. The functioning of GIS-based terrain modelling is discussed in Chapter 7.

A network is an interconnected set of points, lines and polygons that represent possible routes or "pathways" from one location to another, and networks may represent natural features such as waterways, migration routes and vegetation corridors or, more frequently, human engineered structures such as roads, railways, air routes, fencing, pipelines, cables and boundaries. Given the wide array of networks, their modelling is an important function for GIS; for example, it is likely that most aquaculture facilities will need to include network analyses as a fundamental input to their location decision. Network modelling is usually performed using the vector data format. For modelling purposes, networks can be conveniently conceived in terms of links and nodes, with the former being the routeways themselves and the latter being junctions or start and end locations. Values can be assigned to links in terms of distances, travel times, fuel used, financial costs, etc., and to nodes in terms of population, number of businesses, tourist attractions, etc. The functional GIS-based analyses performed using network modelling is described in Chapter 7.

6. Remote sensing and GIS integration

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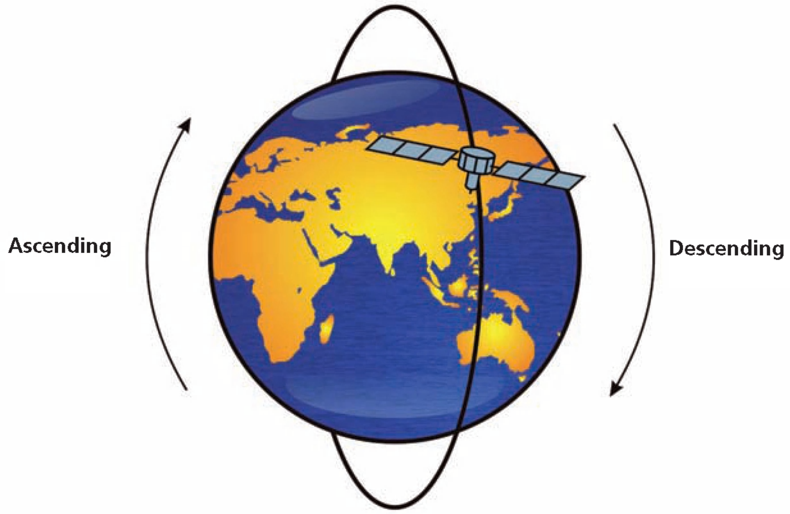
Aquaculture, and especially fisheries, is practised over a large proportion of the Earth's surface and, therefore, data gathering can represent a significant challenge to GIS work. However, satellite remote sensing is increasingly able to provide for these data demands, especially because it provides a unique capability for regular, repeated observations of the entire globe or specific regions at different spatial scales. This chapter introduces the basics of remote sensing and provides practical guidance for planning and implementing the use of this technology, including data sourcing, selection and acquisition, image processing, and the integration of imagery with GIS. The chapter concludes with four case studies showing applications of remote sensing under a range of pertinent scenarios.

Remote sensing functions on the principle that specialized satellite-based sensors can detect electromagnetic radiation (EMR) that is variably emitted or reflected from features on the earth's surface. Recorded EMR values can then be converted into a signal that can be transmitted to ground receiving stations and ultimately displayed as either numerical data or as an image on a computer. EMR energy takes the form of waves, which themselves are classified by their wavelength or frequency such as X-rays, visible light, infrared or microwaves. The source of energy for EMR can be either from the sun or from a radar system that transmits its own electromagnetic energy pulses. Different objects or features on the surface absorb, emit and reflect EMR having different wavelengths in a predictable and repeatable way, i.e. they are said to have recognizable spectral signatures. This allows for the classification of objects or features that are recorded by the sensor, though in many cases it may be necessary to verify (or ground truth) specific features to be certain of the correct identification of the data, e.g. the spectral signature of vegetation or water may vary with the altitude of the sun or with the stage in a plant's growth. There are many types of remote sensing sensors and the technical paper gives details of those relating to fisheries or aquaculture work.

The majority of remotely sensed data are obtained from sensors mounted on satellites. There are two main types of satellite systems:

(i) **Polar orbiting satellites.** These satellites typically orbit the earth at 12 to 16 times per day at heights varying from about 250 to 1 600 km. Their orbits cross each pole and, because the earth is spinning on its axis, each revolution of the satellite passes over a different strip of the Earth's surface (Figure 6). The width of this strip from which data are collected is called the "swath"and this may vary greatly, e.g. typically from 10 to 1 000 km. Individual orbiting

FIGURE 6
Polar satellite orbits



satellites may be operational for several decades and thus vast data sets will accumulate, which are useful for examining spatial changes over seasons or from year to year.

(ii) **Geostationary satellites.** These satellites operate from an orbit of 35 900 km, at which height they are sited permanently over the equator and over the same Earth location. These satellites therefore have a high observational frequency. However, their height means that the data resolution is low, and they are thus used mainly for telecommunications or meteorological purposes.

As well as satellite systems, there are airborne sensors that are mounted in a range of manned or unmanned aircraft (or in balloons). These are not able to provide long-time series of data, but they are able to capture much more specific and detailed imagery.

The data gathered through remote sensing can be characterized in a number of important ways:

- Information content. The varied EMR emissions detected, and their subsequent processing, allow data to be gathered on an increasingly wide range of parameters.
- Spatial extent. This refers to the size of area covered by any imagery.
- Spatial resolution. This is the size of the individual picture elements (pixels) that make up an image, and it typically varies from extremely low resolution (»20 km^2) to high resolution (»1 m^2).
- Revisit frequency. This defines the frequency that observations can be made of the same area.
- Time series. The time period for which consistent observations are available.

- Timeliness. The speed that a product is made available to a user.
- Levels of processing. This describes the amount of processing that the data supplier has conducted before the product is made available to the user.

Different types of remote sensing data are suitable for specific fisheries and aquaculture applications, and for most applications the main types of data are categorized into optical or radar-based imagery. The technical paper provides background on the technical differences between these categories, and detail is provided on the main satellite systems that are being used for data gathering in each imagery category. Here, it suffices to provide examples of the parameters about which information can be gathered using one or other remote sensing method. Optical imagery can provide valuable information on land cover and land use information for inland fisheries applications, ocean condition data such as chlorophyll-*a* and suspended sediment concentrations, bathymetry, sea surface temperature, and data to support coastal zone fisheries and aquaculture management. Through the use of light detection and ranging (LIDAR) detailed topographic information can be derived. Radar-based imagery provides information on sea surface height, surface currents, waves and winds, the flooded status of vegetation or the surface roughness of a waterbody, i.e. these are all parameters where surface height characteristics are variable. The recent Soil Moisture and Ocean Salinity (SMOS) satellite is additionally able to gather radar-based data on marine salinity values.

What are the general areas associated with fisheries or aquaculture that remote sensing information is supporting and where is this work being pursued? These applications areas are described as follows:

(i) **In support of aquaculture development.** Most remote sensing applications in this area are being conducted by the United States of America, though much work is also carried out in a number of rapidly developing Asian countries, but with few examples from European countries. The main issues addressed by remote sensing are strategic planning for development, the suitability of sites, and for zoning purposes. For example, GIS and remote sensing are essential tools to help define locations and quantify expanses of areas suitable for offshore mariculture development. A number of specific examples are provided to show how remotely sensed data can benefit aquaculture development.

(ii) **To support aquaculture practice and management.** Remote sensing applications under this heading are aimed at: (a) the inventory and monitoring of aquaculture and the environment; and (b) examining the environmental impacts of aquaculture. The first of these applications areas is important as a means of evaluating where and to what extent a range of aquaculture developments is taking place, with this work often being in response to the needs for spatial planning. The second applications area is extremely important because it is essential that any environmental impacts from aquaculture are absolutely minimized, and, conversely, it could be disastrous if factors in the environment impact upon aquaculture practices. Examples of relevant remote sensing applications are given.

(iii) For various aspects of marine fisheries monitoring and management. As in aquaculture development, there are an overwhelming number of publications illustrating applications of remote sensing to marine fisheries monitoring or management undertaken by the United States of America or by developing Asian countries; there are relatively few European examples. However, compared with its use in aquaculture and marine fisheries, remote sensing has been relatively little used for inland fisheries. Remote sensing data has been particularly useful in locating optimum fishing locations by sensing those areas where fish aggregations occur, usually in relation to marine productivity or along temperature fronts between warm and cooler waters. Vessel monitoring systems using global positioning systems data also rely on remote sensing techniques. Data from remote sensing are particularly useful in a wide range of fisheries research and modelling, where information on factors such as water temperatures, chlorophyll-*a*, ocean currents and bathymetry may be important inputs to the work.

Of critical importance to the use of remotely sensed techniques are considerations relating to the implementation of remote sensing methods, i.e. so that the data secured can be reliably used within a GIS. Whether or not to implement remote sensing capability is normally dependent on the results of a scoping study. This study helps define the viability of the proposed activity and it addresses important questions, such as:

- What are the overall goals and objectives of the programme?
- What is the physical area of interest?
- What spatial scale and/or spatial resolution is desired?
- What is the frequency of data required, how quickly does the data need to be delivered, and for what time period?
- Can existing data address the information needs?
- Can information provided by remote sensing meet project needs?
- Do remote sensing data need to be integrated with other data and models?
- What is the available budget to buy imagery and complete image processing for the duration of the programme?
- What expertise and tools are available to process and integrate the remote sensing data?

The ability to carry out a scoping study will require a certain level of expertise in remote sensing methods, though the study may be carried out by an external consultant. An essential element of the scoping study concerns remotely sensed data and/or imagery requirements and acquisition. The technical paper provides, by data themes and different satellite systems, detailed information on the range of data available and all the principal sources (suppliers) for this data. There is also a section on data costs, noting that costs per image may be highly variable (usually according to image resolution), that overall remotely sensed imagery is decreasing in cost, and indeed that there is much useful imagery that can be freely obtained from the Internet.

Because imagery can be purchased having varied levels of pre-processing, it means that it is quite likely to need some processing or editing before the data can be directly used in a GIS. This can usually be done by specialized software, most of which is highly compatible with GIS or is, indeed, fully integrated into proprietary GIS. Image processing includes a hierarchy of processes:

(i) geometric or radiometric correction;
(ii) training and validation data;
(iii) image analysis, processing or classification;
(iv) accuracy assessment; and
(v) change detection.

Each of these processes is explained, though the user is likely to need additional information from the data providers, image processing guides, local experts, or from numerous sources on the Internet.

Wider technical support and training in the use of remote sensing is provided under a number of suitable headings:

(i) **Web resources and organizations.** A wide variety of these resources provide valuable information about remote sensing applications in fisheries and aquaculture and also links to useful imagery.
(ii) **Book resources.** Although these tend to be more general introductory books, i.e. because few texts concentrate specifically on remote sensing applications to fisheries or to aquaculture, many of them have sections devoted to ocean or marine applications of remote sensing.
(iii) **Technical training materials.** These are remote sensing tutorial and/or exercise manuals, with some of them including marine themes, and all of them accessible via the Internet.
(iv) **Software and tools.** Two categories of software are listed: (a) remote sensing software that is freely available, much of which may be specific to certain tasks; and (ii) the main proprietary remote sensing software; this varies greatly in its degree of sophistication and, therefore, usually in its price.

The chapter concludes with four case studies. The first study is concerned with the inventory and monitoring of aquaculture and the environment in the Republic of the Philippines (Travaglia *et al.*, 2004). This study was carried out by four experts (with some additional field verification assistance) over a six-month period. The objective was to test, under operational conditions, a radar-based remote sensing methodology for the inventory and monitoring of shrimp farms. The use of radar allowed for the discrimination of ponds and dykes from the surrounding water surfaces and rice paddies, and the fish ponds and dykes detected were quantitatively assessed for the Lingayen Gulf area of the Republic of the Philippines. Data were obtained from two ERS-2 SAR images having a spatial resolution of 25 m, plus a RADARSAR-1 Fine Mode SAR image having a 9 m resolution. The case study details the methodology used including the necessary image processing. The results allowed the area having fish ponds to be very accurately calculated, and, when compared with the area established for 1977 (by manual means), the image showed that a 60 percent increase in fish pond area had occurred. The detection of sea cages was more difficult because of rough water conditions when the imagery was obtained and, because of their small size, there was some uncertainty in identifying fish traps and pens. However, advances in imaging radar since this study was made mean that remote sensing methods are now highly reliable for the inventory of most aquaculture facilities.

The second case study concentrated on the use of remote sensing to monitor and model harmful marine algal blooms in the southern part of the Republic of Chile. This collaborative study was carried out over one year by several small groups of private sector consultants, and it was designed to show how the use of remote sensing methods might assist the salmon farming industry in an area where algal blooms are a frequent problem. This could essentially be achieved by developing a prototype "harmful algal bloom" early warning system. The main imagery used was sea surface and chlorophyll-*a* data obtained from MERIS and MODIS remote sensing systems, with these data being combined with other local oceanographic, meteorological and coastline data. Because daily imagery could be obtained, models could be developed to show the existence and daily distributional patterns of potentially harmful blooms. The case study explains how the GIS-based work progressed, and the authors describe the range of outputs achieved including an estimation of their accuracy. The models developed could also significantly contribute to further aquaculture site selection choices, and they are likely to result in considerable financial savings for the aquaculture industry through an ability to take mitigation measures when required.

The third case study illustrates the use of remote sensing imagery to map seagrass beds in the Zakynthos Marine National Park in the Hellenic Republic, which is based on the work of Pasqualini *et al.* (2005). The importance of the seagrass *Posidonia oceanica* in the Mediterranean cannot be overstated, i.e. because of its role in many coastal processes, contributing to sediment deposition and stabilization, to attenuating currents and wave energy and in supplying a highly productive biological ecosystem. For conservation purposes, it is essential to map the distribution of this seagrass. There are challenges to using aerial or satellite remote sensing imagery for this mapping, mainly because of the fragmented nature of the beds and to the depths at which they might be growing. Various methods have been tried and in this study the authors' objectives were to use SPOT-5 multispectral imagery at three different resolutions to see which produced the most accurate results. The methods used are described in some detail, including the extensive ground truthing (physical verification of seagrass beds) necessary in a study area of some 70 km^2. The results show that even using the coarsest resolution (10 m) quite accurate maps can be drawn (73 percent accuracy), though when the finest resolution was deployed (2.5 m) there was more detailed discrimination of the patchiness of the seagrass beds, with the maps being 96 percent accurate. Since the study was concluded, the WorldView-2 sensing system has been launched, which provides a sub two-metre resolution for this type of work.

The final case study looks at the use of remote sensing and satellite communication systems to establish where fish and squid feeding aggregations occur in Pacific waters off the Japanese coast, and therefore to supply predictions of potential fishing zones in near-real-time to fishing vessels via Internet and satellite connections. The study was a long- term project carried out by university-based researchers, private companies and a regional development agency (Saitoh *et al.*, 2009), with the longer-term aim of managing the fisheries sustainably. A complete system (TOREDAS) has now been developed, comprising four components: (i) data acquisition system; (ii) database; (iii) analysis module; and (iv) Internet and on-board GIS. The case study provides details on the exact development methods used, including the remote sensing data required and their satellite sources. All image processing and subsequent GIS work was accomplished by the development team, and there was strong cooperation from various fishing fleets in terms of supplying marine and catch data and for vessel monitoring system link-ups allowing for the collection of real-time information on likely optimal fishing locations. Illustrative examples of the GIS output are provided that clearly demonstrate the correspondence between fishing vessel locations and chlorophyll-*a* and sea surface temperatures. Although the TOREDAS system could potentially allow for larger marine catches, it is considered that the educational aspects of the system will allow for the appreciation of the needs for sustainable fishing, and other benefits to fishers will accrue in terms of reduced fuel requirements and in time saving when searching for fishing grounds.

The chapter concludes with a brief analysis of the significant advances that are currently under way in the field of remote sensing, especially with regard to the variety of parameters for which data can be gathered, the increasingly higher resolution of the data that can be obtained, significant cost reductions in data, and the timeliness of data. These advances, combined with the increasing ease in integrating remote sensing data into GIS projects and the actual proliferation of data per se, mean that the prospects for the continuing use of remotely sensed data become ever more encouraging.

7. GIS functionality

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This chapter discusses the functional tools and techniques offered by typical GIS software packages. The concern, therefore, is to outline all the major capabilities of GIS briefly in order to distinguish what types of spatial and nonspatial functions can be performed. The range of these functions varies enormously between one GIS and another, and many of the functions could be performed on non-GIS software. There is typically a relationship between GIS cost and the number of functions performed, and there may be numerous smaller software applications that can be acquired to perform specific applications. The terminology for functions will vary between GIS, and different functions may better be performed using either the raster or vector formats. No attempt is made in the technical paper to describe how to perform individual GIS-based functions (as this will vary between GIS software); the intention here is to describe typical functions that a GIS will carry out.

Initially, any digital data to be used for GIS purposes are likely to require some transformation or preprocessing. These are tasks or manipulations that aim to change the data as required to suit the area, scale, theme, etc., of the specific GIS task being undertaken. At the most basic level, these preprocessing functions, such as delete, crop, recode, dissolve, zoom, merge and rotate, are all functions that are important to mapping but that can be performed by many software packages. At a more sophisticated level, and with more direct relevance to GIS work, there is a further range of transformations, most of which are applied directly to digital mapping data. These include: (i) edge matching – allowing neighbouring mapped sheets to exactly match up; (ii) projection changes – so that all mapping conforms to a unified projection; (iii) coordinate transformations – allowing similar georeferencing systems to be used; (iv) rubber sheeting – allows map distortions to be eliminated; (v) geometric corrections – eliminates spatial distortions, usually in remotely sensed imagery; and (vi) structure conversions – allows GIS to toggle between working in raster or vector formats.

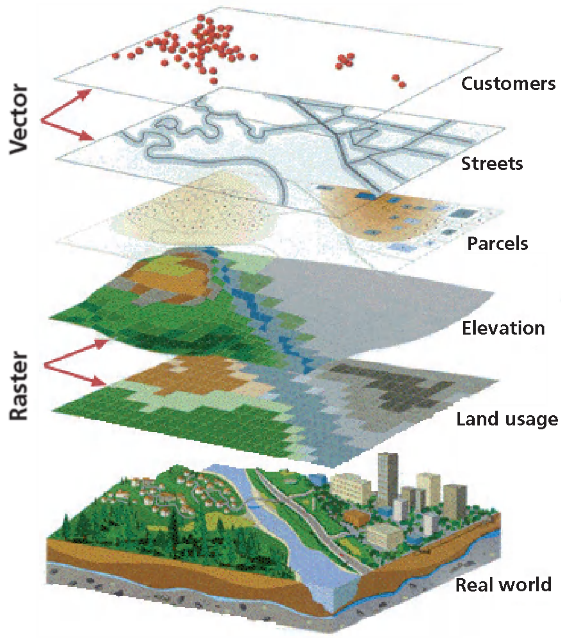
Through these preprocessing functions, the digital data held should be“fit for purpose”. However, there are still data transformation functions that may need performing, and two of these (map generalization and thematic classification) are required because of the huge scale variations that mapping may engender. It is easy to conceive that the scale of a map will greatly affect the amount of detail that can be shown, meaning that a GIS should be able to generalize real-world features so as to suit the scale requirements of individual projects. Generalization can be achieved through functions, such as the elimination of smaller features, the merging of groups of similar features, or the reduction in line complexity. Generalization should be performed on both the graphical features of a map and the named features, and generalization can only be effectively deployed when moving from large scale towards a smaller scale. Thematic classification is important to mapping and to GIS simply because the real world is too complex to show everything on a map. This means that, as with generalization, the map content must be simplified by being sorted into classes, for example, houses, factories, shops, etc., may all be classified as buildings or, when mapping fish species, they might simply be classed as pelagic fish or demersal fish. Classification is perhaps more frequently used in quantitative mapping. For instance, it is often desirable to show fish quantity variations in an area, and this will involve considerations of both the numerical range of the data and how many classes to divide this into. All GIS contain functions that scrutinize the data range and then make decisions on sensible numerical class boundaries. There will always be user options to override these decisions if preferred.

At a more complex level, there are two other basic data transformation functions that are important to most GIS work. The first of these is called "buffering". A buffer is a polygon created at some user-specified distance around a point, line or polygon feature. For instance, a buffer might be drawn around an aquaculture facility that has a notifiable disease so as to demarcate no-entry areas. Buffers can be of any user-defined width and there can be any number of buffers around an identified map feature. Buffers can be very useful in quantifying the extent of any subject of interest, e.g. the GIS can be asked the query "Show me (and quantify) the number of fishing boats registered at 10, 20, 30, 40 kilometres distance from cities x, y and z." The GIS will draw these distance buffers around the three cities, and then using a database of vessel registrations, it will calculate the answers to the query. The second basic transformation function is called "overlaying". Overlaying is the integration of two or more maps to form a new and enhanced map (Figure 7). For instance, a typical government topographic map can be derived from stored digital files containing separate mapped features, such as rivers, woodland, rail lines, roads and towns, and each of these files can be overlayed in desired combinations to create more detailed or preferred maps. To properly overlay maps, they must be in the same mapping projection and at the same scale, and overlaying can be performed using either the vector or raster data formats (though the two formats cannot be mixed for analytical purposes).

When overlaying vector-based maps, file sizes will be considerably increased and maps are likely to need careful editing. For instance, if a county boundary is following the course of a river and maps of these features are being overlayed, the two lines may not exactly match because the two files were created separately, perhaps from different data sources. The main purposes of overlaying are:

- to calculate any relationships that might exist between different mapped layers;
- to create any new or desirable combination of mapped features;
- to allocate weightings to features of variable importance to any mapping project; and
- to carry out map algebra or more complex geostatistical analyses.

FIGURE 7
Selected mapped layers for a specified area using points, lines, polygons, vectors and rasters



Source: Heard (2010).

The technical paper provides further details on each of these purposes for using overlaying functions. When used in combination, buffering and overlaying have the potential to provide a sophisticated range of GIS analyses.

This chapter now turns to the range of measurements that GIS can perform, including simple enumerations or counts, linear distances, areas, perimeters, volumes, directions and angles, plus a range of more sophisticated but less frequently used measurements. A caution is given as to the validity of GIS-based measurements made, this usually being a function of the fact that mapped data are a great simplification (or a generalization) of real-world situations. Measurements are performed very differently in raster formats than in vector formats. In the raster format, if the real-world size covered by one pixel is known, then measurements along the horizontal or vertical axes will be simple to calculate, including area calculations. However, most measurements using raster formats are complicated by the fact that measurements may need to be made along irregular lines in irregular directions, plus the fact that the real-world shape cannot correctly be projected onto a flat mapped surface. However, in general, the use of rasters can produce fairly accurate area and volumetric measurements using very basic algorithms. Measurements based on the vector format have the potential to be far more accurate because the vertices, segments and edges are precisely defined. However, this accuracy comes at the price of far greater computational demands. The technical paper provides further information on the Euclidian and Pythagorean geometry and the computing demands involved in vector-based measurement.

If GIS is to provide objective information on spatial relationships, then it requires examples of more sophisticated measurement techniques. Here, the three main techniques of measuring centrality, proximity and contiguity are briefly discussed. The concept of centrality is extremely important in many real-world situations, especially as it relates to optimizing economic locations. For instance, in the fisheries context, it is important that a fish processing plant can service as many customers as possible while minimizing accessibility costs. Most GIS software have the functionality to establish the mean centroid point of any polygon, and this centroid can also be a useful point from which to measure interpolygon distances. Looking at centrality from a different perspective, it may be of interest to know the theoretical area that might be served from each of many central points. An example might be that many aquaculture sites in a region are selling fish in their neighbouring area. Where ought the boundary lie between neighbouring producers? The GIS will produce so-called Thiessen polygons that cover the whole aquaculture region into idealized "fish market areas", with a fish farm being at the centre of each polygon.

Proximity analysis is concerned with the distances between different features, and this might be thought of in terms of: (i) numerical counts, or in terms of (ii) the spatial pattern revealed by the distribution of any features in an area. With respect to numerical counts, GIS will use a proximity analysis function to calculate the number of objects *a* that are within *b* kilometres of a specified line or point location, e.g. how many fish farms are located within 20 km of a fish processing plant? This form of proximity analysis mainly relies on the buffering function.

When analysing the spatial pattern revealed by a distribution, the researcher is seeking to identify the form of the distribution. It is easy to imagine that fishing boats at sea may be distributed in a point pattern that could be described as:

- random – where there is no discernible pattern in the distribution;
- uniform – where boats are very evenly spaced out across the marine area; or
- clustered – where vessels tend to be in one or more fairly tight clusters.

If one or other of these distribution patterns emerge, then it might be of value to investigate the cause. GIS uses what is called the "nearest neighbour" analysis to identify distribution patterns and this can produce an objective value describing each of the three distributional patterns. The final spatial relationship measurement technique described is that of contiguity analysis. This is similar to an analysis of point distributions, but here the concern is with measuring the dispersion of polygons in terms of their contiguity or spatial autocorrelation. What is therefore being identified here is "to what extent do similar classifications occupy adjacent cells?"In the case of a chessboard, it can easily be perceived that there is no relationship between neighbouring cells because cells alternate between black and white. However, in the real world, there may be a large amount of spatial autocorrelation because for all sorts of reasons similar features frequently occupy similar locations. Identifying marine or riverine areas having high adjacent spatial autocorrelation may be important in terms of the ease in which species may move from one area to another.

Progressing to more advanced GIS functions, the creation of statistical surfaces is next described. A statistical surface can be thought of as a surface area of land or the seabed that has numerical values attached to it indicating a value or coding on the vertical (z) axis. Values can relate to human or physical factors. A simple example would be that all places in a region or country have a current (or a mean) air temperature reading. These temperature readings could form the basis for constructing an isotherm map. Such a map can be constructed by GIS, it being based on temperature readings at sufficient representative sampled points. A temperature map is said to be spatially continuous because temperatures vary gradually over the surface, but other surfaces are spatially discrete because single values or codes may apply to wide areas before suddenly changing, e.g. geology or sea-bottom sediment types. Creating continuous surfaces by GIS relies on the software's ability to perform interpolation. This means that the GIS is required to estimate missing values for any data set based on the distribution of the known sampled data values. GIS will have various interpolation algorithms for achieving this based on the nature of the sampled distribution, the physical characteristics of an area, etc., and the technical paper discusses some of the interpolation methods available. If point sampled data show erratic distributions, then GIS might be used to create a general trend surface. For instance, fish counts of a specific species are likely to vary significantly from one sampling point to another. However, over a wide area it is likely that the sampling counts will gradually reduce (or increase) in a particular direction; therefore, the GIS can create a trend surface map to show the generalized distribution of the fish species across the study area.

The study of GIS functionality now turns from surfaces to linear distributions (or networks). It should be cautioned that not all GIS have the ability to undertake network analyses. Recall that networks are comprised of links and nodes, both of which can have values associated with them (see Chapter 5). Gravity modelling using GIS is important in establishing the relative importance of each link and node in an area based on size and/or distance differences. An example is given whereby towns of various sizes (each town is a node) are connected by a road network (the links). Given that larger towns are likely to attract more usage, but that people are going to use discretion in how far they wish to travel, then using so-called "gravity modelling" the GIS can calculate the number of people who are likely to support the facilities at each town, i.e. this will be the town's sphere of influence. Gravity modelling is useful in terms of where best to locate certain facilities, or in how far it may be worth travelling to catch certain fish species.

A second form of important network analysis is that concerned with optimizing travel or communication through networks (also called connectivity analysis). What is discussed here normally applies to human travel, but the logic could also apply to routes through communication systems, waterway networks, pipelines, etc. Again using the node and link model, it is easy for a GIS to calculate the shortest path through, for instance, a road network between any start and finish nodes. This calculation can be in terms of shortest travel distance, cost or time. Temporary impedance values can be introduced in any selected link for perhaps road works or a major traffic hold-up. This type of network analysis forms the basis on which in-vehicle navigation systems work. A variation on shortest path analysis is the so-called "travelling salesman problem", where the shortest/quickest route is the one that best connects many delivery points. From a fisheries perspective, it might be desirable for a GIS to establish the optimum daily route for the collection of landed fish catches. A second variation on shortest path analysis is the ability of GIS to determine, from any selected node, the number of other nodes that may be accessible in a given time or at a given cost. This might be useful for a fish farmer who wants to establish the number of potential customers that can be served from any nodal points.

An important final type of network analysis is that associated with natural water flow over terrestrial surfaces. Over much of the planet, a network of streams and rivers has naturally become established, with flows usually moving outwards from core highland areas towards low lying coastal areas and thence into the sea (though sometimes water flows are directed towards inland lakes). Based on any river network in a specific area, GIS can perform the following analyses, all of which may be useful to aquaculture site selection or to river fisheries:

- calculation of flow direction and water accumulation;
- derivation of river or stream catchment areas;
- detection of flood storage areas (or suitable dam site locations);
- inundation modelling to detect areas along waterways that are liable to varying degrees of flooding;
- rates of, and areas affected by, point source pollution or disease dispersal downstream through waterways;
- management of waterway extraction along streams or rivers;
- creating likely stream networks in areas that are poorly mapped; and
- peak flow prediction in rivers during storm events.

The basis on which any of these analyses works is described in some detail, especially that concerned with identifying the pour direction and routeways for natural water flows. The technical paper gives many clues to sources of information on all network analyses, including many Internet sites that provide online facilities allowing access to software packages for modelling hydrology.

The last type of GIS functionality discussed is topographic surface analyses. These were introduced in Chapter 5, but here the concern is providing information on some of the GIS analyses that are possible. Using either triangular irregular networks or digital elevation models mentioned in Chapter 5, together with their incorporated elevation data, GIS are able to calculate surface or submarine gradients for any given slope and they can produce complete gradient maps for any area. This information is useful in pond site identification for aquaculture. One associated factor that can be established is aspect, i.e. information on the direction in which slopes are facing, and another GIS function is that of visibility analysis, in which it is possible to determine all parts of an area that are visible from any chosen map location. This can be important if planning applications decree that for particular facilities the visual impact should be minimized (e.g. location of fish cage culture sites).

Any GIS will not be able to provide all desired functionality. To circumvent this, a good GIS will provide a means for users to create their own functions and tools. This is sometimes provided through a simple macro function, whereby a script can be written allowing for repetitive functions to be enacted. More advanced GIS software may allow users to write sophisticated tools using the most current software programming languages, such as C++, C#, Java, Python or VB.NET, and some of these GIS packages have enthusiastic user groups of people who write and share custom tools and who often provide them free online. With experience in the use of GIS, it seems that most functions are possible.

Fish ponds for culture of Nile tilapia, African catfish and African bonytongue, Cameroon

There is considerable potential to expand inland aquaculture in Africa to improve food security. To aid aquaculture planning and management, GIS modelling techniques can be used to identify and map specific sites for fish ponds, and GIS tools can assist in allocating further land and water space for sustainable aquaculture expansion.

Courtesy of José Aguilar-Manjarrez

8. Current issues, status and applications of GIS to aquaculture

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While it is important to explain the purposes of GIS technology, it is also essential that the reader gains a true impression of the realistic capabilities of the technology. This knowledge is best achieved through examples. This chapter provides GIS-based case studies of aquaculture, whereas Chapters 9 and 10 discuss GIS applications to inland fisheries and marine fisheries and also include case studies. The case studies presented in these three chapters have been selected from a number of different sources. They not only illustrate the technical capacity of GIS applications in aquaculture, inland fisheries and marine fisheries, but they also address issues that are of global to local importance and that span environmental, social and economic considerations. The case studies are as varied as possible, and include a variety of GIS-based techniques and differing degrees of complexity. Each study is structured to show various facets of the project, such as the publication date and title, number of staff or researchers, duration of the study, and who the study was aimed at. Before the case studies are introduced, an attempt is made to clarify the main issues that the use of GIS is attempting to resolve within aquaculture, inland or marine fisheries, and an indication is given on the geographical distribution of GIS usage in these sectors. The rest of this chapter is concerned specifically with aquaculture case studies.

Aquaculture is an extremely broad activity in terms of species cultured, environments utilized, geographical distribution, techniques used and the socio-economic milieu in which it takes place. It is also an activity that is practised at varying production and economic scales, i.e. varying from one of many activities on one small farm to a single activity pursued by a multinational corporation. Output from aquaculture can be for direct human consumption, or used as an input to bolster natural fisheries through restocking. Given the huge diversity in aquaculture, it is not surprising that the pursuit of the activity will have strong spatial implications in terms of a range of social, economic and environment considerations. And the implications are two-way in the sense that aquaculture may impact the environment (including social and economic) in which it operates, but this environment can greatly impact the success of the activity. This two-way breadth of spatial implications means that GIS-based analyses are particularly suited to support problem-solving and decision-making in aquaculture.

Turning to the range of issues that aquaculture has recently sought to address, an analysis was made of FAO's GISFish global gateway to GIS, remote sensing and mapping for fisheries and aquaculture (www.fao.org/fishery/gisfish), both to identify the main issues, as well as the sub-issues (which are discussed in the technical paper), and to quantify them (as of April 2012). Although the classification is complicated because many issues may not conform to single (or simple) boundaries, it was found that the 391 relevant studies from the GISFish database (for the period 1985–2012) could be best classified under the following issues:

- **Development of aquaculture (209 records).** As noted here, more than half of all issues being addressed by GIS fall into this classification. These issues mainly relate to the use of GIS for working out the site suitability for aquaculture at the local level, but also for widespread strategic planning of where aquaculture might best be integrated into the development of regional or national plans. It is also important to investigate the likely impacts of aquaculture at any scale and to identify sources of potential external problems to successful aquaculture in any location(s). A number of examples covering the development of aquaculture are discussed.
- **Aquaculture practice and management (124 records).** This is also an important area of concern for aquaculture. Here, the main sub-issues are the inventory and monitoring of aquaculture and the environment, and the environmental impacts of aquaculture, e.g. mainly in terms of carrying capacity and zoning. This is done because there is a strong potential either for aquaculture to have some impact on other primary activities or the reverse situation in which resource-use activities may have an impact on aquaculture success. The availability of high-definition remotely sensed imagery provides an important and relatively inexpensive data source for this issue, and FAO has developed the National Aquaculture Sector Overview (NASO) map collection, which is a selection of Google-based maps (at varying scales) for a range of countries showing aquaculture inventories (mainly by administrative units) and their characteristics (www.fao.org/fishery/naso-maps/naso-home/en). The technical paper discusses the NASO map collection in some detail, and also describes various examples showing why environmental impacts of aquaculture are a many-faceted spatial issue. It also considers why Web-based aquaculture information systems will be increasingly important to the future success of aquaculture.
- **Training and the promotion of GIS (32 records).** This issue is concerned with education about both the usefulness of GIS-based analyses and the training possibilities that are available for learning the principles of GIS. It is therefore addressed to senior management or decision-makers who might have to decide on implementing systems such as GIS and to technical staff who need to know exactly how best to parameterize the system. FAO plays a key role worldwide in the promotion of GIS within the sectors for which it is responsible. However, promotion per se is more regularly conducted by the main software houses and by the organizers of exhibitions, conferences and symposia. Training materials specifically for aquaculture GIS are mentioned in Chapter 4.

- **Multisectoral development and management that includes aquaculture (26 records).** The main issue addressed here is the role of GIS in establishing aquaculture in the context of competing, conflicting and complementary uses of land and water space. The fact that only 7 percent of GIS-based work has addressed this issue indicates that planners and developers may not have taken aquaculture into much account in the overall context of development. The technical paper provides an example of how this issue could be positively addressed within both the emerging contexts of an ecosystem approach to aquaculture or fisheries or as part of a study addressing marine spatial planning.

Two other indicators concerning the recent or current status of GIS work are then reviewed:

(i) An analysis of FAO's Aquatic Sciences and Fisheries Abstracts (ASFA) database of published aquaculture studies to show where GIS work is being undertaken gives not only the basic facts of the spatial distribution of such work, but it also shows the prevailing level of interest or experience in such GIS applications, and this fact itself might be useful with respect to deploying resources for training or technical assistance. Information on the worldwide distribution of GIS applications to aquaculture is presented in both mapping and tabular formats. It is of interest to note that publications come from about 25 percent of all countries, yet about 80 percent of countries report some aquaculture production, i.e. less than one in three countries practicing aquaculture publish reports on their use of GIS. North America, especially the United States of America, dominates GIS-based publications, though many South and East Asian countries are now making advances in their use of GIS.

(ii) The technical paper also highlights some of the main institutions worldwide where aquaculture-related GIS research and projects are pursued. Ten institutions are specifically identified for their contributions to GIS work, with about half of them being located in developing countries.

Attention now turns to the four case studies dedicated to aquaculture. The first case study, entitled "Sustainable options for people, catchment and aquatic resources" (also known as the SPEAR project), was a large-scale, three-year study (2004–07) involving 35 experts from different countries, with the project being based in the People's Republic of China (Ferreira *et al.*, 2008). This study is considered "sophisticated" with respect to its GIS mapping and analyses, though as such it gives a good indication of the high-level potential for GIS work and is an excellent example of a holistic assessment of aquaculture. SPEAR's objective was to develop and test an integrated framework for management of the coastal zone, using two test cases where communities depend primarily upon marine resources, of which a large component is the farming of finfish, shellfish and seaweeds. Full details of the research are available at www.biaoqiang.org. In summary, GIS was used in this project for:

- **Decision support** – in the form of mapping all the key components within the two test-case areas.

- **Modelling** – GIS formed the platform on which a number of models (e.g. catchment, hydrodynamic, ecosystems, aquatic resources) could be parameterized, calibrated and integrated in order to develop a robust ecosystem modelling framework where GIS and remote sensing play an integral part.
- **Visualization** – allowing researchers and stakeholders to best conceptualize all relevant inputs and results.

The SPEAR project represents an example showing how GIS aids the integration of spatial data across different scientific disciplines; it is novel because it combined models running at widely different time and space scales for different ecosystem components; and socio-economic viewpoints could also be incorporated. The technical paper describes how the SPEAR work is now being extended into other spheres of marine shellfish aquaculture.

The second case study, entitled "AkvaVis decision support system", is again a large-scale and quite sophisticated project, which is still ongoing and based in the Kingdom of Norway (Ervik *et al.*, 2008). It employs about eight aquaculture specialists assisted by three GIS technology experts, and their main aims are to inventory and monitor marine aquaculture and its environment, examine the environmental impacts of aquaculture, and develop a Web-based aquaculture information system. Aquaculture is a major economic activity in the Norwegian fjords, and farming is dominated by the production of Atlantic salmon for local and world markets, though diversification into other marine species is being pursued. As with aquaculture elsewhere, increases in production cause problems, not only with potential disease and water quality issues, but also with competition for access to marine space. To help resolve environmental and space conflicts, AkvaVis is being developed as a Web-based interactive site selection, coastal zone area planning, carrying capacity, management and monitoring, and decision support system. The Web site is widely accessible and dynamic, in the sense that it is adaptable to new knowledge and new regulatory frameworks and that it can address the demands from the industry, plus public and private stakeholders. It can further be integrated to other activities as part of marine spatial planning. AkvaVis operates in three modules, two of which are relevant to GIS:

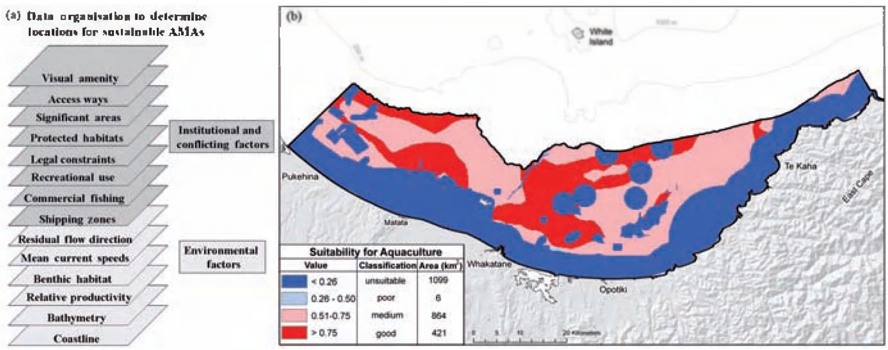
- A *management module* that compiles information needed to optimize aquaculture management, and this includes adopted area management plans and other geographic information of relevance regarding the conflicting use of the coastal area, and information on mandatory environmental monitoring and environmental quality standards.
- A *siting module* that identifies and evaluates the suitability of areas for specified aquaculture activities and provides simulations of their carrying capacities.

The siting module is discussed in detail in the technical paper because of its sophisticated capabilities. Thus, through Web-based interaction with maps of any desired area, potential fish culturists can see the consequences of their desire to locate a new production unit at any specified point. This requires sophisticated and widespread information on existing conditions for all Norwegian marine areas in terms of water depth, quality, hydrodynamics, existing farm locations, benthic fauna, sewage outfalls, and the ability for the GIS to function as a modelling platform that assesses the combined influence of all these marine variables at any location. Location implications can be perceived as both the effect of a new farm on its surroundings and the effect of the prevailing environmental conditions on the proposed new farm. This modelling potential is demonstrated at www.akvavis.no. The interactive capability of AkvaVis allows the users to immediately see the consequences of their choices. AkvaVis combines a broad-scale approach by covering Norway's coastal aquaculture and by including all the main fish and shellfish species under culture. Moreover, it is holistic in EAA social terms by being designed for transparency, public participation and outside scrutiny. The case study usefully concludes with some of the main challenges facing the adoption of such a complex decision-support system.

The third case study is concerned with assessing an offshore open coast area in the Bay of Plenty, New Zealand, as to its suitability for shellfish farming (Longdill, Healy and Black, 2008). The study implemented a framework to collect and analyse a large number of data sets relating to the environmental effects of bivalve culture, competing uses of the marine environment, as well as the productive capacity for aquaculture. To achieve this framework, a network of factors that aid the development of a sustainable and viable aquaculture industry was identified and examined. The study gives details on all the data required, how they were collected and assembled, and how they were standardized and subsequently utilized, including the various models used in order to obtain specified results. The resulting outputs initially provide an indication of the relative suitability of the benthic habitats to assimilate the inputs from suspended bivalve aquaculture for a 2 390 km^2 area of the continental shelf, plus an indication of the suitability in the same area for suspended offshore bivalve aquaculture (Figure 8). More sophisticated temporal modelling was applied to show the relationship between the spatial suitability for bivalve aquaculture and various physical processes (tides, winds, etc.) and the 3D natural chlorophyll-*a* concentrations, i.e. as a measure of natural food availability at different times. From these observations, it was possible to model the influence of siting bivalve production facilities at any preferred location within the bay on the depletion rates of naturally available foods. The results of this exercise provide a measure of the ecological impact of shellfish farming in the Bay of Plenty, though there will always have to be discussions on what acceptable rates and scales of nutrient and plankton change might be. The authors further indicate how their study might be refined, though they note that there will always remain factors causing some limitations to this type of GIS analysis, i.e. such as the favouring of pre-existing aquaculture uses, the unaccounted potential for future change in these uses, the legal setting, or the use of different culture methods. These factors could substantially alter the outcome. Despite these limitations, the use of an ecological model to simulate potential farms and the corresponding GIS analysis represents a valuable and exciting future direction for the use of GIS and aquaculture.

FIGURE 8

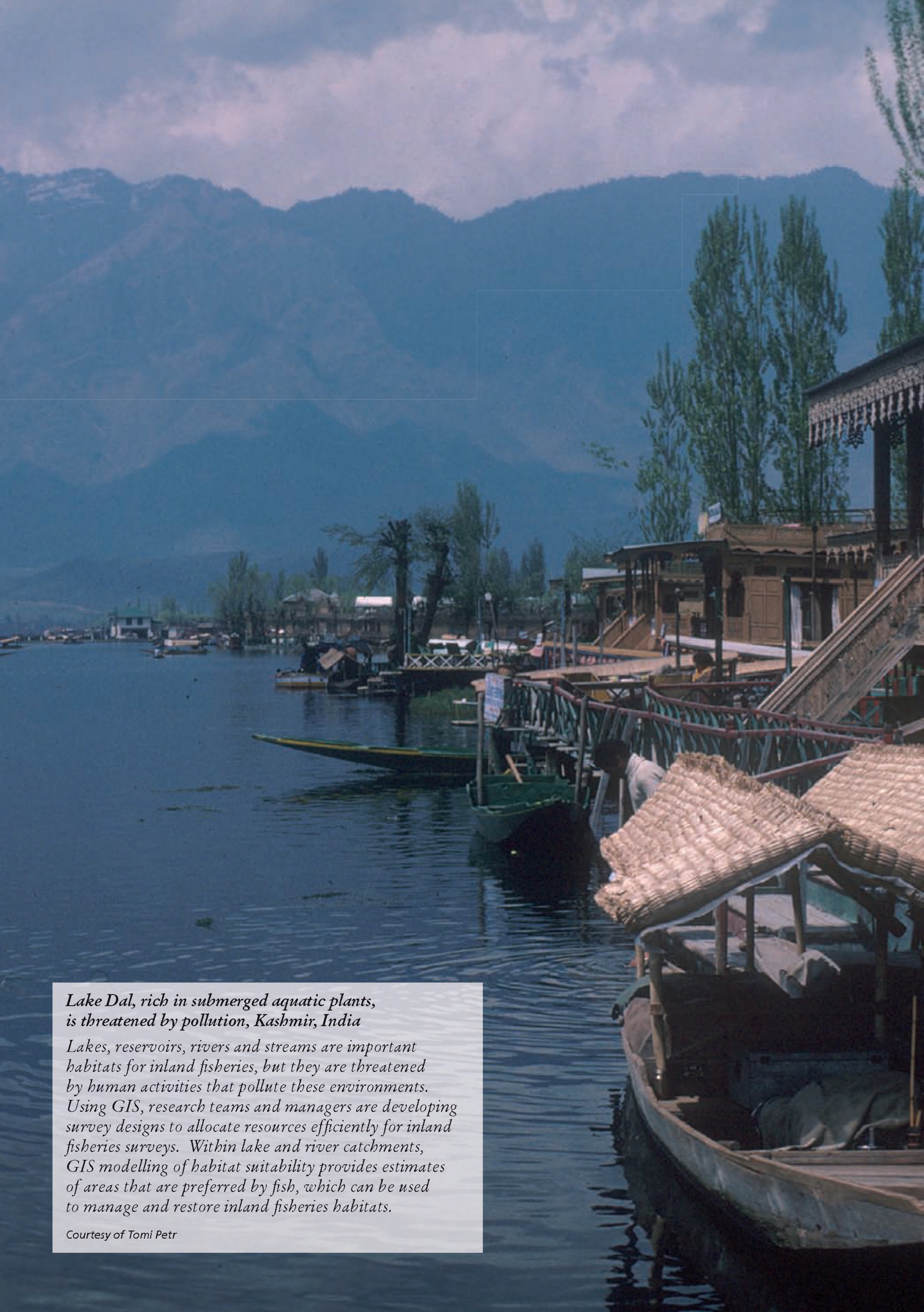
Data layers and organizational structure (a) used to determine locations for sustainable aquaculture management areas (AMAs) and (b) output suitability index classes for suspended offshore bivalve aquaculture within the Bay of Plenty, New Zealand



Source: Longdill, Healy and Black (2008).

The final case study looks at the potential and financial viability of fish farming in the Republic of Ghana, West Africa (Asmah, 2008). This is a fairly basic study carried out by a PhD-level student using precollected data. With the country currently experiencing a 40 percent shortfall in fish needs, it is increasingly important to try to supplement capture fisheries output with production from aquaculture. A key issue in aquaculture development is that of defining its potential location and scale, and thus the objective of this study was to use GIS to assess the potential for small-scale and commercial freshwater aquaculture development in the Republic of Ghana, with a particular focus on tilapia. Secondary data covering the whole country was collected on some 20 variables that were positively required for aquaculture success, plus data on a number of factors that might constrain aquaculture, e.g. the existence of forest or game reserves. Raster-based maps were produced for all variables, with each map being classified according to mapped areas that were considered as being “Very Suitable”, “Suitable”, “Fairly Suitable”, and “Unsuitable”. Each mapped variable was also given a weighting (from zero to one) depending on its relative importance to aquaculture, and different weightings were given with respect to how important the variable was to either small-scale or to commercial fish culturing. The weighted maps were then integrated (including the constraint maps) to produce final maps showing the suitability of all areas for either type of culturing. All tabular, numerical and mapping results are shown in the case study. The models that were used to produce the final maps could be verified by visually comparing their results with the real distribution of fish farms in the country, and it is shown that the results were very encouraging. The authors were finally able to calculate the rate at which fish farming would need to expand in order to catch up with national fish consumption requirements.

While further data refinement and model adjustments could be achieved, the outcome is nevertheless a powerful illustration of the integrative use of GIS systems and their ability to work with and model from widely disparate data sets. The study is based on a relatively simple model structure and, consequently, can be easily replicated for other countries (assuming that the data are available), e.g. to support the preparation of national aquaculture strategies and national development plans.



Lake Dal, rich in submerged aquatic plants, is threatened by pollution, Kashmir, India

Lakes, reservoirs, rivers and streams are important habitats for inland fisheries, but they are threatened by human activities that pollute these environments. Using GIS, research teams and managers are developing survey designs to allocate resources efficiently for inland fisheries surveys. Within lake and river catchments, GIS modelling of habitat suitability provides estimates of areas that are preferred by fish, which can be used to manage and restore inland fisheries habitats.

Courtesy of Tomi Petr

9. Current issues, status and applications of GIS to inland fisheries

W. Fisher (Cornell University, Ithaca, United States of America)

This chapter is concerned with GIS applications made to inland fisheries. These include fisheries in freshwater rivers, lakes and reservoirs. Although these GIS applications have increased rapidly since the late 1980s, this area of fish production receives less attention than either aquaculture or marine fisheries. This is probably because inland fisheries are often practised in remote areas, at a semi-subsistence level, or are recreational in many developed countries, and data on most aspects of the fisheries are scattered, fragmented and frequently unsuited for use as inputs to GIS. The GIS-based inland fisheries work has concentrated on mapping the distribution and abundance of fish species and mapping and modelling habitats in rivers, reservoirs and lakes, and relating the two. Much of the material included in the chapter on inland fisheries comes from either Fisher and Rahel (2004) or from the series of symposium proceedings published by the Fishery-Aquatic GIS Research Group (Nishida and Caton, 2010).

With respect to the main issues affecting inland fisheries that are currently being addressed by GIS, five main thematic areas of study are identified. They are:

- **Visualization and species distribution modelling.** Mapping and visualizing fish distribution and their abundance and aquatic habitats remains the most common use of GIS in inland fisheries. This visualization is accomplished by simply using GIS as a mapping tool that offers significant versatility in scale, presentation, classification, categorization, etc., and examples are given to demonstrate this versatility. Species distribution modelling evolves from the relationship between species distributions and their habitats, and is a valuable tool for managing and conserving inland fishery resources.
- **Fish movements.** Mapping fish locations and measuring rates of fish movement provides information for managing populations and their habitats. Movement measurement can be achieved through tagging and then catching tagged fish, or through various radio or ultrasonic telemetry devices, with both methods providing important georeferenced fish locations for the mapping of selected species.
- **Habitat modelling.** GIS is widely used as a platform to model fish habitat in inland rivers and lakes, particularly to assess habitat suitability in relation to physical (e.g. flow, depth, substrate) and chemical (e.g. temperature, dissolved oxygen) conditions. Models can be constructed from independent data or from data collected in the field. These data are incorporated into mathematical models that combine the habitat factors and in some cases

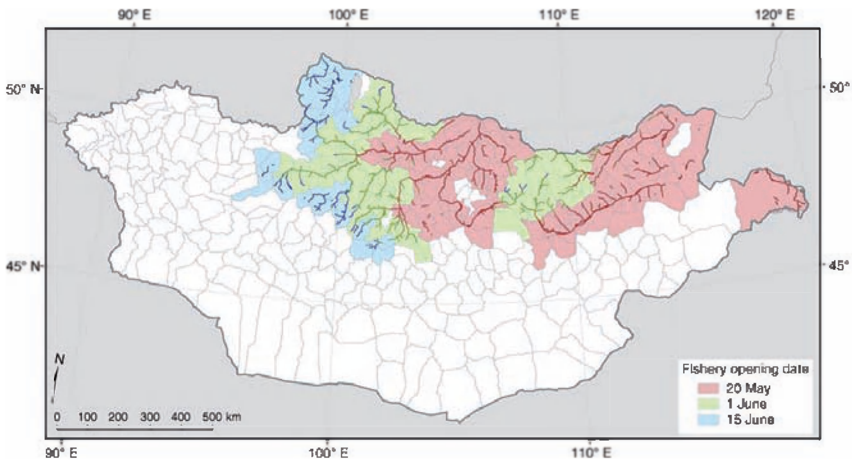
weight them according to their importance based on statistical analyses or expert opinion.

- **Watershed management.** Streams and lakes drain watersheds where land-use activities, topography, local geology, soil types, hydrology and many other factors can affect the runoff of sediment and nutrients into streams or lakes, thereby affecting water quality plus fish populations and communities. Understanding the relationship between these watershed factors and fish population and communities enables resource managers to prioritize areas for restoration and protection.
- **Spatial design and conservation planning.** Developing designs for survey site selection in streams, rivers, reservoirs and lakes enables researchers and managers to efficiently allocate resources for fisheries surveys. Also, at a larger scale, habitat suitability classes can be assigned to varying stretches of river within large catchment areas so as to provide estimations of class areas and then probable species abundances within the catchment according to species habitat class preferences. For example, Figure 9 shows a map of recommended fishery management zones developed by Vander Zanden *et al.* (2007) for the giant Eurasian trout (*Hucho taimen*) in Mongolia based on spawning dates and potential habitat.

Four other factors concerning the recent and/or current status of GIS work in the area of inland fisheries are briefly examined:

(i) A break-down of the number of records appearing, under various thematic headings, in FAOs GISFish database between 1985 to about 2009 showed that most of the 224 records were for GIS applied to assess habitat quality/quantity linked to plant and animal abundance and distribution – 67 records; followed by classification and inventory of habitats – 29 records.

FIGURE 9
Map showing the three recommended management zones based on opening dates for fishing for giant Eurasian trout in Mongolia



Source: Vander Zanden *et al.* (2007).

(ii) An analysis of FAO's ASFA database showing where studies on inland fisheries using GIS were carried out between 1996 and 2010 showed a dominance by North America, with some 56 studies being carried out there. However, recent evidence shows that this dominance is declining, with inland fisheries GIS work now being pursued in 32 countries, many of which are in the developing world.

(iii) A second analysis of the main institutions where GIS work on inland fisheries was being pursued between 1996 and 2010 found that nearly all the main institutions were located in developed countries, and that there were relatively few institutions pursuing this type of applied work. This is unsurprising given the highly technical nature of the work and the fact that most inland fisheries are not commercial and are thus not valued so highly.

(iv) The chapter also describes in some detail the types of spatial tools (e.g. GIS, remote sensing, spatial models) and analyses that are possible for both the larger bodies of standing freshwater (lakes and reservoirs) and the linear networks that comprise rivers and streams. In the case of the former, many terrestrial, aerial (spatial) GIS methods can be deployed, and in the latter case most GIS functions within the so-called network analysis may be applicable (see Chapter 7).

The first of three case studies, exemplifying typical work undertaken by projects linking inland fisheries to GIS, is entitled "A spatially explicit resource-based approach for managing stream fishes in riverscapes" (Le Pichon *et al.*, 2006), a sophisticated study carried out by six research scientists and managers based at two institutions in the French Republic. The study aims to provide a riverscape approach in combination with spatial analysis methods to assess multiscale relationships between patterns of fish habitat and fish movements. Riverscape is defined as the "mosaic of heterogeneous and dynamic habitats which to most observers is often hidden beneath the opaque layer of water", and it is the underwater, riverine equivalent of the terrestrial landscape. GIS can be a valuable tool to assess the degree of relationship existing between a fish species and any identified component of the riverscape, e.g. shallow areas with riffles, deep pools in the river and areas with dense riverside vegetation. This relationship may vary according to species, age of fish, time of day, season, fish activity, state of the water, etc. However, rather than following the more commonly used habitat classification approach, here the authors classified habitat by defining the resource-based (i.e. spawning, feeding and resting) habitat patches preferred by individual fish species. An understanding of the spatial and temporal dynamics of fish and their movements has a major influence on fisheries management and on habitat conservation and restoration.

Fieldwork was carried out in the upper Seine River, in the French Republic, and the species studied was Barbel (*Barbus barbus*). The authors describe in some detail the study area, the methods for establishing habitats, the scales and resolution that they worked to (spatial precision), the data themes used, the parameters measured, the map layers produced, some additional freeware GIS that was integrated with ArcInfo GIS, and the modelling used. Most of the modelling aimed to assess the likelihood of the fish species occupying certain habitat patches, the degree of connectivity between patches, and the likelihood of fish actually reaching their feeding, resting or spawning areas (their different habitat patches). The study concluded with a discussion showing the value of this work in terms of realistically assessing the different habitats utilized for the whole life cycle of a species and the effects that this could have on predicting any prioritization of stream restoration and species management, i.e. based on the spatial proximity of habitats and different spatial scales. Although there would be many challenges to replicating this project, it offers a glimpse of the work that is possible through the use of GIS, though the authors also point out the difficulties of working in aquatic environments that experience continual spatial and temporal change.

The second case study, conducted by three researchers and two government agency fisheries managers during the 1997 to 2002 period, looked at predicting fish yields in reservoirs located in the Democratic Socialist Republic of Sri Lanka (Amarasinghe, De Silva and Nissanka, 2004). In this country, there are numerous reservoirs whose primary purposes are to provide irrigation water for agriculture and to act as a location for the island's artisanal inland fisheries, where species consist mostly of exotic cichlids, Mozambique tilapia (*Oreochromis mossambicus*) and Nile tilapia (*Oreochromis niloticus*). Most reservoirs have received little fisheries management attention, and thus little was known about actual or potential fish yields. In this study, the authors used GIS to quantify land use in nine reservoir catchments, and they related the fish yield to land-use patterns, selected limnological characteristics (conductivity, chlorophyll-*a*) and reservoir morphometry (area and capacity). The statistical methods used showed highly significant relationships between fish yield and forest cover, shrubland, and ratios of these (reservoir area and capacity) and the morphoedaphic index. The authors further suggested that, with the aid of GIS-derived information, they could provide an accurate yield assessment for reservoir fisheries. The study methods involved the use of ArcInfo GIS and, for the reservoirs studied, data were obtained to allow for the production of all relevant map layers, including 16 land-use types covering the reservoir catchments, morphological data relating to the lakes, and a variety of water-quality parameters. These data allowed the morphoedaphic index to be calculated for each reservoir. Fish catch data for the reservoirs were established for the 1997–99 period, and these data were expressed as fisheries yield (kg/ha/yr) and fishing intensity (boat days/ha/yr). Based on the above data, regression models were developed and principal component analyses were performed. The results of these GIS-based studies showed that land cover type, particularly forest cover and to a lesser extent shrubland cover, was strongly linked to reservoir morphometry and directly related to fish yield in the reservoirs. Thus, land cover influences nutrient supply, which can result in increased production from the aquatic ecosystem. In order to optimize future fish yields, reservoir management needs to pay greater attention to catchment land cover types.

The final case study on applications of GIS to inland fisheries looks at the conservation of freshwater biodiversity throughout the state of Missouri in the United States of America (Sowa *et al.*, 2007). This was a long duration study (1997–2006) by four university-based research scientists whose aims were to develop a practical strategy to halt the decline of long-term species noted in many North American river systems. A special need was to identify gaps in existing efforts to conserve freshwater biodiversity and to prioritize efforts to fill these gaps. The study was part of a larger study to identify areas of high species richness and endemism that may be filled by establishing new management or protected areas or by implementing changes in land management practices. Four primary GIS data sets were used in this study: (i) river ecosystem classification; (ii) modelled species distributions; (iii) public land ownership/stewardship; and (iv) human threats. The technical paper gives details on how each of these data set areas were compiled and mapped. Mapping of riverine ecosystems was carried out at a hierarchy of scales in order to identify, classify and map distinct ecological units and habitats of all rivers in the state of Missouri. Predicted distributions of 315 aquatic species were made from nearly 6 000 collection records using a suite of seven environmental predictor variables relating to stream size, stream gradient, stream temperature and stream flow. GIS was used to map the modelled distributions. An assessment was made of where all gaps in aquatic species distributions occurred in areas classified as "public land" – because conservation measures could only be made obligatory in streams or rivers located on these lands. The final set of maps showed human threats, and these areas were interpreted in terms of a measurement of the degree of human disturbance (related to 11 types of possible disturbance) that could be affecting freshwater ecosystems.

After all the relevant data were assembled and mapped, a variety of analyses were pursued that together indicated which parts of Missouri's river networks would be most suited for the aquatic conservation of specific species. For instance, stream stretches (reaches) of varying lengths that were located in areas considered to have "reasonably secure conservation plans and management actions that would benefit biodiversity conservation" were identified, and only these reaches were considered as being suitable for conservation purposes. The number of species presently occupying reaches of specific quality or stream length was also calculated, as was the length and location of suitable streams (for conservation) within each major river catchment. Based on all the GIS output, a team of aquatic resource professionals identified and mapped a set of aquatic conservation opportunity areas (COAs) that represented the breadth of distinct riverine ecosystems and habitats in Missouri. The 158 selected COAs contained 6.3 percent of the total stream length in the state, but they could provide suitable protection and habitat for 296 identified native aquatic species. Although the total amount of data and the range of analyses used were considerable, it was suggested that this effort was well worthwhile in terms of it being an essential task in helping to ensure the future for most species, i.e. species that often live in degraded aquatic environments situated on private lands where conservation may be impossible.

Shrimp trawl fisheries

Marine fish stocks are under increasing threat from a range of spatially based problems that might be natural or involve socio-economic factors. To best manage spatial problems, systems such as GIS and remote sensing are now being extensively deployed. For these systems to be effective, it is important that spatially based catch and fishing effort data can be recorded from electronic fisheries logbooks or via vessel monitoring systems. In many parts of the world, vessels such as this one are actively acquiring appropriate data.

Courtesy of John Mitchell

10. Current issues, status and applications of GIS to marine fisheries

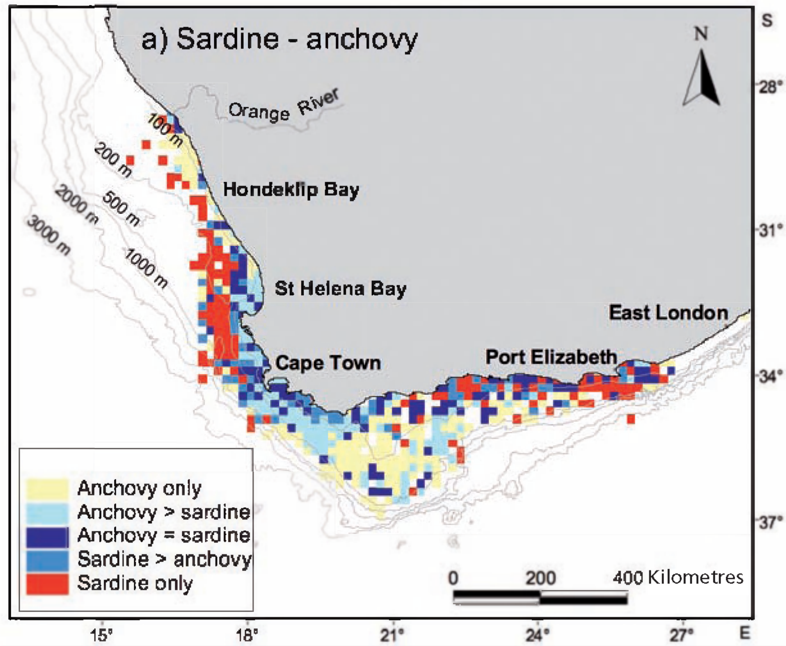
G.J. Meaden (FAO consultant, Canterbury, United Kingdom) and
F. Carocci (FAO Marine and Inland Fisheries Branch, Rome, Italy)

With respect to applying GIS as a tool for fisheries and aquaculture management or research, it is arguably more difficult to apply GIS in dynamic environments (e.g. marine fisheries, inland fisheries and offshore mariculture) compared with more static terrestrial environments. The reasons for this include the vastness and often remoteness of the areas being studied, the expense of obtaining suitable data from these areas, the fact that marine areas should be considered in terms of three or four dimensions, and the difficulties of mapping moveable objects – fish, for example – in moveable (non-static) aquatic environments. Along with these challenges, a number of factors such as overfishing, pollution, environmental degradation and resource competition, are causing large areas of the marine environment to be in spatial dis-equilibrium (out of a natural balance). As well as the main issues currently being addressed by GIS applications to marine fisheries, this chapter examines the spatial distribution of these analyses and concludes with three case studies illustrating a range of GIS usages.

There are a large number of ways in which GIS is presently being utilized to assist in marine fisheries management or research. The main ways (or themes) are

- **Distribution displays.** This is the construction of maps to show the distribution of any single theme or feature, or combination of marine and/or fisheries features. Distributions maps form the core of most modelling or GIS-based analyses.
- **Marine habitat mapping and analyses.** Establishing the essential components of fish habitats is an ideal way to utilize GIS, e.g. perhaps with a view to aquatic conservation designations.
- **Resource analyses.** These quantify and display the disposition and dynamics of any physical or biotic marine resource or combination of resources. For example, Figure 10 shows the potential interactions between two species having no predator/prey relationship (anchovy and sardine) that are competing for the same planktonic resources in South African coastal waters.
- **Modelling.** These functions include work on illustrating themes, often in a simplistic or general way, or there may be predictive modelling to show the outcome of potential decisions or actions. Modelling lies at the core of much marine GIS work.

FIGURE 10
The interaction between anchovy and sardine stocks in South African coastal waters



Source: Drapeau *et al.* (2004).

- **Monitoring management policies.** Fisheries management involves many spatially based decisions, e.g. in order to sustain fish yields fishing effort needs to be optimally deployed, and perhaps recorded via data obtained from electronic logbooks or vessel monitoring systems.
- **Ecosystems relationships.** Large numbers of marine relationships can be usefully delimited by GIS use, e.g. seeking predator/prey relationships, or relationships between fish distributions and any environmental parameter.
- **Marine protected areas (MPAs).** GIS can assist in identifying suitable areas for species or habitat protection or for the exclusion of fishing, and for analysing the results achieved through the designation of these areas.
- **Marine spatial planning.** This involves determining marine allocations so that all competing users of the marine space can best function sustainably. This may be complex given the number of the often conflicting parties involved, the frequent need to cross international boundaries, and the variety of spatial considerations.
- **The creation of economic surfaces.** Allowing researchers to model the likely income derived from fishery products based on alternative management and resource extraction scenarios.

- **Ecosystem approach to fisheries.** GIS is the ideal tool to assist in identifying ecosystems dis-equilibrium, and to predict and depict scenarios for improved management practices.

In each of the above thematic areas, examples of GIS are provided and further details are given. Over the past decade, the range of these themes has not expanded greatly, but the sophistication of the work has increased and current work is more likely to include complex modelling, geostatistics, animations, 3D and 4D analyses, and other processes.

Four other indicators concerning the recent and/or current status of GIS work are then reviewed:

(i) A breakdown of the number of records appearing, under various thematic headings, in FAO's GISFish database between 1990 and 2012 showed that most of the 360 records were for GIS applied in the context of ecosystems (i.e. approaches to fisheries, modelling, ecoregions) – 140 records; followed by management (i.e. integrated, regulations, systems and planning) – 67 records; marine protected areas – 30 records; habitats – 27 records; and species distributions – 20 records.

(ii) Using FAO's ASFA database, 207 records were obtained showing the geographic location where marine fisheries GIS work was conducted between 1996 and 2010. Of these records, 57 cited no specific location, and of the remainder more than half of the work was based in the United States of America, with much of the rest carried out in developed countries. This is unsurprising given the potential complexities and costs associated with undertaking GIS work that relies on data collected from a widespread and often hostile physical environment. It may be some time before much GIS-based work appears from many developing countries, but at least they will have existing work from which to obtain project ideas and methods.

(iii) An examination was made of the locations of a selection of the main institutions where marine fisheries GIS is being pursued. Because nearly all of this work is research oriented, it is again unsurprising to see that most of this work is undertaken in developed countries.

(iv) Finally, as a means of demonstrating progress that is being made in respect to GIS applications, Box 10.3 in the technical paper shows insights into some of the perceived trends and/or status in GIS as ascertained from individual observations made at the conclusion of the 2008 Rio de Janeiro GIS/Fisheries Symposium. These comments demonstrate the progress since the previous symposium in 2005.

In order to exemplify recent work being undertaken in respect to GIS applications to marine fisheries, three case studies are described. The first case study is entitled "Towards the use of GIS for an ecosystems approach to fisheries management: CHARM 2 – A case study from the English Channel" (Meaden *et al.*, 2010). This sophisticated example comes from a developed world area where up to 12 researchers worked over a six-year period. Although the case study exemplifies advanced GIS functionality and output, this is valuable for establishing the wider possibilities of the system. The aims of the CHARM project were to develop materials for a series of atlases and a Web site to help with resource management of the busy marine area (the English Channel) lying between the French Republic and the United Kingdom of Great Britain and Northern Ireland. Resource management included the incorporation of EAF considerations, the creation of a wide range of newly mapped resources, developing habitat models, and suggestions for locating marine conservation areas. Although work on the CHARM project was allocated so as to make best use of individual institutional strengths, maximizing the integration of activities was also fundamental to project success. Data inputs came from disparate sources, including national and local government offices, local university studies, specially commissioned marine benthic surveys, a range of existing specialist surveys including annual or semi-annual fishery surveys by national fishery agencies, GIS-based modelling, and remotely sensed data. All GIS work was performed using ArcView V.9.2. The technical paper briefly describes a selection of the output achieved, for example, the distribution of some benthic species, the mapping of fisher's perceptions as to the location of their main exploited commercial fishing grounds, and the use of Marxan software to establish potential marine conservation areas according to specified criteria. All project outputs can be seen on the project Web site at www.ifremer.fr/charm. The authors acknowledged the many challenges encountered during the implementation of the projects, but the results achieved by the CHARM team allowed for a vastly increased knowledge of the Channel's ecosystems and resource distributions.

The second case study, though very specific in content, covers a wide geographic area. This was a two-year project that used GIS and remote sensing as tools to help delimit suitable habitat for humphead wrasse throughout the Republic of Indonesia, Malaysia and Papua New Guinea (Oddone *et al.*, 2010). This species is in severe decline throughout its Indo-Pacific range, and it is important that the habitat distribution is identified with a view to future stock enhancement and conservation. Previous evidence has shown that more than 95 percent of the species live within 100 m of coral reef edges. This study evaluates the use of freely available Landsat-7 satellite imagery, collected between 1999 and 2003, for the mapping of shallow reef areas in order to locate suitable humphead wrasse habitats. The first phase of the project established that the Landsat imagery was of sufficient resolution to identify inner and outer reef edges and that buffers could be reliably drawn on either side of the reef edge so as to depict 200-m wide "corridors" of reef habitat. Once the methodology had been tested and approved, the second phase of the project involved obtaining all 279 of the freely available Landsat images covering the appropriate marine areas in the three study countries. All reef edges in these images were then digitized in order to capture locational data for all 20-m wide reef-edge habitat zones. Using the GIS methods described, the total reef areas suitable for humphead wrasse were 11 892 km^2 in the Republic of Indonesia, 941 km^2 in Malaysia, and 5 254 km^2 in Papua New Guinea. Based on previous reef estimate work, it is likely that these estimates are reliable. A knowledge of reef area and typical wrasse densities might give clues as to the species yield potential and thus to economic productivity for this species. The authors also described some of the challenges facing this work, but further noted that similar methods could be easily replicated and applied in estimating habitat potential in shallow marine waters for other species.

The final case study in this chapter is entitled "Spatial assessment and impact of artisanal fisheries activity in Cap de Creus". The study was carried out over a two-year period by a Master's degree student (with academic staff assistance) and concentrates on a small area of the Mediterranean Sea northeast of the Kingdom of Spain (Purroy *et al.*, 2010). As with many European marine waters, this area suffers from intensive and extensive overfishing from commercial, artisanal and recreational sources, which has led to severe stock depletions and widespread habitat degradation. There is also a major problem with the lack of fishery monitoring and enforcement. As there is a strong recognition that steps must be taken to reverse stock depletions, this study aims to provide information that helps to catalogue problems in the area, which also aids in defining an expanded MPA in the area and which thereby contributes to a long-term fishery future, especially for the local artisanal fishers. The marine environment here is interesting in that the wide coastal shelf is penetrated by a major marine canyon, which offers contrasting ecosystems, a rich species biodiversity, highly variable bottom substrates and a range of ecological niches. The specific objectives of this project were to accumulate detail on the numbers of fishers, the main areas fished and the species targeted, plus the varied fishing methods used. Data on fishing-related matters were obtained from government fishery departments and from FAO, and other data came mostly from the national mapping agency. For GIS purposes, the 1 145 km^2 study area was divided into 500 m^2 cells, and a range of relevant raster-based mapping layers was constructed from the data using ArcView and ArcCatalog GIS software. The range of GIS-based output achieved is described, including maps showing fishing methods deployed, gear types used according to the fisher's home port, and the fishing impact in terms of the variety of gear used in each 500 m^2 cell. The latter map shows a relationship between the number of gear types employed and the distance from the coast; most areas considered valuable for conservation were those where the least number of gear types had been used. The study concludes with a clear recognition of ways in which the whole GIS-based project could usefully be extended.

11. Emerging themes or issues in fisheries and aquaculture GIS

G.J. Meaden (FAO consultant, Canterbury, United Kingdom) and
J. Aguilar-Manjarrez (FAO Aquaculture Branch, Rome, Italy)

Although world marine fish production has reached a plateau of about 80 million tonnes annually, fish produced from aquaculture has increased by approximately 50 percent during the past decade. The combined total value of fish sold by fishers and aquaculturists is now likely to have reached US$200 billion, and over 500 million of the world's population are supported directly or indirectly by fish production. These facts provide indicators that both fisheries and aquaculture are very significant activities and, as such, they will continue to need the input of both research and management. From the perspective of GIS and remote sensing, this recognition must be significantly bolstered because of all the world's production activities fisheries and aquaculture are the most spatially extensive, and a large range of production types takes place in hugely varied environments and at vastly differing scales. Because of this importance, it is vital to examine emerging themes or issues in both fisheries and aquaculture.

A number of preliminary considerations need to be made with respect to themes and issues:

(i) Only issues having a spatial context are examined here, although in practice this is most issues.

(ii) Although the terms "themes" and "issues" have distinct meanings, in the context of this chapter they are used almost synonymously. This is because GIS is being deployed as a spatially based problem-solving tool, and there is an implication that within specific thematic areas there must be an issue that needs to be addressed.

(iii) The term "emerging" themes is used because there is already evidence that these themes are developing. Therefore, the term "future themes (or issues)" is avoided because of the degree of conjecture involved.

(iv) It is important to be aware that many emerging themes or issues can be part of a related chain of issues, e.g. the issue of climate change can lead to changing water temperatures which in turn leads to range changes of fish species, etc.

(v) Themes or issues themselves must arise from drivers or catalysts for change, and it is sometimes difficult to differentiate between a "driver" and an emerging "issue" or indeed an "emerging trend".

(vi) It may also be difficult to differentiate between "current issues" and "emerging themes or issues". Here, emerging themes or issues are fields of study that are likely to become more important in the near future.

The rest of this chapter can be conveniently divided into three main sections. The first section looks at the drivers affecting spatial approaches to fisheries or aquaculture research or management-related work; the second section examines current issues and developments affecting work in GIS or remote sensing; and the third section discusses in some detail the emerging themes relating to spatial aspects of fisheries and aquaculture.

As there are many drivers that could affect the progress of fisheries or aquaculture, the concern here is only with identifying the main ones. The drivers are listed approximately such that they move from external towards internal, i.e. from those having indirect influences on the progress of fisheries or aquaculture towards those having more direct influences. Drivers themselves will be of differing importance according to local circumstances and, indeed, some drivers will be of no relevance at all in specific regions or areas. The main drivers identified are:

- Human population increases, and the consequent effects on food demand.
- Changes in atmospheric processes, mainly from climate change and its consequences.
- Contractually based supply chains, mainly for marketing, industry consolidation and quality control.
- Fuel and/or energy costs, which are increasing relatively rapidly.
- Education and information, which concern both the potential offered and how to accomplish the required activities best.
- Protein needs, food security and poverty alleviation, e.g. to help meet millennium development goals.
- Socio-economic development, including business opportunities and optimizing production locations and costs.
- Improving governance, relates to the need to improve the means by which fisheries and aquaculture are managed and controlled.
- Capital availability which may vary from time to time, from area to area, and between the public and private sectors.
- Changes in consumption preferences will impact upon production quantities among species.
- Ecosystem degradation and environmental awareness is linked to the recognition of sustainability and the essential need to improve many existing bio-physical systems.
- Freshwater access and availability, which throughout much of the world, is an increasing problem occurring at an accelerating rate.
- Stakeholder participation in decision-making meaning that, with an increasing move towards both EAA and EAF, a wider range of stakeholders will be involved in decision-making.
- Certification in fisheries and aquaculture is being applied in order to give certain quality guarantees in terms of sustainability, food sourcing, production fairness, etc.
- Genetic modification of aquaculture species is concerned with moves to develop species that have specific, desirable traits.

- The demise of many commercial wild fish stocks will oblige fishers to change their target species, and it will encourage greater aquaculture production.
- Global growth in aquaculture production, i.e. in much the same way as terrestrial agriculture expanded in earlier times, will cause significant impacts in a variety of ways.
- Controls on recreational angling mean that more regulation is likely to be imposed because in some areas recreational fish catches are probably exceeding commercial catches.
- Changes in fisheries management, e.g. as EAF and marine spatial planning expand and as stocks dwindle further, the scale of fisheries management will significantly increase.

In sum, the drivers affecting fisheries and aquaculture development show that their combined impacts are likely to be large and they will initiate many spatially related changes. But these are not the only factors driving changes in the use of spatial tools in the fisheries and aquaculture spheres. An array of developments and issues in the spheres of GIS and remote sensing is also driving change. Because GIS and remote sensing both function in a highly diverse yet integrated technological field, it is often difficult to isolate individual "driver components" of GIS or remote sensing. Nevertheless, this has been attempted in this section. Again, only the main points are listed here, with more detail being provided in the technical paper.

- **Continuing advances in computing environments.** This is a "catch-all" issue encapsulating the advances that are continually ongoing in the world of computing, and that show no signs of declining. On a world scale, these developments increasingly make GIS and remote sensing more accessible.
- **The development of new spatial tools.** These comprise a wide range of proprietary and open source software, plus "add-on" programs capable of performing an almost infinite array of tasks that aid in mapping and spatial analyses.
- **Improvements in remote sensing imagery.** Future imagery will improve in terms of resolution, cost reduction, parameters surveyed, image processing capabilities and image delivery times.
- **Maps as an ideal medium for communication (geovisualization).** Significant improvements in map availability and visualization will continue through initiatives such as Google Maps, in-vehicle navigation and other cartographic improvements.
- **Interactive GIS via the Internet.** The use of GIS over the Internet is increasing exponentially, and the ability of integrated mapping functionality through "hotlinking" is greatly aiding the dissemination of spatially based data and information.
- **Data ownership and acquisition.** Although this may be a problem area in terms of data ownership and costs, undoubtedly the availability of mapping is increasing exponentially.

- **Data gathering instrumentation.** A proliferation of spatial data will occur through both a wider choice of handheld GPS-based devices and through more complex satellite technologies, as well as through fixed and mobile marine sonar technology.
- **Advances in geostatistics and data spatial modelling.** Further major developments in GIS applications to fisheries and aquaculture will come in the coupling (or integration) of geostatistics and spatial models to GIS functionality.
- **Mobile GIS delivery.** A host of developments will continue that combine to produce computing environments where most GIS tasks can be accomplished "on the run" or away from a desk. This is in terms of both the portability of the technology and the previously mentioned optimization of small-screen visualization.
- **Continuing standards improvements for data collection and data transfer.** These developments will continue as a means towards more universal interoperability of all computing systems. However, progress is quite slow because considerations here must operate across a wide range of associated fields.
- **The seamless integration of data sets.** Important advances are being made in developing formats or structures allowing for seamless data set integration or in developing simple algorithms that permit differently structured data sets to be integrated.
- **Accuracy, uncertainty and errors in GIS.** A range of measures are being implemented to ensure that fisheries or aquaculture data, which are often prone to error or uncertainty, can be confidently accepted.

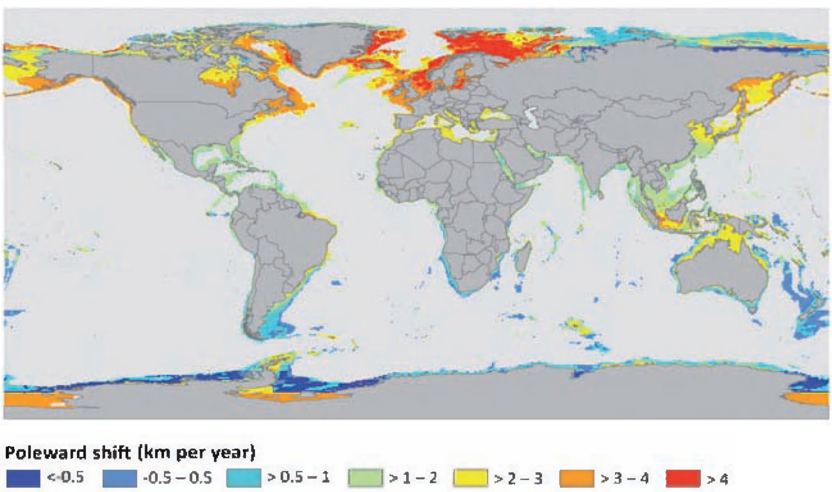
As a result of the previously described drivers, forces are continually driving change with respect to spatial factors relating to the broad subject areas of fisheries and aquaculture. Here, an attempt is made to identify and classify the main themes that are emerging as a result of these changes. It is of course difficult to precisely identify these themes and to speculate on the degree to which a theme can be said to be "emerging". However, it is likely that in many cases themes will be an extension of current work and that they will form the core of future spatially related work. Discussion of themes that have already been described in Chapters 8, 9 and 10 are omitted, and again emerging themes are simply listed in no particular order.

- **The production of different aquaculture species.** There are currently three lines of debate with respect to the optimum species for aquaculture production: (i) should farmed production concentrate on higher trophic level species with the food resources coming from the sea; or (ii) should production concentrate on lower trophic level herbivorous species, thus reducing energy inputs and losses; or (iii) should consumer food preferences alone determine aquaculture production choices? Whatever thinking prevails, there will be strong spatial implications for production location choices and for future fish marketing, both of which will provide opportunities for GIS modelling and analyses.

- **The potential impacts of aquaculture on the environment.** Although an older issue, this subject will become increasingly important as aquaculture continues to expand and intensify, and as the need for environmental controls become more stringent and diverse. It must also be recalled that this is a two-way process, with the environment affecting aquaculture and aquaculture affecting the environment, and both processes can operate over wide spatial areas. The technical paper gives details on the range of environmental disturbances that may occur, the means that farmers can use to reduce environmental impacts, and some ways in which GIS can be utilized in helping to achieve this impact reduction.
- **Management of freshwater resources for aquaculture.** Because of climate change, increases in human population and the consequent need to increase food production, the availability of freshwater in many regions is a rapidly increasing challenge. As water security is a top priority for inland aquaculture, planning for the constant availability of this is a task that GIS can assist in, especially with respect to the modelling associated with spatial differentiation in water supply availability. If aquaculture gradually adopts methods that use water recirculation systems, then this too will have repercussions on alternative location preferences for fish farming.
- **Offshore mariculture.** Recent technological developments are now allowing mariculture to be successfully accomplished in what were previously relatively hostile environments for aquaculture, i.e. open coastal waters. The opportunities for production expansion here are very large indeed, but in view of the number of human, biological, physical and meteorological variables involved, locations will need to be carefully optimized through marine spatial planning and GIS-based analyses (Kapetsky, Aguilar-Manjarrez and Jenness, 2013).
- **Growth of inland fisheries and recreational angling.** Inland fisheries and recreational angling show a number of similar characteristics. They are both extremely widespread activities, often practised in relatively remote areas, usually practised on a small-scale, have relatively limited management constraints, and little reliable data are available on the scale of the activity in terms of fish catches and production uses. However, it is reliably surmised that the activities are increasing and fish restocking is more frequently necessary. Given the very obvious spatial components associated with these activities, it is clear that the future opportunities (and indeed necessity) for spatially based management are hugely significant.
- **The consolidation of the fishing and aquaculture industries.** Although there are some moves towards a reduction in scale of both capture fisheries and aquaculture activities, when examined holistically both sectors are witnessing production consolidation and a growth in enterprise size. This is largely being achieved through various horizontal and vertical integration movements designed to achieve economies of scale. Clearly, these movements will have a strong influence on the spatial dispersal of various sectors of both the fishery and aquaculture industries, and the direction of these movements may best be optimized through spatial analyses.

- **Rebuilding depleted marine and freshwater stocks.** Although freshwaters in many regions have a long tradition of being restocked when necessary, this has not been common in marine waters because of factors relative to costs, uncertainty, the scale required and the difficulty of measuring success. However, as marine stocks especially become increasingly endangered, the incentive towards restocking grows. But the spatial complexities of doing this, and in calculating the necessary carrying capacity of waters concerned, may be extremely complex and indeed are becoming more so with increasing ecosystem changes and with the effects of climate change. For example, Pereira *et al.* (2010) predict latitudinal range shift for demersal marine species of up to 4 km per year from 2005 to 2050 (Figure 11), and that pelagic species will migrate even faster because of higher surface water temperatures. Success for restocking might only be achieved through the fairly sophisticated use of both remote sensing and GIS techniques.
- **The recording of fishing vessel activities.** In an era when both overfishing and illegal fishing are commonplace, there are a number of reasons why fishing vessel activity might be recorded. The technical paper describes a variety of reasons and methods for collecting fishing activity data. Thus, as well as basic vessel monitoring systems that rely on satellite recordings of vessel locations, there are now moves in many countries to instigate fisheries electronic logbooks. These can provide detailed data on catches by species, fish landings, fishing methods, locations of activities, etc., and these data represent very useful inputs to GIS for both research and management purposes.

FIGURE 11
Predicted latitudinal shift of demersal marine organisms between 2005 and 2050 as caused by climate change (excluding areas > 2 000 m in depth)



Source: Pereira *et al.* (2010).

- **Evaluating fisheries management practices, including sustainability.** Over the past half century, the management of capture fisheries has become an increasingly complex subject. This has partly arisen because management has too often been unsuccessful, with many stocks continuing to decline, and thus there has been the need to incorporate ever more management measures. Because these measures almost all involve spatial considerations, then in an electronic era it is unsurprising that GIS has materialized as a potentially useful tool. For the present, most evaluation of management practices occurs in the form of government directed research, but increasingly the use of GIS is permeating down so that it becomes a useful tool at fishing company level, or even at individual vessel level. In many cases, it is sustainability issues that are promoting these more sophisticated management practices.
- **Threats and changes to marine and freshwater ecosystems.** Continuing human population growth allied to rising resource consumption is having a negative impact on a range of aquatic ecosystems. The main threats to such ecosystems include: (i) vast accumulation of plastic within large oceanic gyres; (ii) severe oxygen depletion in assorted aquatic systems and areas; (iii) an increasing range of biosecurity problems; (iv) climate change and the threat of rising sea levels, increased storminess, marine acidification, species home-range shifts, and marine invasions of exotic species; (v) various forms of pollution; and (vi) flow modifications in rivers. All of these perturbations have a strong spatial component, thus allowing for GIS-based investigations or management.
- **The standardization of habitat (and other) classifications.** Because the world in which fisheries or aquaculture functions is so complex in terms of social, economic and environmental considerations, then in order to research any specific theme or issue the researcher is obliged to utilize simplification through the classification of virtually all data held. In order to give any classification used more utility, there is a move towards the standardization of data descriptions and classification classes. Two examples of standardization are in the categorization of marine habitats and of bottom sediment classes. There are many debates in progress aiming to agree to international data standardization, and when agreements are reached then the usefulness of GIS analyses will be greatly increased.
- **Working at variable scales and resolutions.** Data on aquatic environments are now being collected and accumulated at an accelerating rate; the tendency is for such data to have a greater range of resolution, with more emphasis being given to data at a smaller resolution, i.e. because data can be usefully converted from small to large resolution, but not in the other direction. With improvements in resolution, which is also associated with data collection from a wider range of parameters, the field opens up for a far broader range of potential studies and therefore of GIS-based analyses. These developments will be especially important to increasing EAF and EAA work that must consider parameters whose data collection scales are likely to be highly variable.

- **Studies of temporal change in fisheries and aquaculture thematic areas.** It seems highly likely that considerable efforts will be made in the immediate future to study temporal changes with respect to both fishery and aquaculture themes. This becomes increasingly possible now that data sets covering comparatively long time periods are accumulating. There is much value to be had from studies examining changes through time or that can assess the validity of some of the early GIS and/or remote sensing work in terms of its methodology and outcomes.

12. Overcoming the challenges to fisheries or aquaculture GIS work

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Given the range of thematic areas that are encapsulated within the broad areas of "GIS", "fisheries" and "aquaculture" and the spectrum of knowledge that must be utilized, it is unsurprising that there will be challenges to working within any of these areas. Challenges are exacerbated by the requirement to be working in a three-dimensional environment that may be in constant motion and where the scale of the data needs is extremely large, certainly when compared with the majority of terrestrial GIS work. This chapter describes the nature of the main challenges and provides clues as to how these challenges might be overcome. Although challenges may be broadly considered as being intellectual or theoretical, practical or organizational, economic, or social and cultural, here they are considered in subsections derived from these headings.

(i) **Mapping moveable variables.** In aquatic environments, not only do most of the objects being mapped move, but the environment itself (the water) also moves. This creates obvious challenges for mapping, but they are reduced for aquaculture as most mapping is of fixed or permanent features. Attempts, however, must be made to map moveable species or objects because without doing this little marine-based GIS work could be achieved. For many marine-based movements there are degrees of regularity, many of which can be estimated, e.g. diurnal or seasonal migrations or large-scale ocean currents and tides, and therefore generalized maps can be drawn. The real challenge is to map chaotic movements, though even these can often be modelled such that at a coarser scale they can be tentatively mapped. Alternatively, data for mapping may be gathered at short time intervals allowing temporal mapping. Advances in data gathering, such as the use of tagging to gather data movements against time, now contribute significantly to the development of movement prediction models. However, considerable thought must always be given by the GIS user to the optimum resolution or scale at which GIS-based work involving movements is best carried out.

(ii) **Multiple scale and resolution.** Scale is concerned with the relationship between the mapped distance or area and the corresponding real-world size or area, whereas resolution is concerned with the smallest size of a feature that can be mapped or measured. Both should incorporate a spatial and temporal dimension. The movement and size of aquatic environments or objects takes place across a large spectrum of scales and resolutions, and there is a long history of discussion on the appropriateness of the scale of study. For marine-based GIS work, data may be gathered at a range of scales or resolutions, and throughout the technical paper examples of work at varying scales have been given. Finding the optimum scale or resolution for a particular project may only be obtained by trial and error (experience), though the geographic area and the marine processes involved will provide obvious clues. Caution is given about the use of data for a single project that has been gathered at highly variable scales, i.e. because when data sets are integrated the value of the results may only be as good as the coarsest data used. With the advent of increasing EAF or EAA work, it is likely that scale or resolution challenges will be enhanced because a greater range of data inputs will have been gathered according to mixed spatial criteria.

(iii) **Handling 2.5D, 3D and the 4th dimension.** Whereas most terrestrial GIS work is confined to two dimensions (plus the 4th time dimension), for marine-based work it may be necessary to consider both the 2.5 and the third dimension. The difference between these is that in the 2.5D objects are fixed to the marine seafloor, which can be of varying depth, whereas in 3D objects can be of any variable depth on the z axis. While many GIS have the capacity to operate within these dimensional variations, the main challenge is to obtain mapped output that can be meaningfully interpreted in all dimensions. There are also other significant challenges with respect to the large data requirements for 2.5D or 3D work. The technical paper provides examples of how 2.5D and 3D mapping is being achieved and, in many cases, this is best accomplished by sequential spatial or temporal "animated mapping", i.e. as used in cine-films.

(iv) **Application of spatial models and statistics.** What is being considered here is the use of GIS as a software platform or activity surface on which numerical models, usually in the form of equations, may be conceived, evaluated or tested. Once established, a model can be used again in similar situations (or at different times), having been, for example: (i) suitably adjusted to suit perhaps different species; or (ii) through changes in geographic area; or (iii) with the addition of extra variables; or (iv) with adjustments to the weighting of variables. Models can be run on specialized software and then integrated into most GIS, or they can be run directly within a GIS. The challenges to model use can be in their requirements for the use of advanced mathematics and statistics, in identifying the best combination of variables to be included in the model or the problem of spatial and temporal autocorrelations and the identification of true dependence or independence between variables, and in securing statistical significance of the data being used. To overcome challenges relating to modelling, it is recommended that familiarization with, and use of, some of the spatial analysis tools be made.

(v) **Optimizing visualization and mapping methods.** GIS output is conveyed via tables, graphs and dominantly maps. In order that these illustrative methods convey a clear message, it is important that the message is accurately depicted and perceptually easy to synthesize. Good quality maps should follow basic rules concerning, for example, legend construction and content, scale delineation, number of classes used, word placement, etc, though there is freedom to accommodate individual mapping styles and preferences. The challenge for GIS workers is in achieving cartographic output having acceptable and comprehensible visual qualities. Most GIS have a range of acceptable output styles, but GIS workers have to use discretion with regard to factors such as classification ranges, font style and placement, colour mixes and the range of data to convey. A problem to achieving success with visualization is that individuals have widely varying perceptions as to what constitutes good quality mapping. The technical paper gives suggestions on mapping considerations and advice on where additional guidance can be obtained.

(vi) **Integration of socio-economic considerations.** The need to integrate social and economic considerations into EAA- or EAF-based management means that a sustainable future for fisheries or aquaculture can only be achieved if recognition is given to matters such as the provision of employment, the availability of labour, the benefits of sustaining local communities, dietary advantages of secure food supplies, and the achievement of equity in the use of marine space. This integration of socio-economic data presents additional challenges to GIS work because much of the data is difficult to classify, values may be hard to measure, social data are scarce in many areas, participants in projects may be reluctant to divulge data, mapping boundaries to social or economic classes is difficult, and some data can only be subjectively evaluated. It is likely that initial EAF or EAA work will be "exploratory,"in the sense that experimentation or conjecture will be needed with "trial-and-error" techniques being used. This being the case, it will be useful if early projects can be undertaken where there is some degree of certainty about GIS results, i.e. until such time as experience has been acquired. It will also be useful if experience can be shared between groups, and if alliances with other GIS groups can be formed so as to share learning and information in social and economic concepts, issues, methods and resources.

(vii) **Data gathering and assembling.** Although data acquisition has long been a challenge to GIS work, it still remains a prime challenge. There are a number of reasons for this, including: (i) the relatively large costs involved; (ii) uncertainty on the exact nature of some data requirements; (iii) the difficulty in acquiring exact data requirements; (iv) the uncertain quality of data accessed; (v) the precision of the data available; (vi) the standards required in terms of structure, format, projections and classifications; and (vii) can statistically valid data be provided? Further details on problems associated with adequate data acquisition are given in Chapter 3 and in Box 12.1 of the technical paper. There is little doubt that significant advances are being made in data acquisition, with data gathering systems and data sources growing at an exponential rate. But with the growth in the range of requirements for GIS work occurring at ever-increasing scales and resolutions, then for some time the challenge of data provision may continue to be one step ahead of meeting data needs.

(viii) **Subject breadth and organization.** Although each of the areas of "GIS", "aquaculture" and "fisheries" are clearly identified subject areas, their existence is essentially linked to other main subject areas, including oceanography, marine ecology, climatology, agriculture, biology, remote sensing and branches of information technology and marine construction. Working in this breadth of applications areas increases the complexity of the work undertaken in terms of the overall knowledge required, the linkages and communications channels, and the range of information and data that might be required. Added to this there are now considerations relating to marine spatial planning and EAF and EAA. Most of the GIS-based work being pursued in fisheries and aquaculture is small-scale and undertaken in scattered private and public companies and institutions, and these conditions are not always conducive to optimizing the chances of successful and well-tested applications. Chapter 4 of the technical paper provides significant detail on the range of support being offered in the disparate subject areas. The various technologies associated with the Internet as a vehicle for information acquisition, for data exchange, and for interactive GIS also serve to reduce the challenges of subject breadth, fragmentation and isolation that were previously more prevalent.

(ix) **Work management and control.** Challenges associated with work management and control mainly occur at the scale of an individual GIS worker or smaller organization. Because so much GIS work in fisheries or aquaculture is pursued in smaller organizations, it means that GIS project groups will be small, with workers being obliged to carry out all or most of the many necessary tasks and to have a high degree of initiative. The challenge here then is in keeping up with developments, scheduling the work, getting access to support, and usually dealing with a wide range of people and possible problems. Challenges are helped if robust management support is available, and by having formed links with other GIS groups engaged in similar aims, having a good knowledge of avenues for external advice and having the time and resources to attend courses, conferences, and workshops plus other forms of networking. If the optimum working milieu cannot be established, then other solutions to obtaining GIS functioning may be sought through linking with other institutions or departments or through contracting out any GIS work.

(x) **Promotion of GIS output.** There is concern that the use of GIS does not receive the promotion that it deserves, i.e. with respect to the utility of the software and the scale of the spatially based problems associated with worldwide fish production. Reasons for this include: (i) the specialized nature of the work; (ii) GIS output is usually only promoted in the grey literature; (iii) there are few conferences or workshops to showcase GIS work; and (iv) because GIS is only a problem-solving tool for spatial analyses, then it is the problem itself that attracts most attention. Additionally, the majority of GIS output is only passed on to decision-makers and thus it may receive little recognition. Given the potential scale of problems confronting aquaculture and fisheries, it is vital that these challenges to adequate promotion are met. Although there are relatively few hard copy publications or relevant conferences and workshops, it is likely that the growth of the Internet will be the significant spur to promoting GIS, and, indeed, this is already happening through FAO's GISFish Web site, through interactive fisheries and other biological data mapping, through numerous online videos and through interactive aquaculture-based simulations. Additional spurs to GIS work in fisheries and aquaculture will come through the increased needs for marine spatial planning and for EAF and EAA related projects, through the spread of suitable spatial and geostatistical models, and through the establishment of marine conservation zones.

(xi) **Expenses associated with fisheries and/or aquaculture GIS.** A theme occurring throughout the technical paper is that the implementation and pursuance of fisheries or aquaculture GIS might be an expensive applications area. Thus, apart from initial capital costs of establishing the system itself and securing trained personnel, there are likely to be significant costs associated with data acquisition. Data costs could be high owing to the expense of gathering data in widespread marine aquatic environments, plus the costs of acquiring satellite imagery and other digital data sets. Continuing operating costs can also be high, especially in developing countries that might have to pay "western prices", and, indeed, high costs could be proving a barrier to even acquiring knowledge about GIS. Challenges associated with costs can be overcome by implementing GIS at a low and/or relatively simple scale, sharing computing facilities with other compatible users, obtaining free and open source software (FOSS), seeking data sets on the Internet, and approaching companies, public authorities, or universities for any free or low-cost digital data.

(xii) **Obtaining funding.** Though fisheries are an extremely widespread activity, supporting hundreds of millions of people worldwide, the fact that they mostly take place on a small-scale or as semi-subsistence activities mean that surplus funding is seldom generated. Any funding obtained is unlikely to be on a large scale, and the future of funding may depend on the perceived output results from the GIS project. The likelihood of GIS and/or remote sensing work proliferating (and thus being funded) will probably be much higher if these tools can be integrated as essential elements of wider projects. Funding for fisheries GIS must usually be obtained from government sources or through various types of donor support. In recessional times, this funding may dry up completely. Because cost–benefit analyses showing the value of GIS work are difficult to substantiate, this too prevails against easy access to funds. The challenge for the GIS enthusiast might therefore be to convince his or her organization that GIS is very much more than a "luxury, peripheral add-on". The challenge can be met through the production of high-quality visual output that is well appreciated and understood, and through an added appreciation that most problems derive from an imbalance in the spatial domain and that the needs for marine spatial planning, EAA and EAF are a tacit recognition of this. The financial outlay on GIS may be a small price to pay compared with the enormous challenges faced from rapidly dwindling fish stocks.

(xiii) **Overcoming inertia relating to the cultural ambience.** The social or cultural ambience of a country, region or even a workplace can have a major effect on the acceptance of technological innovations. For instance, in inward looking or closed societies or in circumstances where outdated or entrenched attitudes may persist, there may be very few people emerging who are able to act as "champions for GIS" and who can therefore promote the use of these digital systems. So, there may be little familiarity with GIS or, indeed, the circumstances where it might prove to be useful. Also, there is often reticence about passing on or accumulating data with regard to fish catches and capture locations. So, in some areas information systems still have little relevance to existing cultural norms. These challenges might best be met by a "top-down" approach, where senior management, or experts from external agencies, brief a workforce on advantages that a technology offers, and in turn this information is disseminated throughout an organization or working group. Alternatively, a "bottom-up" approach may be adopted, whereby a demand for change is engineered from within an organization, perhaps by a middle-level employee who has gained access to GIS knowledge via education or through the Internet. A further alternative is through getting fishers or aquaculturists to work with scientists as a means of appreciating their often opposing perspectives on the management of their activities.

(xiv) **Gaining support and advice.** Support for GIS and/or remote sensing work will be much higher if these tools: (i) can be integrated as essential elements of wider projects (e.g. on climate change implications for fisheries and aquaculture, or strategic planning for offshore mariculture development); (ii) can focus on issues/themes that illustrate the many benefits that GIS can provide to support problem solving and decision-making; or (iii) can be designed to match the needs, interests, finances and capacities of the target users or stakeholders.

(xv) **Transcending political or international boundaries.** It is clear that there will be little relationship between areas demarcated by designated political boundaries and those areas in which fish species inhabit. This duality of marine space division (political jurisdiction versus natural ecosystems) may lead to challenges with regard to resource management, especially where more mobile marine species are concerned. Important implications for GIS work occur in terms of setting spatial boundaries for analyses, acquiring funds for joint projects, for the management and content of projects and for data resourcing. Many attempts have been made to achieve regional fisheries cooperation between neighbouring countries or within groups of neighbouring countries, for example, the European "Common Fisheries Policy"or the 17 regional fisheries management organizations controlling the high seas. However, most of these attempts at cooperation have been unsuccessful. The challenges of transcending political differences are likely to be ameliorated through the necessity of collective working, e.g. on EAA, EAF or marine spatial planning projects.

(xvi) **Developing geographic cognition and spatial awareness.** This challenge refers to an appreciation of geographic thinking and perception. Thus, a person with good geographic cognition is able to recognize factors such as: (i) spatial patterns in the landscape, e.g. clustering, ubiquity, adjacency; (ii) they can visually discriminate the implications shown by any mapped distributions; (iii) has a sound knowledge of local geography and geographic relationships; (iv) is aware of the locational suitability for various types of activity; or (v) is aware of spatially variable production functions that might control fisheries or aquaculture production. These kinds of abilities allow GIS workers to have an instinct for the type of work that a GIS project could best accomplish, or they may get a feel for whether GIS output is likely to have validity. Related to this is the appreciation that problems affecting fisheries or aquaculture are likely to be rooted in spatial differentiation, i.e. that different locations have favourable or unfavourable abilities to provide for the essential factors of production, with location being the key to business success. This challenge must be met through workshops, conferences, reports, books, etc., all placing a greater emphasis on spatial awareness and geographic understanding, and, indeed, these ideas are slowly emerging through concepts such as marine spatial planning and through the rapid spread of geographic technologies such as Google maps, in-vehicle navigation systems, global positioning systems and the emergence of the GeoWeb environment, i.e. a relatively new term that implies the merging of geographical (location based) information with the abstract information that currently dominates the Internet.

13. Conclusions

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In the foreword to FAO's flagship fisheries publication, *The State of World Fisheries and Aquaculture* (FAO, 2010b), there is an encouragement for "actors at all levels in the (fisheries and aquaculture) sector to make better use of the Internet, GIS, remote sensing and other technological advances to safeguard biodiversity and ensure a sustainable future for the sector"; it is broadly these factors that are addressed by this publication. Within the context of fisheries and aquaculture, it has been necessary to delve into a wide range of subsectors of these broad subjects, with the aim being to provide sufficient explanation that allows newcomers to GIS and remote sensing to readily comprehend what is being explained. This publication has enabled two previous FAO publications in fisheries and aquaculture GIS (Meaden and Kapetsky, 1991; Meaden and Do Chi, 1996) to be updated and considerably expanded, and it is to be hoped that this present publication can make a greater impact towards achieving sustainability for fisheries and aquaculture. Given the fact that EAA, EAF and marine spatial planning philosophies are now prevailing, it is necessary to think more broadly about the spatially based challenges to optimizing productivity from aquatic resources.

Within the marine spatial planning context, the European Union (European Commission, 2012) has recently identified six maritime functions that need to be integrated into marine spatial planning work: (i) maritime trade and transport; (ii) food, nutrition, health and ecosystems services; (iii) energy and raw materials; (iv) living, working and leisure in coastal regions and at sea; (v) coastal protection and nature development; and (vi) maritime monitoring and surveillance. It is likely that most future approaches to managing marine areas will be required to integrate all or most of these functions, and there is no doubt that GIS will be the technological basis on which this management will best function. Thus, the majority of challenges faced by these functional areas have a strong spatial component, and the use of GIS in the terrestrial domain has very adequately proved its functional capabilities and success. Additionally, examples have been provided in many places in the technical paper (e.g. Chapter 12) to show how GIS is now able to cope with the demands of most spatially based analyses in the challenging marine and aquaculture spheres.

However, the use of GIS and remote sensing in the fisheries and aquaculture fields still faces challenges associated with a knowledge of its capabilities and potential. At the present time, much of the fisheries- or aquaculture-based GIS output comes from the United States of America. The reasons for this are discussed and, given the overall resources it has, in many ways its dominance is not surprising. There are now indications that other countries are beginning to make headway with GIS work, especially in the aquaculture field. Most of the emerging GIS work is coming from the newly developing countries, especially those in East and South Asia, and because these areas face huge challenges in terms of population pressures, rapid rates of development, resource depletion, environmental degradation and competition for freshwater, then the incentives to utilize GIS will be constantly reinforced.

In countries where development is typically slower, although GIS studies for both fisheries and aquaculture are beginning to appear, little of this work is being published or promoted. In order to promote further GIS work, capacity-building measures need to be put in place allowing for the necessary infrastructure to be available to support enhanced GIS expertise and infrastructure. It is important that GIS capability is available to allow the multidisciplinary work associated with EAA and EAF to be pursued. For the least developed and more remote regions of the world, it may be some time before the widespread use of spatial technologies for fisheries and aquaculture development and management is achieved. However, except for a few core heartland areas, this remoteness, lack of population, lack of infrastructure and therefore lack of need mean that there will be little necessity for GIS capabilities.

The technical paper has placed considerable emphasis on how GIS might best be initiated. This includes a detailed chapter on the necessary stages for successful GIS implementation and another chapter on meeting GIS challenges. The conclusion chapter reinforces this by providing a table with the main answers to the question: "What is the way forward to successful GIS work?" The table differentiates between "establishing the existing situation" and "establishing an enabling capability", and for both these areas the large number of suggested tasks is likely to initiate further questioning, research or investigation. The answers to many of the suggested tasks are, indeed, provided in this technical paper.

Wherever GIS or remote sensing methods are used, it is essential to remember that these applications work at a wide variety of scales. "Scales" can be viewed in two main contexts:

- Functional or operational scales relate to the size of a GIS operation in terms of investment and personnel employed. This varies between the "personal area network" and upwards to a "wide area network" scale. Because there is an easy ability to upgrade GIS systems when required, there is no need to begin GIS or remote sensing work at a sophisticated level.
- The geographic area covered by a project could vary from a localized scale to a world scale. The technical paper has provided examples or GIS case studies of all different scale areas. The ability to utilize GIS and remote sensing across different spatial scales is extremely useful in terms of data inputs to GIS, in terms of geographic cognition, and as a means of initiating collaborative working with neighbouring regions or countries.

The production of fish demanded in a more affluent world whose population is increasing by 80 million per year will pose a significant challenge. Meeting this challenge will certainly involve more stringent management and research, plus more complex forms of management that incorporate the broader concepts embedded in EAA, EAF and marine spatial planning. From the foregoing material in this technical paper, it is easy to envisage that the challenge will be met through the use of a suite of fisheries and/or aquaculture management tools, many of which will be linked to GIS because of its unique capacity of spatial analysis in conjunction with providing output in a range of easily comprehensible tables, maps and graphs. Because GIS has the capability to function at a huge variety of degrees of sophistication, it will be capable of being adopted almost universally. This is a technology that deserves to be enthusiastically promoted.

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Annex 1

Table of contents of full publication

AVAILABLE ON ACCOMPANYING CD–ROM

This publication is an essential guide to understanding the role of spatial analysis in the sustainable development and management of fisheries and aquaculture.

This technical paper is an easy-to-understand publication that emphasizes the fundamental skills and processes associated with geographic information systems (GIS) and remote sensing. The required spatial data and computer hardware and software are outlined, as well as the considerations necessary to implementing a GIS. Current issues, status and applications of GIS and remote sensing to aquaculture, inland fisheries and marine fisheries are described to illustrate the capabilities of these technologies.

Emerging thematic issues having a spatial context in fisheries and aquaculture in the near future are also described, and finally useful clues as how best to overcome challenges to accomplishing GIS work are addressed.

This publication is organized in two parts to inform readers who may be at varying levels of familiarity with GIS and remote sensing. One part is a summary version and is addressed to administrators and managers, while the other is the full document intended for professionals in technical fields and for university students and teachers. The full document is available on a CD–ROM that accompanies the summary version of the publication.