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552

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

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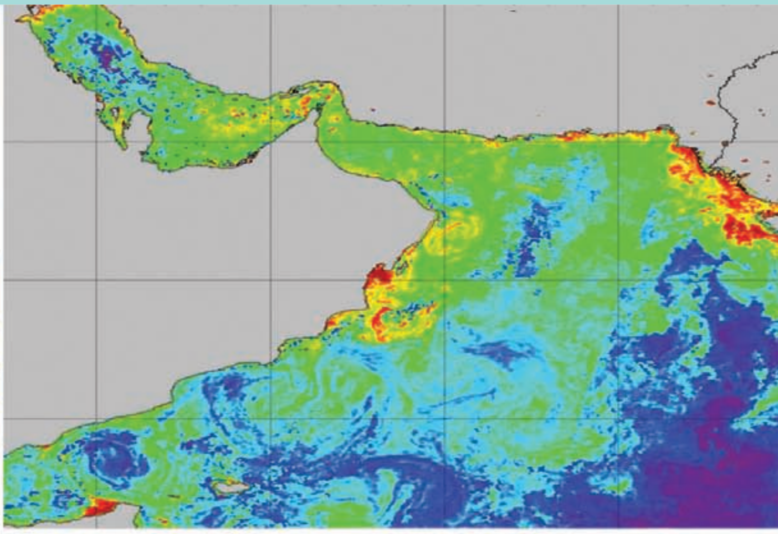

Cover photos:
Clockwise from top left: Double-rigged shrimp trawler with cod end of one net about to be opened (courtesy of Robert K. Brigham, NOAA's Fisheries Collection); Chlorophyll concentrations in the Gulf of Oman region (courtesy of ACRI-ST InfoceanDesk environment monitoring service from EU FP7 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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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 in this CD–ROM.

Meaden, G.J. & Aguilar-Manjarrez, J., eds. 2013.
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Abbreviations and acronyms

ALOS	Advanced Land Observing Satellite (from JAXA)
AOI	area of interest
ASAR	Advanced Synthetic Aperture Radar (from ESA)
ASFA	Aquatic Sciences and Fisheries Abstracts (FAO)
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
AUV	autonomous underwater vehicles
AVHRR	Advanced Very High Resolution Radiometer (from NOAA)
AVISO	Archiving, Validation and Interpretation of Satellite Oceanographic Data
AWRD	African Water Resource Database
CAD	computer-aided design
CASI	Compact Airborne Spectrographic Imager
CEFAS	Centre for Environment, Fisheries and Aquaculture Science
CHARM	Channel Habitat Atlas for Resource Management
CNES	Centre national d'etudes spatiales (French space agency)
COAs	conservation opportunity areas
COML	Census of Marine Life
CPU	central processing unit
CRFM	Caribbean Regional Fisheries Mechanism
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CZCS	Coastal Zone Color Scanner
DBM	database management
DEM	digital elevation model
DMBS	database management systems
DMC	Disaster Monitoring Constellation
DO	dissolved oxygen
DSL	digital subscriber line
DTL	digital terrain model
EAA	ecosystems approach to aquaculture
EAF	ecosystems approach to fisheries
EEZ	exclusive economic zone
EIA	environmental impact assessment
EMR	electromagnetic radiation
EOS	Earth Observing System (from NASA)
ERS	Earth Resources Satellite (from ESA)
ESA	European Space Agency
ESL	Environmental Simulation Laboratory
ESRI	Environmental Systems Research Institute
FAN	FAO Aquaculture Newsletter
FAO	Food and Agriculture Organization of the United Nations
FIRA	FAO Fisheries and Aquaculture Department Aquaculture Branch
FOSS	free or open source software
FTP	file transfer protocol
GAP	good aquaculture practices or Gap Analysis Program
GHRSST	Group for High Resolution SST
GIS	geographic information system
GISFish	Global gateway to geographic information systems, remote sensing and mapping for fisheries and aquaculture
GOES	Geostationary Orbiting Earth Satellites
GPS	global positioning systems
GUI	graphical user interface
HAB	harmful algal bloom
HF	high frequency radar
HSI	habitat suitability index
ICES	International Council for the Exploration of the Sea

IFREMER	Institut Francais de Recherche pour l'Exploitation de la Mer
IMTA	integrated multitrophic aquaculture
IOCCG	International Ocean-Colour Coordinating Group
IRS	Indian Remote Sensing
ISO	International Organization for Standardization
ISP	Internet service providers
IT	information technology
IUU	illegal, unreported and unregulated
JAXA	Japan Aerospace Exploration Agency
LAN	local area network
LANDSAT	Land Remote-Sensing Satellite
LDCM	Landsat Data Continuity Mission
LEACAT	Lynx Exploration Archivist Cataloguing and Archiving
LiDAR	light detection and ranging
MCE	multi-criteria evaluation
MERIS	Medium Resolution Imaging Spectrometer
MESH	Mapping European Seabed Habitats
MGET	marine geospatial ecology tools
MIRAS	Microwave Imaging Radiometer with Aperture Synthesis
MODIS	Moderate Resolution Imaging Spectroradiometer
MPA	marine protected area
MSI	Multispectral Imager
MSP	marine spatial plan
NACA	Network of Aquaculture Centres in Asia-Pacific
NASA	National Aeronautics and Space Administration
NASO	National Aquaculture Sector Overview
NEST	Next ESA SAR Toolbox
NOAA	National Oceanic and Atmospheric Administration
OCM	Ocean Colour Monitor
OSGeo	Open Source Geospatial Foundation
OSTM	Ocean Surface Topography Mission
PALSAR	Phased Array L-band Synthetic Aperture Radar
PAN	personal area network
PDA	personal digital assistant
PSU	practical salinity units
RFMO	Regional Fisheries Management Organization
ROV	remotely operated vehicle
SAR	synthetic aperture radar
SeaWIFS	Sea-viewing Wide Field-of-view Sensor
SMOS	Soil Moisture and Ocean Salinity
SPEAR	Sustainable options for People, catchment and Aquatic Resources
SPOT	Systeme Pour l'Observation de la Terre
SQL	standardized query language
SST	sea surface temperature
SWH	significant wave height
TIN	triangulated irregular network
TIROS	Television Infrared Observation Satellites
TOREDAS	Traceable and Operational Resource and Environment Data Acquisition System
TSM	total suspended matter
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
UPS	uninterruptable power supply
USB	universal serial bus
USGS	United States Geological Survey
UTM	Universal Transverse Mercator
UVS	underwater visual census
VMS	vessel monitoring systems
WAN	wide area network
WCMC	World Conservation Monitoring Centre
WGS84	World Geodetic System 1984

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

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

1.1 SPATIAL CHALLENGES CONFRONTING FISHERIES AND AQUACULTURE

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

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

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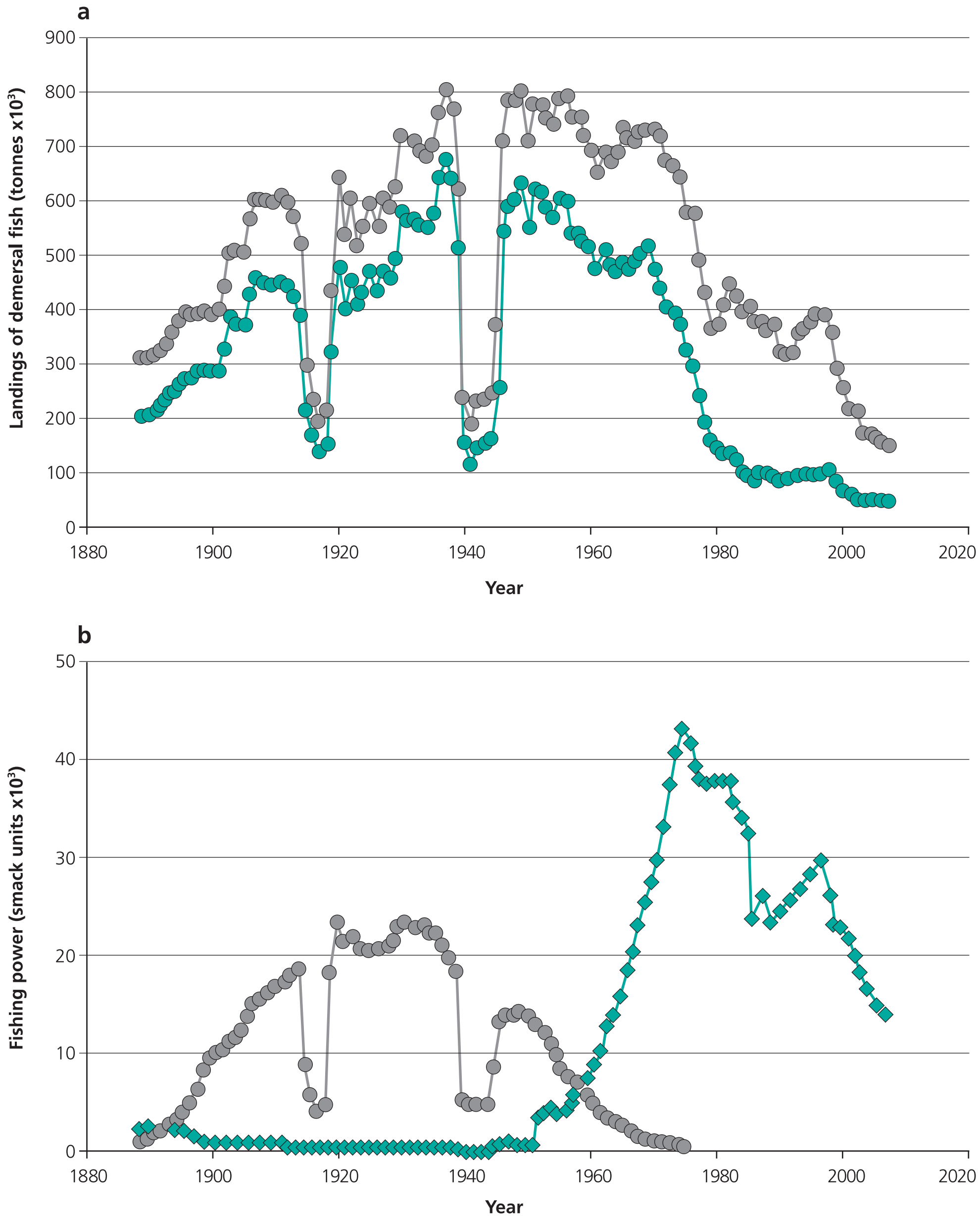
1 Unless otherwise stated, the term "fishery" in this technical paper will refer to both marine and inland fisheries.

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

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

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

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



Source: Thurstan, Brockington and Roberts (2010).

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

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

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

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

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

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

BOX 1.1

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

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

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

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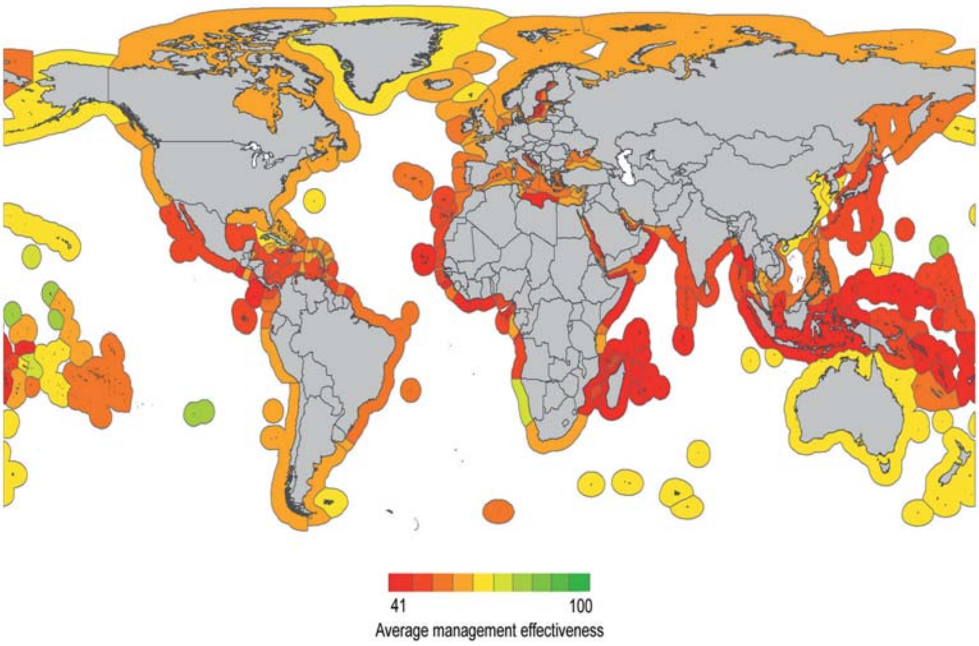
6 Examples of poor or inappropriate management include: lax or insufficient legal enforcement powers; poor catch recording including under-reporting; excessive discarding in order to attain legal quotas; over-generous subsidies to support fisheries growth; insufficient incentives for fishers to decommission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

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

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

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



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

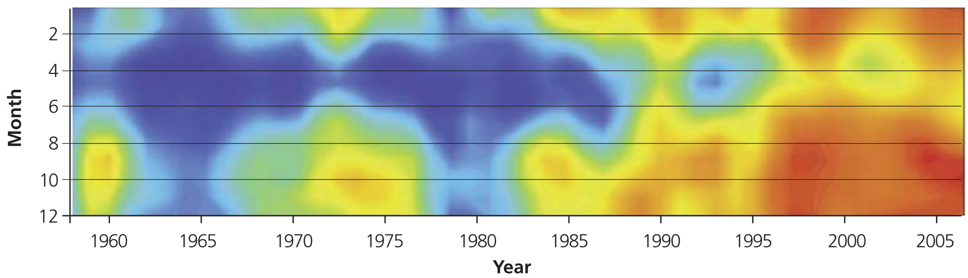
To add to these basically anthropogenic and/or institutional problems, it is likely that fisheries are experiencing problems from sources that are not within their direct control, i.e. so-called external factors. These include matters such as climate change,

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

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

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

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



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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

1.2 WHAT ARE GEOGRAPHIC INFORMATION SYSTEMS?

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

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

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

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

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

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

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

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

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

BOX 1.2

The operational characteristics of a modern GIS

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

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

Source: Updated from Lo and Yeung (2002).

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

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

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

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

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

BOX 1.3
Major application areas for GIS

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

1.3 THE EMERGENCE OF GIS AS A SPATIAL TOOL

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

1.3.1 A brief history of GIS

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

Early innovations (1960–1980)

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

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

Era of commercialization (1980–1995)

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

BOX 1.4

Examples of early GIS innovation projects

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

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

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

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

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

Era of mass exploitation (1995–present)

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

1.3.2 Reasons for the growth in GIS

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

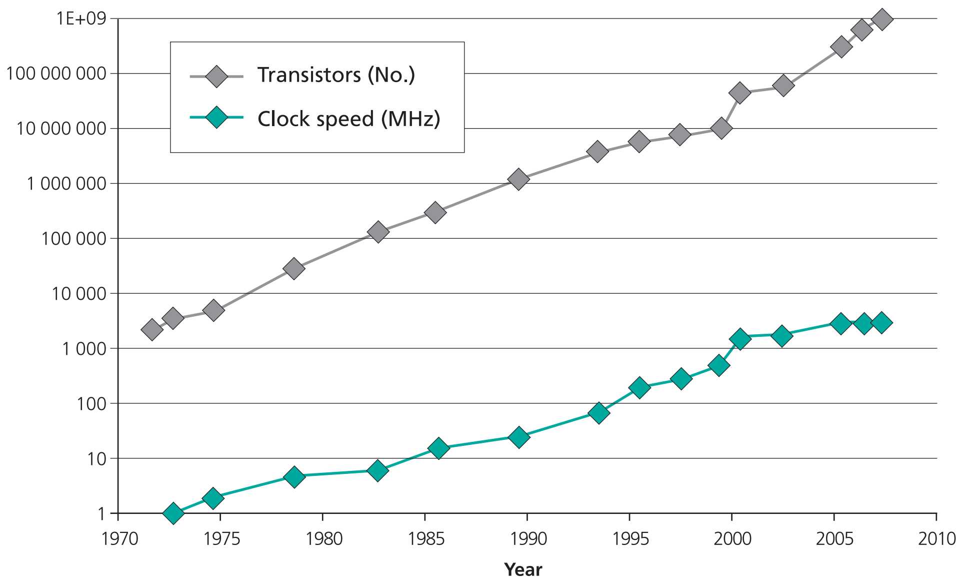
The growth in computing power

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

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

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

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



Source: Megrey and Moksness (2009).

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

[21] Megrey and Moksness (2009) note that there are limits to making circuitry smaller and in managing electrical movements and heat through the circuits.
[22] Modern drives now pack as much as 75 GB of data onto a single 3.5 inch platter.

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

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

Progress made in parallel developments

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

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

BOX 1.5
Parallel developments that link to GIS

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

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

Source: Adapted from Meaden (2009).

The proliferation of data

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

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

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

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

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

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

The increasing demand for GIS output

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

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

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

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

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

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

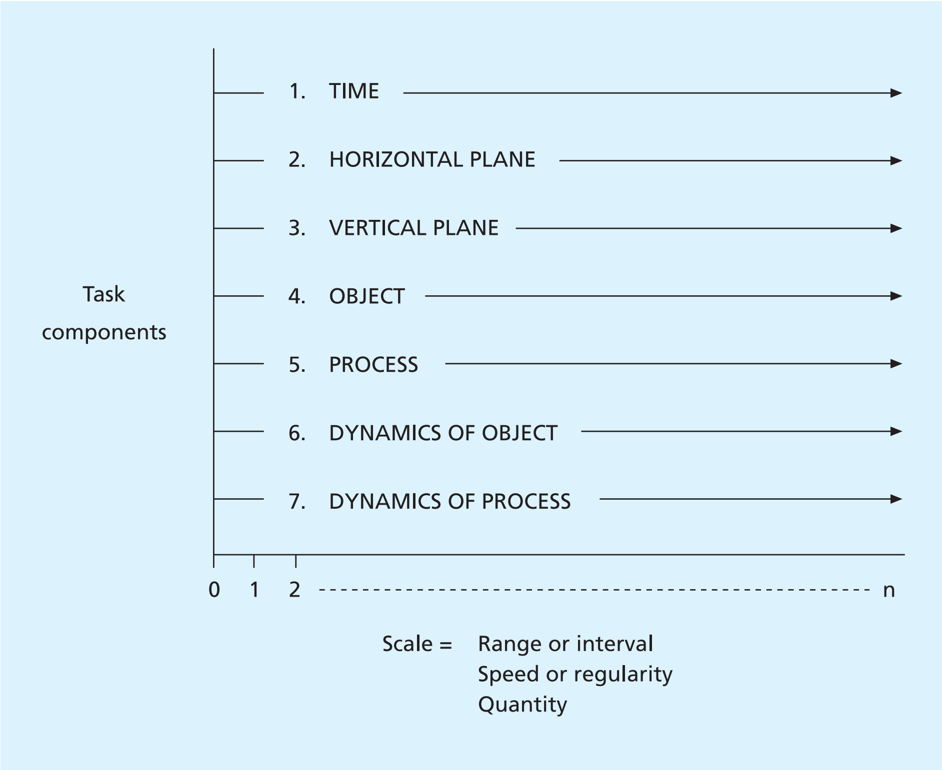
The use of GIS for any fisheries purpose was slow to materialize, this largely being a function of the paucity of marine data and of the complex milieu that is the aquatic or marine environment. Meaden (2000) has previously shown that this complex milieu can be conceived in terms of the "task components"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

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

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

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

FIGURE 1.5
Task components of a fisheries-based GIS



Source: Meaden (2000).

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

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

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

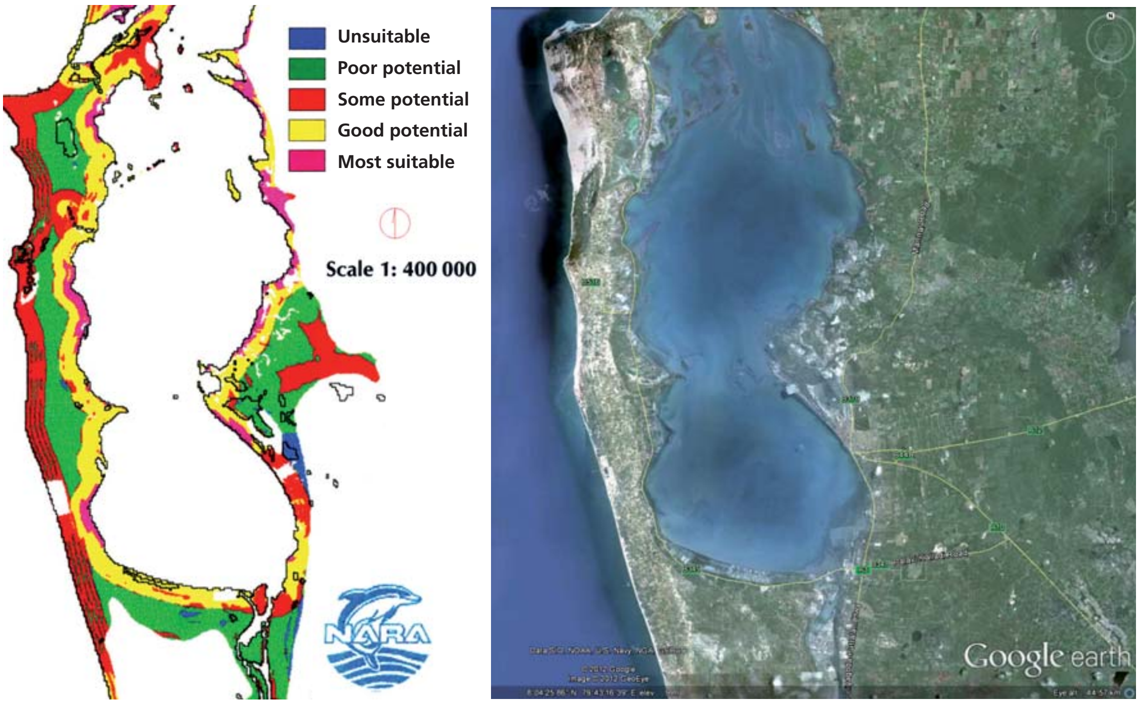
Fisheries theme or topic	Examples of studies
Mapping and atlases	Selvik *et al*. (1993); Ostrowski (1994); Ramster (1994); Carocci and Majkowski (1996); Ramos, Sobrino and Jiménez (1996)
Habitat Mapping (riverine and marine)	Gordon (1994); Liebig (1994); Somers and Long (1994); O'Brien-White and Thomason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

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

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

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

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



Location: 8°5′6.72″N; 79°46′14.15″E

Source: Meaden (1999).

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

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

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

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

1.5 THE AIMS AND THE STRUCTURE OF THIS TECHNICAL PAPER

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

In preparing a technical paper that impinges on a complex mixture of themes and topics, there is inevitably a problem in arranging a logical sequence of the material. Although a consensus has been reached on the arrangement of chapters, some readers might find it necessary to "skip around" the document in the order that it makes best sense to them. Figure 1.7 attempts to show the progression of stages through a GIS project and the human influences affecting these process stages. The left-hand column divides all the human inputs into internal (from within the group or organization) and external inputs (outside sources that may influence the GIS process stages). The main body of the right-hand flow diagram shows the linkages among successive stages that will typically be performed during the completion of any individual GIS-based project. It is important to note the feedback loop, which essentially means that the final information output from the GIS can either: (i) be directed towards any of the human inputs so that they are better informed on spatial-based matters relating to fisheries or aquaculture; and (ii) inform any further GIS work, e.g. perhaps as a result of models developed or any methods used. All of the process stages are covered by this technical paper.

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

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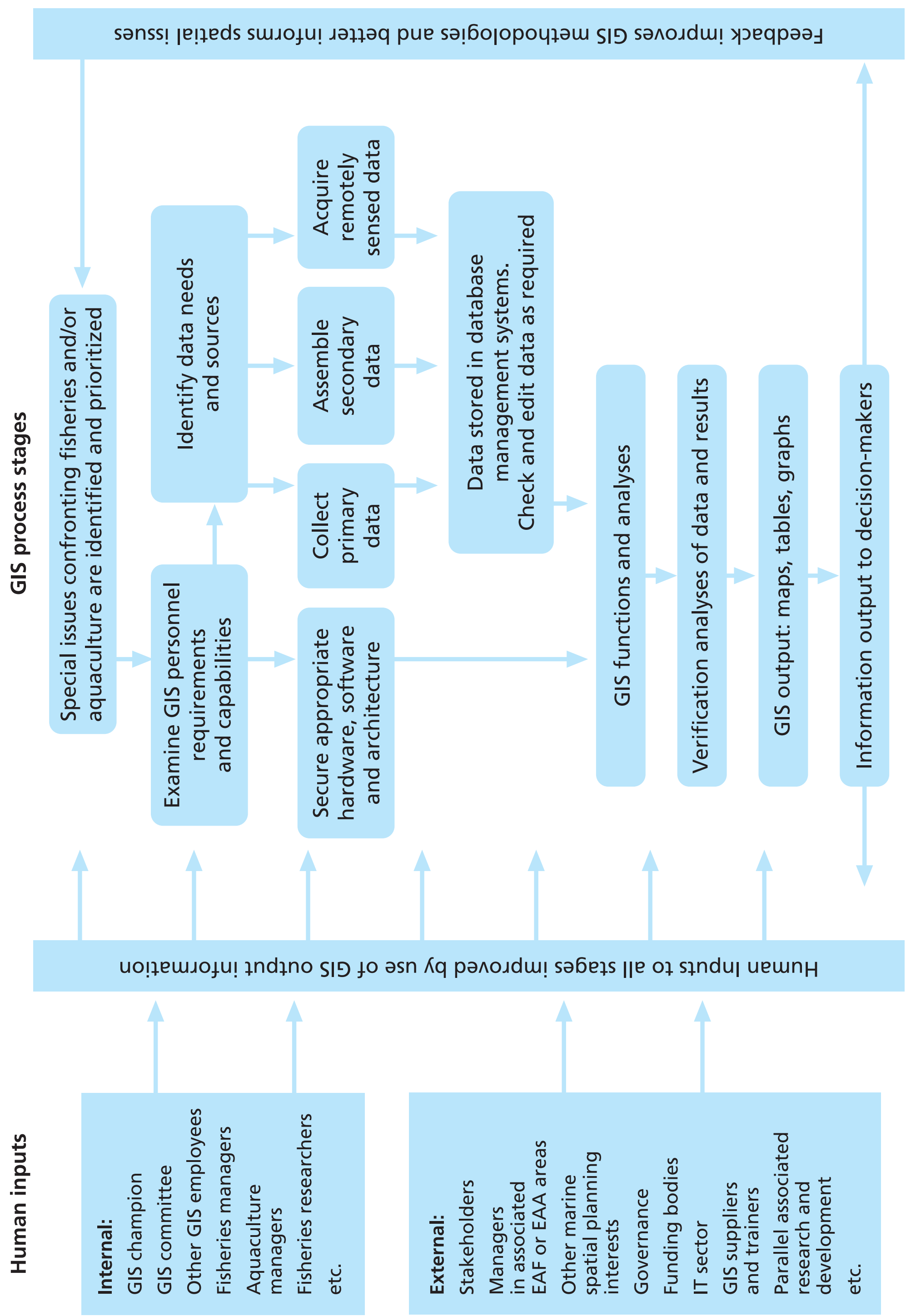
[30] The symposia are organized by the Fishery-Aquatic GIS Research Group based in Saitama, Japan, and details of their most recent programme can be found at www.esl.co.jp/Sympo/5th/Final%20 announcement.pdf .

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

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

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

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



2. GIS hardware and software for fisheries and aquaculture

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

2.1 INTRODUCTION

This section is concerned with the technological infrastructure needed to support the GIS operations. The approach taken here is to assume that the GIS is being assembled from scratch, although in reality it might be necessary to integrate a GIS into an existing information technology (IT) structure so that some or all of the hardware and software requirements may already be procured. This chapter will cover four main areas related to hardware: (i) hardware for data collection and inputs, (ii) processing and storage hardware, (iii) GIS output devices and (iv) GIS architecture. The chapter also looks at the range of GIS-related software that might be procured. As with most facets of IT, advances occur very rapidly with respect to both hardware and software needs, so information described here is likely to date quickly. This rapid technological advance is undoubtedly beneficial in the fisheries and aquaculture sectors because it provides the opportunity to expeditiously tackle a far wider range of problems than could previously be addressed. Megrey and Moksness (2009; p.2) importantly note that improved technology 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". However, because there will be many circumstances, particularly in developing countries, when users are obliged to use more dated equipment, some hardware that might be considered as "nearly obsolete" will be described. Because there are almost an infinite variety of hardware items that could be of use, it is only possible to cover main items. A perusal of computing hardware trade magazines or Web sites will provide useful additional information on basic items.

With regards to the software, those proposing to adopt GIS packages have fundamental, though different, types of choices to make. Is it better to use existing proprietary software or to go down the possibly riskier route of adopting free software? What software will best suit the requirements? And to what extent are there specific fisheries or aquaculture GIS, and will they tackle the tasks required? Many readers will be unfamiliar with free or open source GIS software, so the content of Box 2.1 captures the spirit of this option, showing that the user might need to enter a world that can be rather specialized, but the gains from doing this can be substantial in terms of cost reductions, endless software possibilities, and in working in a milieu containing a powerful group of people willing to share experiences. Though this world of jargon and acronyms might scare the user, this need not be the case, and the section on software attempts to convey some of the wide range of possibilities.

One software option that will not be considered in detail here is that of doing all (or most) GIS mapping via the use of Web-based software applications. The reasons for this are: (i) this is currently a relatively complex route to achieving mapping and analysis aims; (ii) the user is at the mercy of having to use what is available online (which may not be the most appropriate programs and there may be relatively few GIS-based functions); and (iii) the bandwidth for Internet delivery may not be sufficient to receive and process data over the Internet. However, with current advances in this field of software delivery, then it is likely that this option will be worth exploring during the next few years, and indeed Box 2.2 provides a recent comment from the Design Research Laboratory at the North Carolina State University in the United States of America on why the use of Web-based GIS might be useful. For those wishing to explore this software option further, the following Web sites may be consulted:

- eSpatial: www.espatial.com;
- GeoMicro: www.geomicro.com/gis;
- Cadcorp: www.cadcorp.com/products_geographical_information_systems/web_based_gis.htm;
- Free Geography Tools: http://freegeographytools.com/2010/giscloud-an-online-geographic-information-system-application.

BOX 2.1
A quote giving the flavour of open source software

"At a GIS-related conference a couple of years ago, I presented a 3D visualization system for fisheries data, and the response from the group was impressive. Not because what I did was so great, but that it could be done with "free" software. There is a real growth in fisheries GIS worldwide, especially in the third world, supporting coastal fisheries management and aquaculture, and budgets for Arc and Oracle spatial are limited.

The most impressive thing I have found with Open Source GIS in the last couple of years is the interoperability. I can download shapefiles, e00 data or many other formats. Use avcimport, ogr2ogr, shapelib, shp2pgsql to extract & reformat, or load into PostGIS. I can query/browse with psql, pgaccess or graphically with QGIS/JUMP, I can analyse with GRASS or R and prepare high quality publication maps with GMT. Then toss mapserver at it to Web-enable the stuff. Add some GPS capture software."

Source: Wood (2004) (http://osdir.com/ml/gis.postgis/2004-06/msg00112.html – accessed 10 December 2012).

2.2 HARDWARE FOR DATA COLLECTION, INPUTS AND OUTPUTS

In Chapter 3 attention will be given to the capture of primary data (defined in Chapter 3), and in doing so, a range of input capture devices will be described. This equipment, therefore, needs little further discussion here. However, not all data are captured in the field as primary data, and some data are collected and processed by equipment that bridges several categories of hardware. This section briefly considers hardware for initial data inputs and analyses, plus hardware that allows for office-based data inputs.

2.2.1 Hardware for inputting data

This section examines: (i) computing for data collection and analyses; (ii) scanners; and (iii) digitizers. As well as describing the hardware itself, there is also a brief description of functionality.

Computing for data collection and analyses. This category of hardware is essentially an extension of the personal digital assistants (PDAs) (see Section 3.5.1). However, it is looked at here because the equipment can be considered as multifunctional with emphasis probably being given to its ability not only to capture data but also to its GIS-based computing functionality. Here, the discussion focuses on ruggedized handheld tablet computers. This category of equipment also overlaps with the more traditional laptop or palmtop computers. For many data collection purposes in the marine, fisheries or aquaculture sectors, it will be important to have a robust device commensurate with frequent adverse physical conditions, and it is of extra value to carry out data collection in conjunction with access to full computing powers including, perhaps, access to a larger screen, to GIS software and to the Internet (allowing for two-way data transfers). This computing equipment would not generally include mobile telephone functions, though some computers have digital photography and route-finding capabilities. It would also allow for a range of GIS functions to be pursued in real time. Figure 2.1 illustrates one of many brands of ruggedized handheld or tablet computers that come in a wide range of prices and functionality.[33] Ruggedized equipment is particularly useful if data need to be collected while in "hostile" environments, for example, at sea on board survey vessels. Data captured might frequently be downloaded to a desktop computer for further processing and use.

BOX 2.2
Why use Web-based GIS?

Web-based GIS is becoming more and more prevalent as time passes. The World Wide Web is a useful tool for gathering and manipulating data and information. Most information that is available in the world is now available over the Internet. Now much the same is true concerning GIS information.

Where formerly an individual would have had to buy an expensive software package to use and manipulate the data needed for GIS, the same is not so today. With the advent of Java-based programming, software applications for Web-based GIS work are now available. Some of these programs require the user to buy some software, and others require plug-ins to be added to Web browsers, but some require no special software additions at all. These use only the capabilities of existing Web browsers.

Because of these advances, many people who were not easily able to obtain information can now have it at their fingertips. People who have an interest in gathering information can find it accessible like never before. For the first time, the public can examine the same information as the policy-makers for hands-on examination of GIS material. Talk about citizen involvement!

Another useful facet of using Web-based GIS is that the people giving the information are completely in charge of the amount of information made available to the public. If there are privacy issues surrounding certain information, then it need not be made accessible to others. It is that simple. People cannot use or abuse information that they do not have. With Web-based information distribution, there is no need to worry about information "falling into the wrong hands".

With Internet connections becoming faster and faster, the amount of information that can be transferred over the Internet is staggering. Soon people will be able to examine GIS data while in a foreign country in order to make a purchasing decision on property that they have never seen. Analysis of data by a widely scattered group can also be accomplished in a faster, more efficient manner when the information is available almost everywhere in the world.

Source: Adapted from Design Research Laboratory at North Carolina State University at www.ces.ncsu.edu/depts/design/research/WECO/policyGIS/why.html (accessed 10 December 2012).

[33] See www.esri.com/software/arcgis/arcpad/key-features.html for a cheaper model.

FIGURE 2.1
A typical ruggedized tablet computer

Source: Maine Technical Source (2009).

FIGURE 2.2
Large format scanner

Source: Softcover International Limited (2011).

Scanners. Scanning also converts analogue[34] mapped or graphical data into digital formats, though here by the use of various scanning devices. Unlike digitizers, which capture user-selected data, scanners capture all the information from mapped or other sheets,[35] and the data are captured in a regular grid of pixels (see Section 5.8.2). Scanning works on the basis of two main principles. There is either a scanning photosensitive head that moves backwards and/or forwards over a static object that is being scanned, or the scanning head is static and the object moves in front of it. There are a range of different types of scanners varying from large format (Figure 2.2) to small flatbed scanners, and the type best used will depend on the size of any paper mapping to be scanned and on the cost that can be afforded. The detail to which scanned data is captured varies from about 400 to 2500 dpi (dots per inch). The amount of detail needed will largely be a function of the use to which any scanned images are put, and consideration must be given to the very large storage requirements for high-resolution images plus the burden on computing power.

Scanning can be used for several purposes in GIS. Scanned images can form an excellent backdrop to, for instance, road maps. Scanned images are also used as a digital filing system for maps. But perhaps the most common use for scanning is that it provides the on-screen images for heads-up digitizing (see digitizing below) or for automated vectorization.[36] It is worth noting that several authors (Longley *et al.*, 2005a; Lo and Yeung, 2002; Heywood, Cornelius and Carver, 2006) comment on the large number of processes that must be gone through from the initial scanning process to the resulting output being readily used for GIS purposes. Because a large format scanner is unlikely to be used much by most fisheries or aquaculture GIS offices, then a cheaper option would be to seek other means of obtaining scanned output, perhaps through the use of a commercial scanning office.

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[34] See Section 3.5.1 for an explanation of analogue.

[35] This is advantageous because all data are quickly and usually accurately captured, but disadvantageous because GIS files need to be free from the "clutter" of wording, creases in the map, coffee stains, etc., and scanned files are unintelligent as they cannot differentiate between different information on a map.

[36] Vectorization means that, if clear and uncluttered mapped images are available, it is possible for a light sensitive device to follow required lines on a map capturing their location as (x,y) coordinates.

Digitizers. This form of hardware is used to convert graphical data, i.e. usually lines, points or polygons on maps, into digital data for GIS use. Digitizers are rapidly being phased out as a useful piece of equipment because more and more mapped data are being initially captured in a digital format by other means, e.g. by data loggers, PDAs or by digital scanning, or because on-screen digitizing is performed. However, it is important to discuss it here because there are circumstances when digitizers could still be utilized.

FIGURE 2.3
A large, adjustable digitizing table

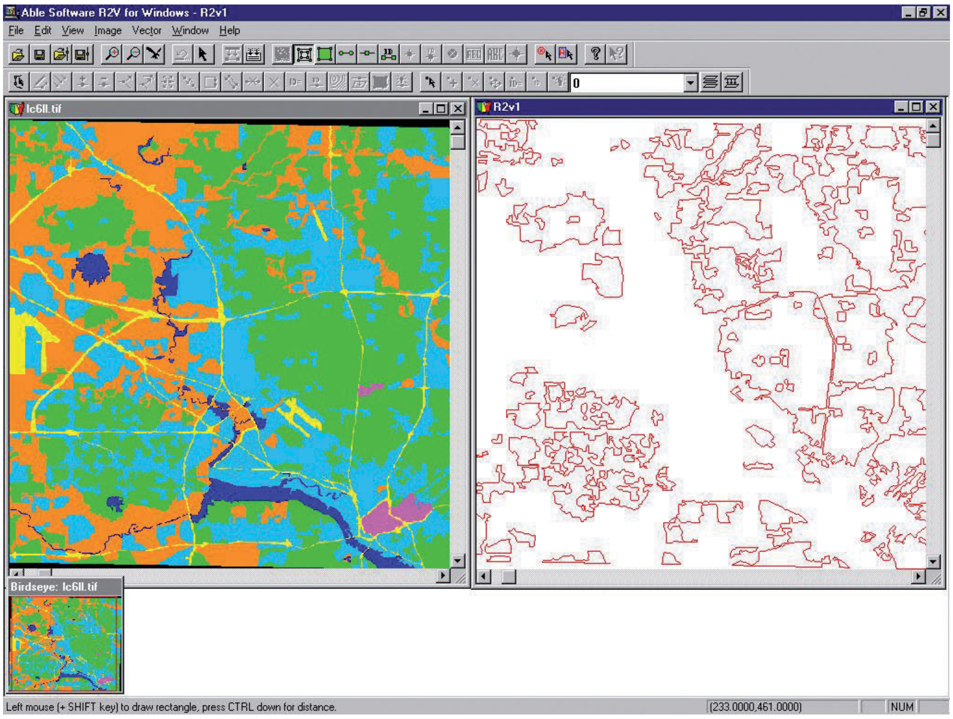
Source: The Logic Group (2012).

Figure 2.3 illustrates a typical digitizing table. Digitizers come in different sizes, from very large "tables" (~1.5 m wide) to small digitizing tablets (~30 cm wide). Embedded in their surface area is a fine grid of wires that will allow for interaction between the digitizing table and the cursor. A paper map is fastened to the surface and is registered so that exact geo-coordinates will be captured.[37] The cursor (or puck), containing a fine cross-hair set into a magnifying glass, is tracked along any line that needs to be digitally captured. While tracking is taking place, the operator either continually clicks on the cursor and every clicked point is captured as a georeferenced point, or the cursor is set to operate in "stream mode", whereby a point is automatically registered at a set time or distance interval, typically every 0.5 seconds or every 0.5 mm. The cursor or puck usually has a number of keys that allow for additional information to be collected, such as thematic codes, line thicknesses, colours or other identifiers. Georeferenced points are typically captured to 0.02 mm resolution. The digitizer is linked to a computer containing digitizing software and to a screen so that the user can see which lines have already been captured. It is usual to capture data on individual themes, e.g. rivers, county boundaries, forested areas, and to hold each theme (or map layer) as a separate file.

Today, it is far more likely that on-screen digitizing (also commonly referred to as heads-up digitizing) will be done. Instead of the map being fastened to a table or tablet, the map will be shown as an on-screen image that has been scanned in. The digitizing operation is then carried out in much the same way as described above, but using the normal mouse and cursor and working with digitizing menus that may come as part of the GIS software. As shown in Figure 2.4, dual or split screens can be used so that both the original map and the already digitized lines can be viewed. Here, the green (woodland) areas have been digitized from the original map on the left. Digitizing is recognized as being skilled, but very time consuming and thus a labour-intensive task. For this reason, much high-volume digitizing work has been completed by specialist companies based in the People's Republic of China or the Republic of India where costs may be less than 25 percent of those in more developed economies.

[37] Registering usually requires capture of the location of three or more control points, usually situated at the corners of the map to bedigitized. Any GIS software used then "registers" exactly where the map is georeferenced relative to anywhere on the planet.

FIGURE 2.4
Screen image of raster to vector conversion software functioning as a split-screen display for digitizing



Source: Able Software Corp (2011).

2.2.2 Processing and storage hardware

The major hardware item examined under this heading is the computer itself. Section 1.3.2 outlined the tremendous advances that have occurred in computer technology over the past half century, and these have been enabled by developments in the wide range of parallel technologies that together contribute to the broad IT area. Technological advances have been accompanied by huge relative cost reductions such that computing is now available to a very broad spectrum of the public, government and business. This section simply gives advice on the attributes or specifications that computers being used for GIS work might aspire to and points out some of the peripheral devices or add-ons that might be useful.

Until comparatively recently, computers came in four categories denoting their respective computational power, i.e. mainframe, minicomputers, workstations and desktop computers. About 20 years ago, minicomputers were phased out, mainly because workstations increased their capacity so as to take over the role of minicomputers. In the last decade, workstations and desktops have virtually merged, but there has been a rapid emergence of laptop computers as a new category. Mainframe computers remain as a very wide range of powerful machines, with the most powerful of these being referred to as supercomputers. Box 2.3 briefly describes the current terminology for the most popular range of computer devices, and the prominence of mobile computing can readily be seen. As almost all GIS work can now be performed on desktop or laptop computers, the discussion can focus on these products and, indeed, because laptop capabilities now nearly equal those for most desktop computers, these two categories can be treated as equals.

In an area such as computing, where technological advances are rapid and constant, it is difficult to advise definitively on computer specifications. However, given that work in the fisheries and aquaculture fields tends to be very data intensive and rather

BOX 2.3
The present hierarchy and terminology of general computers

Large: Super – Minisuper – Mainframe – Server – Supermini
Micro: Personal – Workstation – Home – Desktop
Mobile: Laptop – Portable – Tablet – Palmtop – Organizer – Pocket – Notebook – Personal digital assistant – Programmable calculator – Smartphone

Computer typology will vary between countries and within different business sectors. There is also a range of much more specialist computing devices.

complex, as is the case for GIS software, then these more sophisticated needs should be met by the use of "top-end" computing power. Financial restrictions may make this difficult for many users, so a careful check needs to be made on what GIS functionality can be obtained for any given expenditure on computers. Box 2.4 gives guidance as to the desirable specifications for any computer being used as a stand-alone machine for fisheries-related GIS work. If the computer is to be part of a network that is linked to a server (see below), then there may not be the need for such high storage capacity. However, if a stand-alone computer is to be used for highly data intensive projects, e.g. perhaps using many remotely sensed images or large amounts of sonar-derived acoustic data, storage should be increased to 1 terabyte. For those wishing to do GIS work using Apple Macintosh computers, the options are more limited than for conventional PCs.[38]

BOX 2.4
Suggested computer specifications for undertaking fisheries and aquaculture GIS work

The following are the present suggested minimum computer specifications that might apply for GIS-based work (for guidance only):

Operating system:	Linux, Unix, OS X, Windows XP or Windows Vista
Processor speed:	Intel dual-core 2.5 Ghz
Random access memory:	4 GB
Storage (disk memory):	500 GB
Video/graphics card:	256 MB DVI card
Wired network card:	10/100/1000 MBPS Ethernet card
Wireless network card:	802.11 B/G compatible
Disk drive:	CD-RW/DVD combo drive

Users of Macintosh computers may need to check these requirements. The specifications are for "high-end" machines and apply to 2012. There are other operating systems available and various suppliers make all of these items.

As well as the basic capacity of the computer, there are other considerations to be taken into account. Any computer used should have serial or USB ports,[39] a mouse, keyboard and at least one monitor. Flat screen monitors using liquid crystal display (LCD) technology are now the norm and, as pointed out above, more than one monitor can be useful[40], but not essential, for many GIS tasks. As maps are best

[38] GIS/Apple Macintosh options are summarized at: www.cartographica.com/article.php?story=20060228220202157 and www.gis2gps.com/tools/macpage.htm.

[39] USB ports have now largely replaced serial (and parallel) ports. This means that a range of devices such as mice, keyboards, memory sticks, scanners, digital cameras and external hard drives can all use identical plug-in facilities.

[40] Having more than one screen can significantly increase the work productivity rate: see Kim Komando Show: www.komando.com/columns/index.aspx?id=1488.

visualized at a larger size than is textual material, a minimum screen size of 22 inches (55 cm) is recommended, and the dpi of screens should also be of high definition (perhaps up to 2560 × 1600) and have a fast refresh rate in the range of 85 Hz.

It is also vital to consider digital storage media. Although any computer may have its own large storage capacity, it is essential to have back-up provision provided by some sort of external device or medium. There are four main ways of achieving this:

- **File server.** This is a separate computer with high data storage capacity, which is linked to other computers forming part of a local area network (LAN) (see Section 2.2.4). It means that there is no need for all files and data to be stored on each computer in the organization, allowing each desktop computer in the LAN to have lower specifications.
- **External hard drives.** These are similar to an ordinary internal hard drive, except that they are mounted on a disk enclosure and are simply plugged into a USB port. There is now a huge range of external drive options in terms of size and price with even small drives having up to a 1 terabyte capacity (for examples, see LaCie Srl: www.lacie.com/it/products/range.htm?id=10036). However, they are often less rugged and may be more bulky and expensive than memory sticks (see below).
- **Optical disk drive.** Examples of these are CD–ROMs or DVDs. One or the other of these disks is usually integrated into modern computers though they may be external and plug into a USB port. They can both read and record and are mostly used for distributing digital information or data. During the 1990s, CD–ROMs replaced floppy disks and magnetic tapes, but these have mostly given way to memory sticks and DVDs.[41]
- **Memory sticks.** Also called pen-, flash- or thumb-drives, these sticks, which plug into a computer's USB port, can store large amounts of data (typically 4–64 GB). They have advantages over CD–ROMs in terms of their memory capacity, their ruggedness, their reliability, their speed and compactness, and their ability to erase and thus rewrite. They are now frequently used for data back-up purposes.

There are two other important hardware items associated with computing that are discussed here: (i) uninterruptable power supply; and (ii) wireless routers and modems

- **Uninterruptable power supply (UPS).** This is a free-standing piece of equipment that provides emergency power when the main supplies are interrupted through complete failure or through voltage changes. UPS differs from an emergency power supply in that it provides instant power continuity, usually for periods of up to 30 minutes. UPS vary in size according to the amount of power that they need to protect. They are extremely important for computing because they can prevent severe data losses, especially in areas prone to frequent power cuts, and they can be programmed to automatically save any data.
- **Wireless routers and modems.** As most data will nowadays be delivered via the Internet, serious consideration must be given to making data delivery as efficient as possible. Traditionally, a wired connection has been made between the computer and the Internet source, and this has used telephone lines, a modem[42] and other DSL (digital subscriber line) technology. However, use of phone lines and DSL modems meant that data delivery speeds were very slow. In the 1990s, many urban areas were connected to cable networks allowing cable TV and broadband[43] Internet access via a cable modem, and data delivery speeds to computers

[41] Because of their higher storage capacity and the fact that they can play video films, DVDs have replaced most CD–ROMs from the business computing marketplace, though the latter remain important for audio purposes.

[42] Modem is short for "modulator-demodulator". Basically a modem converts an audio signal into a digital format and vice versa.

[43] The term "broadband" has gradually evolved to now describe Internet connections that range from 5 to 2 000 times faster than earlier DSL technologies. The concept of broadband incorporates both connection capacity (bandwith) and speed. Higher transmission speeds have been achieved mainly by the use of fibre optic cables.

FIGURE 2.5
A typical wireless router

Source: SlipperyBrick (2009).

were greatly increased.[44] Today, the technology for Internet download is more frequently based on wireless connections. Through the use of the wireless wide area network (WWAN), information is transmitted from an Internet source to the computer. For the transmission to function, the computer must be within receiving distance of a wireless router – in a so-called "hot spot" area which may have a radius of 30 metres.[45] Figure 2.5 illustrates a wireless (WiFi) router, whose purpose is to facilitate both incoming and outgoing communications through determining the next network point to which a data packet should be directed. It is likely that the future for Internet transmission will mostly rely on wireless technology and, indeed, most computers are now sold with the necessary wireless network (Ethernet) card to allow for this. For further information on wireless technology, see Discovery Communications, LLC: http://computer.howstuffworks.com/wireless-network1.htm.

2.2.3 GIS output devices

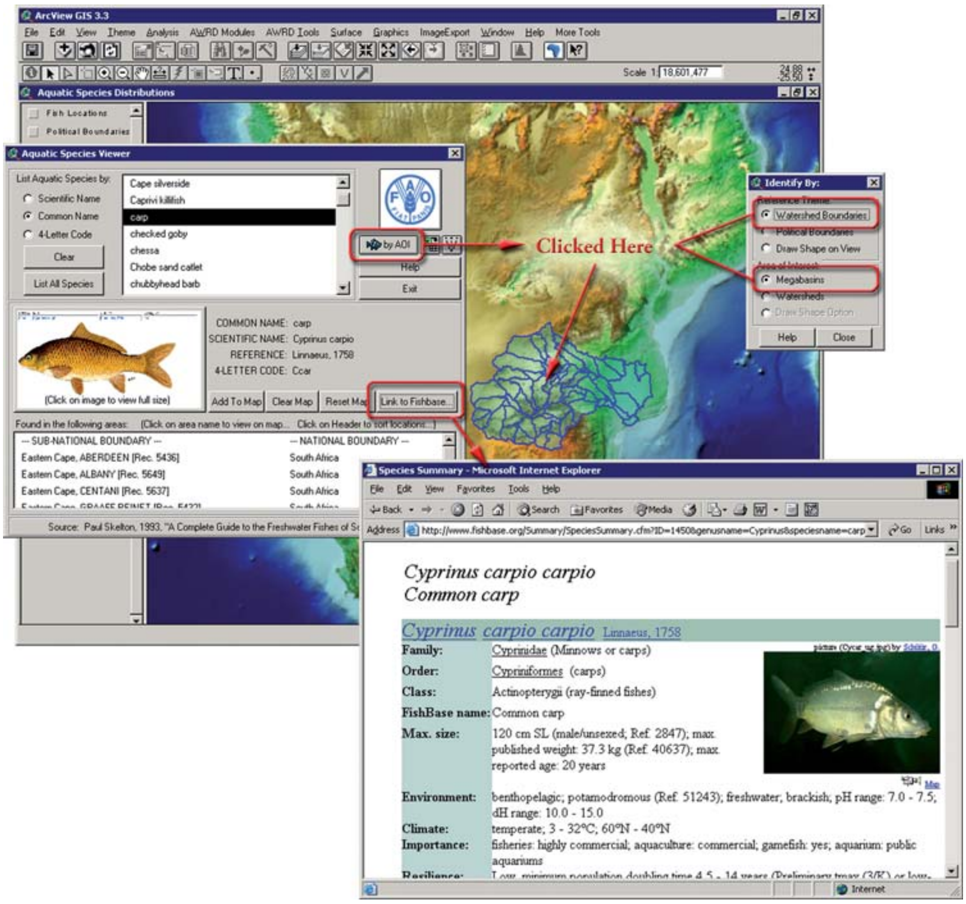
Although GIS output may be in various forms (textual, mapping, graphs, tables, spatial multimedia, etc.) and it can be sent to disks, to the screen, to the Internet or for hard copy output, under this heading two broad categories of GIS output can be distinguished. These are hardware for temporary, ephemeral output devices (soft copy) and hardware for permanent output devices (hard copy).

- **Ephemeral output devices.** This type of output includes graphics, maps or text that is temporarily displayed on the computer monitor – so the computer screen becomes the hardware output device for ephemeral images. These screen images can be used immediately by the GIS operative in any number of ways before being cleared from the screen (output) by either being deleted or saved as a file. Figure 2.6 illustrates screen output using Environmental Systems Research Institute (ESRI) ArcView GIS software. Items are usually filed via the use of hard drives, optical disks or memory sticks (see Section 2.2.2). Filed images may typically be stored as GIF, JPEG, PDF or TIFF images, or using the "Print Screen" on the computer keyboard, the images can be directly "pasted" into any document or slide, or into Microsoft Paint or Paint Shop Pro for further editing. Any material filed can be subsequently distributed (output) by, for instance, creating slide or multimedia shows, or by transmission to the World Wide Web. Material forming part of a slide or multimedia show is usually displayed via the use of a data projector. This is a device that projects computer output onto a white or silver fabric screen that is wall, ceiling or tripod mounted. Data projectors

[44] The bandwidth of the connection may be an important constraint to Internet use in many countries and users are advised to check on this before relying on the Internet, especially for down-loading large data sets.

[45] So-called WiMAX (Worldwide Interoperability for Microwave Access) technology is now emerging. This is designed to provide faster wireless access (3 Mbit/s) over far greater distances, i.e. perhaps 50 km.

FIGURE 2.6
Computer-generated temporary (ephemeral) screen output



Source: Jenness, *et al*. (2007).

typically accept resolutions of 800 × 600, 1024 × 768 or 1280 ×1024 and may also support standard video from a VCR, DVD or cable box. Data projectors are primarily associated with the ubiquitous Microsoft PowerPoint presentations.

Increasingly large amounts of data and information are being made available as output to the Internet. This is normally accomplished via the use of a Web-space provider or Internet service providers (ISP). These are companies that, after registering with them, will allocate the supplier space on one of their file servers. This service is frequently available free of charge. Using software called a file transfer protocol (FTP), any operative or organization creating desirable digital output can send copies of files from its own computer to the ISP, which will distribute the files via the Web on its behalf. All files given to the ISP will need to be properly organized in a logical system of files and directories, and any hyperlinks will need to have been established. GIS cartographic output over the Internet may be in the form of maps in reports, in atlases, or in virtually any source where maps can be of benefit to the supplier. Data for GIS can also be delivered in a similar manner. The following Web address provides additional useful information: www.ntchosting.com/encyclopedia.html.

- **Permanent output devices**. These comprise a wide range of plotters and printers. It is sometimes difficult to differentiate between these categories, but generally, plotters will draw lines, polygons, etc., usually on a paper or film medium, whereas printers will use one of several other means of reproducing graphical output, e.g. inkjet or laser printing. Table 2.1 summarizes the main hard copy output devices, listing them in increasing order of average cost. The output speed of printers is usually measured in “pages per minute” (ppm) for A4 size sheets. Printing of GIS generated maps can frequently be at lower speeds because of the density of information on a mapped page. Compared with the output to the screen, obtaining permanent hard copy output is slow and expensive. The range of colours obtained is usually less than on the screen, especially from plotters where the maximum may be only six. To obtain a large size output can be very expensive in terms of capital outlay for the printer or plotter and for supplies of consumables such as paper, film and inks. All output devices must be installed[46] so that they can communicate with the computer, and not all brands of equipment are compatible. Pen plotters have essentially become obsolete because inkjet technology is now of exceptionally high quality and output is rapidly obtained using an almost infinite array of colours. In fact, for most GIS-based work, users would utilize inkjet or laser printers, and both of these come in a large range of models, sizes, quality, etc.

TABLE 2.1
Summary of main hard copy output devices

Device	Colour	Speed	Resolution	Other comments
Inkjet printer	Mainly colour	A4 size = mono 5–30 ppm Colour 4–20 ppm A0 size = Colour 1–2 ppm	600–200 dpi	The most used hard copy output device. Advantages in terms of speed and cost. Millions of colours potentially available. Low-cost desktop versions may have low resolution and quality.
Pen plotter	4 to 6 colours	Ball point pen = 100 cm/sec Ink pen = 5 cm/sec	Drum: 0.025 mm Flat: 0.0075 mm	Can be large drum or flatbed. Flatbeds vary from A4 to A0 size. Quality output using ink is better than ballpoint. They cannot produce a solid region of colour.
Laser	Mono	A4 size = 100–200 ppm	600–1200 dpi	A4 size output is very inexpensive, though hardware is more expensive than for inkjet printers.
Colour laser	Colour	A4 size = 50–100 ppm	500–1000 dpi	The capital cost of these printers makes it difficult to compete with colour inkjets for small volume work.
Thermal wax	Colour	Less than 1 ppm	300 dpi	Produces high-quality colour prints, but is slow and expensive.
Electrostatic	Colour	A0 size = 1 ppm	200–400 dpi	Despite low costs for output, the high cost of these printers makes them difficult to justify for GIS work.

2.2.4 GIS architecture

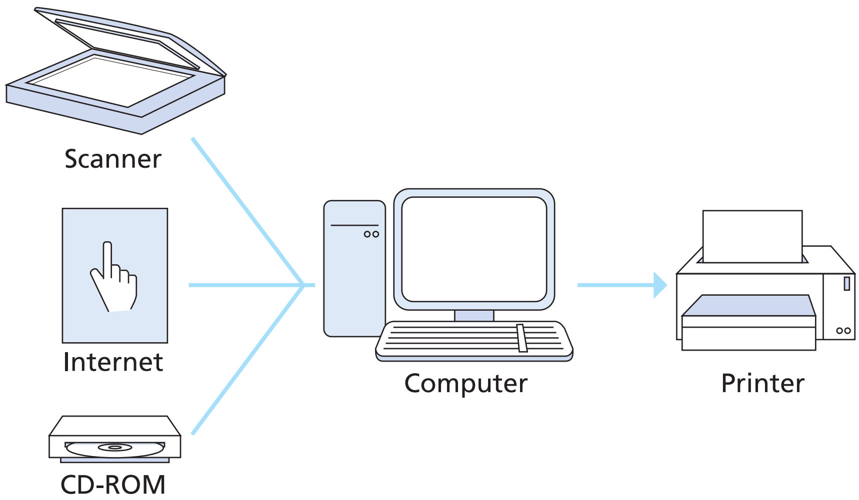
Here, the concern is with bringing the hardware devices together in order that the whole GIS can function in an optimum manner – it can be envisaged as hardware configuration. It is important to state that there is an almost infinite variety of ways in which hardware devices can be configured for GIS purposes, and the architecture that is finally adopted will be a function of the computing hardware that is inherited, the capital outlay available, the purposes of the GIS, the size of the organization doing the GIS work and a knowledge of what is available plus any personal preferences. Whatever system is adopted, there will be a possibility to readily make changes, additions and upgrades. Each of the systems described will be conceived in terms of networks, and the discussion on these will proceed from the simple to the more complex. Further details on the general aspects of computer networks may be found at: Micro2000: www.micro2000uk.co.uk/network_info.htm; or Techi Warehouse: www.techiwarehouse.com/cms/engine.php?page_id=d9e99072.

[46] This means that an installation process is performed whereby information about the device being installed is given to the host computer.

Personal area network

Although it is perfectly possible to undertake fisheries GIS work as an individual who is only deploying a computer and probably a printer, this so-called "stand-alone" configuration will not be discussed here, as nowadays any valuable fisheries GIS work would almost certainly be linked to a broader public, almost certainly via the Internet. So the simplest architecture considered is the personal area network (PAN). Figure 2.7 illustrates the main components of a PAN configuration.

FIGURE 2.7
Main components and linkages in a personal area network computer architecture

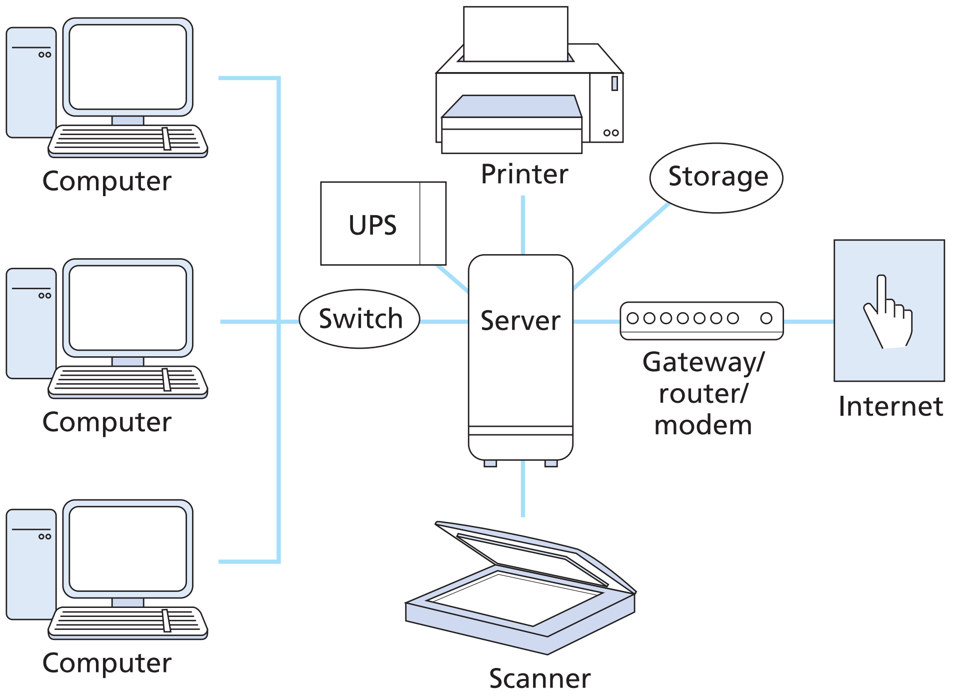


Here, a single desktop or laptop computer is linked to a normal array of peripheral computing devices. As it would be virtually impossible to undertake valuable fisheries or aquaculture GIS work without having access to the Internet, this link is shown. Internet access is important for both inputs to the GIS work (data and information) and for outputs from the GIS work. To achieve Internet access, it is vital that some sort of "gateway device" is installed, and this can be physically integrated to both a router and modem (see Section 2.2.2). A "gateway device" is any appliance that allows different parts of either the local area network (see below) or a wide area network (see below) to be functionally connected. Connections from the computer to the gateway and then to the Internet may be through a wired connection, but are now increasingly being achieved through wireless means. Both printer and scanner are likely to be A4 size, with the former being inkjet or laser. Additional hardware such as a laptop, memory sticks, any optical storage media and a modem might also form part of this basic configuration.

Local area networks

A local area network (LAN) would be a far more typical computer configuration for fisheries or aquaculture GIS. This derives from the fact that most of this work would be carried out in office or research laboratory situations, where several people may be working together on projects and where some of the equipment and most of the data would be shared. Figure 2.8 gives some idea of a LAN configuration, though there could be almost infinite variations in terms of actual devices and hardware capacity to this basic model.

FIGURE 2.8
Main components and linkages in a LAN computer architecture



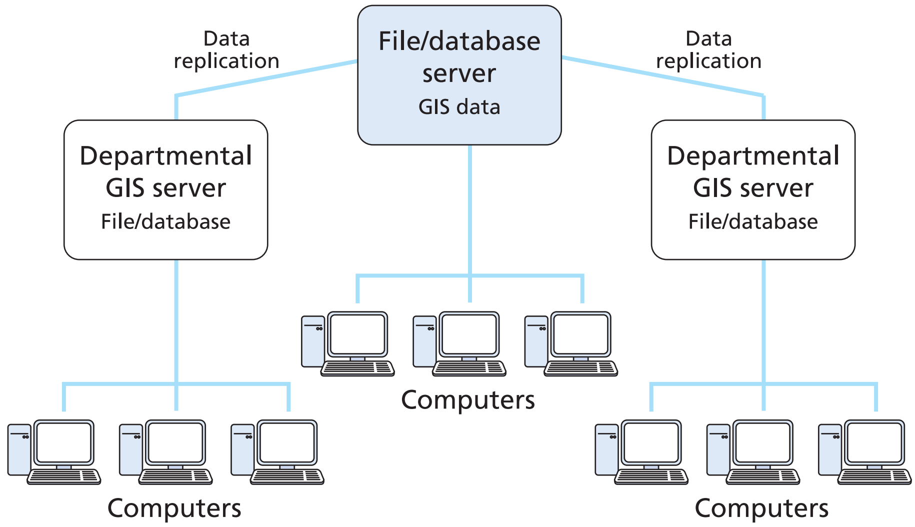
In the LAN configuration, there are likely to be a number of desktop computers according to the number of staff doing GIS (or other) work, with additional computers (including laptops) being easily accommodated. Because of the additional workload (relative to a PAN situation), a server will likely be deployed. Servers can store data files that are likely to be used by at least several of the employees, or they can do processing, etc. They can also facilitate the sharing of the various devices, meaning that it is not necessary for all of the computers to be capable of doing all functions or storing all data. The switch connects segments of the network. Printers and scanners can also be linked to the server, so there is no need for each person to have their own. A UPS is important in terms of data and file security in times of power failure. As in the PAN network, there is access to the Internet via a combination gateway/router/modem. It can be seen that a LAN network has considerable cost savings over a PAN, in terms of equipment saving, software licences and workload management, and the GIS sector of the LAN can be integrated to other sectors of a business or institution. Additional information on LANs is given at Farlex, Inc. (http://encyclopedia2.thefreedictionary.com/Local-area+networks).

Wide area networks

A wide area network (WAN) is basically an extension to a LAN, but instead of acting locally (usually within one office or institution), the WAN may be an area, regional, national or international network of linked computers[47]. Strictly speaking, as it also consists of a massive series of linked computers, the Internet itself is an example of a WAN. However, in terms of a fisheries or aquaculture GIS, the WAN may comprise the related work going on in dispersed institutions, e.g. within perhaps a larger university or fisheries research institutes or government fisheries departments.

An example configuration is shown in Figure 2.9. WANs function mainly as a convenient way of gaining remote site access for e-mailing, file transfer, etc., and access to the WAN by any PAN or LAN is gained via the router, which typically relies on wireless connections. Additional information on WANs can also be obtained from: Farlex, Inc. (http://encyclopedia2.thefreedictionary.com/Wide-area+networks).

FIGURE 2.9
A wide area network (or a distributed computing environment)



2.3 GIS SOFTWARE FOR FISHERIES AND AQUACULTURE

Before any discussion of specific GIS software for fisheries or aquaculture purposes can take place, it is necessary to place limits on what can be discussed. This is because the range of software that could be employed is very wide indeed and therefore the discussion is restricted only to software that might be of direct use. It does not cover software such as operating systems, word processing, databases, spreadsheets, image processing, graphical packages, digitizing software or remote sensing, any of which might be used in combination with GIS. There are a number of options that may be pursued in obtaining appropriate software:[48]

- to purchase a general proprietary package;
- to purchase a ready developed software system from a third-party user;
- to develop in-house software;
- to employ consultants to write new software;
- to obtain free and/or open source software;

[47] A WAN is sometimes referred to as a "distributed computing environment".

[48] Given that GIS can cover a wide range of applications, a single software does not often provide all the features and functions needed to carry out all the GIS tasks needed by a user, so it is common practice to use more than one software. GIS software selection is entirely dependent on the user's needs and capacity (i.e. hardware and trained personnel) to achieve the desired objectives.

- additionally, it is possible to acquire “extension tools”, which are customized packages that can be added to a GIS in order to undertake particular GIS-based tasks.[49]

For the present purposes of this technical paper, it is assumed that the means of developing in-house software is not available and that, in terms of mainly cost and known GIS needs, it would not be appropriate to employ a consultant to develop what might have to be a very comprehensive software package. The software considered can best be examined under three headings:

- general proprietary GIS packages;
- specialist marine fisheries software;[50]
- free and open source GIS software.

2.3.1 General proprietary GIS packages

Here, proprietary software is defined as that which is supplied and owned by a private company, in the sense that it owns licensing arrangements and places restrictions on how the software can be used. Although proprietary GIS software packages first became available nearly 50 years ago and the number of such packages rose rapidly until the 1990s, today rationalization and concentration has occurred to the extent that only a few major companies dominate the field offering important general-purpose GIS packages. That is not to say that there are not a much larger number of GIS software products that are available and which have been developed by many proprietary software companies for more specific purposes. Moreover, many GIS users have adapted general proprietary GIS for fisheries and aquaculture-related spatial analytical[51] purposes.

All the main proprietary GIS packages consist of a collection of subprograms that together give the GIS software its wide range of functionality. The components of a GIS package should allow for at least the following minimum range of functions:

- for the input, editing, manipulation and export of geographic data in industry standard formats (e.g. jpeg, tiff, gif, etc.);
- usually for digitization and for textual entry and display;
- for geographic query, analyses, modelling, visualization and graphics display;
- for database management (DBM);
- for graphical user interface (GUI) allowing easy access to tools.

Many proprietary GIS also have separate software “modules” that can be added to the core GIS to enlarge the range of program functionality. There is frequently an additional charge made for these modules.

The price of proprietary GIS software packages varies greatly, according to: (i) the functional range of the complete package: (ii) the buyer;[52] and (iii) the number of seat licences bought. Some GIS suppliers market various suites of programs that function as “add-on” modules to the main program, and which sometimes add significantly to the overall cost. Some proprietary GIS programs can be purchased cheaply if the user is willing to buy an older version and, indeed, older versions can sometimes be obtained free. Generally speaking, software that is designed to operate using the raster model (see Chapter 7) will be cheaper than software that supplies both raster and vector functionality.

As all main proprietary GIS software products vary significantly in terms of their range of functions, it is difficult to make objective comparisons between products. In

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[49] Two examples of customized extension tools can be found in: (i) Recommendation Domains for Pond Aquaculture (www.fao.org/fishery/gisfish/id/4815); and (ii) African Water Resource Database (www.fao.org/fishery/gisfish/id/2822).

[50] To the author’s knowledge, there is no proprietary software specifically for aquaculture-related GIS work. The closest example is a specialized GIS software called MarGIS (www.marcon.ie/website/html/margisdemo.htm).

[51] “Spatial analytical” purposes may also be described as “geospatial” purposes.

[52] Buyers influence the price of software because discounts may be given, for instance, to educational users.

fact, GIS product purchase would seldom be based on its functionality or ease of use, but more on "what others use" and familiarity with well-branded software. Therefore, when purchasing software, it is extremely important to consider not only what the GIS is capable of doing relative to its price, but also factors such as the ease of finding GIS operatives trained in the use of specific software, plus the support given to software,[53] the quality of the visual output, and any compatibility (or interoperability) issues. Most proprietary GIS software providers have now developed products based on so-called "open standards" – this is to ensure a high level of interoperability across platforms, databases, development languages, and applications.[54] Table 2.2 provides a brief overview of some of the main proprietary GIS software, with "comments" being derived from user groups and discussion forums. Although these products will have been developed for normal terrestrial geographic analyses, they have all been utilized somewhere for aquaculture or a range of fisheries GIS purposes. A complete and updated list of commercial (proprietary) software can be found at www.spatialanalysisonline.com/SoftwareCommercial.pdf.

2.3.2 Specialist marine fisheries software

Some readers may wonder why those engaged in spatial decisions relative to fisheries or aquaculture do not simply acquire suitable software that has been developed for that purpose. The answer to this is quite straightforward. From an inland fisheries or aquaculture perspective, there is little point in developing specialized GIS. This is because these activities are more or less terrestrially based and so conventional GIS software capabilities can be deployed for almost all prospective analyses. For marine aquaculture, the situation is somewhat different and their spatial considerations would be more aligned to those of marine fisheries. However, for marine fisheries, specialist GIS software has been very slow to emerge, and this has largely been a function of the following:

- The necessity of capturing, handling and managing data, and performing spatial analyses, that are largely in three or four dimensions and that are concerned with mapping mainly moving variables. Few conventional GISs handle the vertical dimension, and maps of moving variables may have very low statistical significance.
- Fisheries tend to be a fragmented activity, in the sense that it has traditionally functioned as numerous small enclaves of activity, and as such has not warranted the development of a complex management tool.
- The functionality of any GIS developed for fisheries purposes would need to be very wide indeed, i.e. because there are so many facets and dimensions to the activity, and there would be few markets for such a large (and probably expensive) multifunctional software package.
- Terrestrial spatial analyses can function in an environment containing numerous physical or anthropogenic boundaries and other mappable structures, i.e. features that can form points and lines on maps. In the open sea, this is far more nebulous.

These restrictions have meant that it is difficult to identify specific market sectors for fisheries GIS, so few groups have seen an opportunity to benefit financially from developing specialist fisheries GIS software. There have been developments in marine, oceanographic and/or coastal GIS software applications and these have been documented in Valavanis (2002) and Wright *et al.* (2007).[55]

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[53] Importantly, this support could include not only official back-up support from the software provider, but also support from other in house or easily accessible colleagues or acquaintances.

[54] For more information on open standards and interoperability, see ESRI (www.esri.com/library/whitepapers/pdfs/spatial-data-standards pdf) or Open Geospatial Consortium (www.opengeospatial.org/standards).

[55] Many marine and coastal software applications are listed at Capn' Dawn J. Wright and OrSt: (http://dawn-drupal.science.oregonstate.edu/soft).

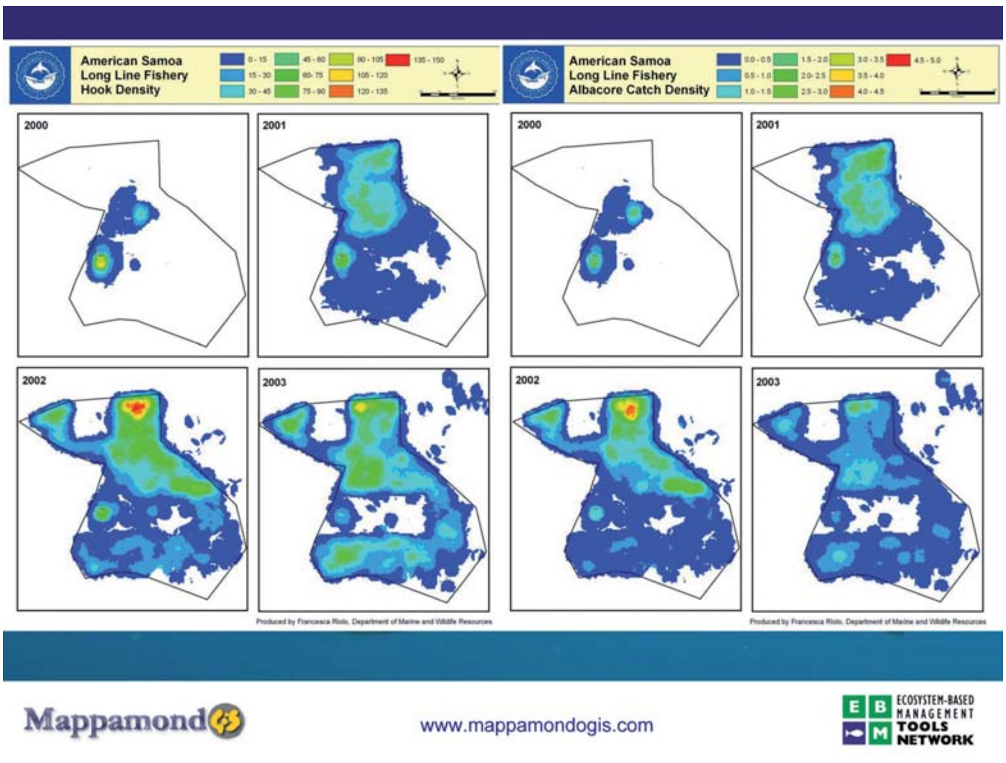
TABLE 2.2

Overview of five main proprietary GIS software

GIS company (Web address)	Main products	Product strengths	Comments
ESRI (Environmental Systems Research Institute) (www.esri.com)	ArcView ArcInfo ArcGIS Engine ArcGIS Server ArcExplorer ArcPad plus others	• Online and instructor-led training • Extensive almost worldwide support, including user forums. • Wide range of specialized products. • Large market share means extensive familiarity with most products. • Basic software has a wide range of tools. • Wide range of additional services and data provided.	World's largest GIS by market share. Quite complex to learn. Easily copes with raster and vector. Demonstration products available online. ESRI publishing produces many GIS-related books. Runs on Windows and Unix platforms. ESRI sponsors a very popular annual GIS conference.
Clark Laboratories Clark University (www.clarklabs.org)	IDRISI Taiga Land Change Modeler Earth Trends Modeler	• Very inexpensive package – only US$95 for a student licence. • Provides nearly 300 modules for the analysis and display of digital spatial information. • Capable of very sophisticated GIS work. • Incorporates remote sensing image processing. • Made for the Windows platform. • Comprehensive tutorial material and technical assistance makes learning easy.	Developed within a university research environment. An integrated GIS and image processing software. Started in 1987, IDRISI is often used in teaching and research. The decision support modules are unique in that they specifically address multi-objective, multi-criteria resource allocation decision problems, as well as problems of assessing and incorporating uncertainty in the decision-making process.
Pitney Bowes MapInfo Corporation (www.mapinfo.com)	MapInfo Professional V.10	• One of the easiest GISs to use • Extensive training provision. • Made for the Windows platform. • Designed for easy visualization.	Since 1986, a commercial general-purpose product aimed mainly at the business market. This product integrates well with other Pitney Bowes business packages. Users still looking for an active discussion group.
Intergraph Corporation (www.intergraph.com)	GeoMedia Professional (one of many GeoMedia spatial products)	• Extensive training and technical support provision. • Many special purpose modules integrate to the basic product. • Wide range of functionality. • Claims to have the most comprehensive GIS on the market today.	This longstanding product integrates well with other applications. The company has been trying to broaden its horizons towards research uses. It provides a range of spatial management services, mostly to government departments. Difficult to gather neutral information on their GIS products.
CDA International Ltd (www.manifold.net)	Manifold Release 9	• Low-priced system gives good price to feature ratio. • Runs on all recent versions of Windows. • Impressive array of vector- and raster-based functionality. • Claims to have the most powerful database capabilities of any GIS. • Easy-to-use system. • Thriving online user group at www.georeference.org.	A new product compared with most commercial GIS. Prices for the basic Manifold software are in the US$250–US$350 range – more expensive versions are available containing more tools. Output from the GIS is basic compared with other GISs. Good range of technical support and accessories. Difficult user interface.

Despite the challenges outlined above, there has been progress in developing fisheries GIS software. Until the 1990s, almost all marine fisheries GIS work was performed on proprietary GIS software and examples of this work can be found in Nishida, Kailola and Hollingworth (2001). During the 1990s, GIS specialist applications were emerging that developed systems allowing for a limited range of marine and/or fishery GIS functionality, or niche software was being adapted to marine problems, e.g. to give 3D portrayals of fish shoals or bathymetry. There is now increasing work being promoted on applying small software applications to undertake specific GIS tasks, with much ofthis work being based on free and open source software (see Section 2.3.3) (Gill *et al*., 2001; Wood, 2004; Wood and Dunn, 2004; Bordalo-Machado, Sousa and Matos, 2007). Some efforts have been made to integrate GIS functionality with fisheries electronic logbooks in order to map fish catches (Kemp and Meaden, 2002; Mikol, 2004), and Kiyofuji *et al*. (2007) report a modular fisheries GIS to support effective low-cost fishing around Japan. However, notwithstanding the many specialized software applications, few of these have been multifunctional in the sense that they could be called a comprehensive fisheries GIS. A recent multifunctional proprietary application that has emerged, one that integrates to ESRI's ArcGIS 9.x, is Fishery Analyst produced by Mappamondo GIS (see Mappamondo GIS: www.mappamondogis.it/products.htm). To quote the distributor "The main functions are quantitative estimation and visualization of catch and effort and their variation in space and time, analysis of fishing vessel utilization, data quality control, and deriving information on the location of important economic and threatened species. The application provides a

FIGURE 2.10
Output from Mappamondo GIS showing the development of albacore tuna catches around American Samoa from 2000 to 2003



Source: Riolo (2008).

Note: Maps produced by Mappamondo GIS using Fishery Analyst (www.mappamondogis.it/fisheryanalyst.htm). Data derived from the monitoring program run by the Pacific Islands Fisheries Science Center in Hawaii and the Department of Marine and Wildlife Resources in American Samoa.

user-friendly analysis interface allowing for easy and diverse output production. The interface allows the user to choose the analysis to perform (effort, catch density, catch per unit of effort etc.) and to select data on criteria such as year, vessel name and/or size, and fish species caught." An example of output from Mappamondo GIS is shown in Figure 2.10. Very recently, Mappamondo has launched a Web-based version of its fisheries GIS software called "Fishery Analyst Online" allowing the user to perform online many of the functional analyses mentioned above (see also Mappamondo GIS: www.mappamondogis.it/products.htm).

The only dedicated multifunctional fisheries GIS software package to have emerged is Marine Explorer produced by the Environmental Simulation Laboratory in Saitama, Japan (Environmental Simulation Laboratory Inc., 2007). This menu-driven software has been developed over the past 15 years as a joint public/private sector project. Marine Explorer can be used to input, store, manipulate and display a full range of fisheries or oceanographic data in both vertical and horizontal dimensions, with output being in mapping, chart or other graphical forms. The system has an integrated simple spreadsheet format for data entry and storage, though it can be linked to external databases and to remotely sensed data sources such as satellite or acoustic systems. Besides simple analyses, it can perform complex tasks such as fishing ground forecasting (to predict promising fishing grounds in real time), geostatistical analyses and abundance estimations. Table 2.3 outlines the main functions and illustrates software applications that can be integrated to Marine Explorer. It is now being used by more than 200 governments and research and university fishing agencies in 12 countries.[56]

2.3.3 Free and open source GIS software

Most groups already working in fisheries or aquaculture GIS will have chosen a core proprietary GIS and will presumably have become familiar with it. Given the length of time taken to gain this familiarity, in most cases it will be worth continuing with the chosen GIS and, indeed, the use of existing GIS software will generate an immediate return in terms of expediting analysis and modelling outputs. However, dependence on known software can deprive users of the flexibility to adopt an open-minded approach to resolving spatial problems. Thus, there are an increasing number of ad hoc GIS applications and spatial information systems designed to collate, manage and visualize spatial information related to a range of terrestrial and marine circumstances. Because of the need to have more flexibility, they are mainly based on open source software and, indeed, they can often be categorized as "freeware". They are discussed here both because of the greater flexibility that these programs may offer to the user and because of the significant cost savings than can accrue.[57]

It is important to describe the difference between "free" and "open source" software (FOSS). Free software (freeware) first emerged in the 1980s from the Free Software Foundation (FSF) established in the United States of America by Richard Stallman. The FSF took an opinion that software source code should be free and freely distributed as a matter of principle and not price, and they were sceptical of the power that could accrue through commercial control of software. The user is free to run, copy, distribute, study, change and improve the software - having access to the source code and to any software manuals is an essential free right to accomplish these freedoms. In the late 1990s, Eric Raymond founded the Open Source Initiative whose more pragmatic focus was on the commercial adoption of FOSS and the software development process used, i.e. rather than the ideology of

[56] See Marine Explorer Support on the www.esl.co.jp for more details.

[57] For example, the Norwegian Mapping Agency has recently switched to using the free GNU/Linux operating system for their online map servers at a saving of 2 million Norwegian kroners (US$327,000).

TABLE 2.3
Functional capabilities of Marine Explorer

Major functional areas	Examples of functions	Software applications Program environment
Spatial information database	**General GIS functions** • Spatial data entry, update, sort, search, filtering, etc. • Quality control **Special functions for fisheries and aquatic data** • Worldwide bathymetry database • Fine-scale local bathymetry database • Sonar and echosounder (mass data) processing • Satellite data processing, e.g. SST, ocean colour, sea surface height, etc.	• MS/Excel • MS/Access • Other databases • Satellite data • Processing programs (20 types) GeoTiff (acoustic data processing)
Visualizations and mapping (2D and 3D)	**General GIS functions** • Visualization by symbols (50 types) • Overlay (128 layers) • Polygon (for non-grid type data) • Composite satellite images **Special functions for fisheries and aquatic data** • Contours (horizontal and vertical) • Buffering (EEZ, MPA, moratorium area) • Presentation of bathymetry • Trajectory of conventional, archival and pop-up tags • Tracking of the movement of vessels (GPS) • Pinger tracking of animal movements • Management (detection of IUU vessels, effort control, and monitoring fisheries by VMS) • Satellite (SST, chlorophyll-a, sea surface height and currents) • Current data (ADCP) • Echosounder (fish distributions from echograms) • Sonar (composition of mosaic images to depict bathymetry)	• MS/Dot NET • Framework • Surfer • GeoTiff (acoustic data)
Spatial/ numerical analyses	**General GIS functions** • Computations of area and distances **Special functions for fisheries and aquatic data** • Gridding (catch, CPUE, SST, etc.) • Contour (density) estimations by kriging techniques (SST data from CTD) • Computation of average and anomaly distribution • Habitat Suitability Index (HSI) • Pinpoint forecasting of fishing and oceanographic conditions by match-up analyses using grid data including satellite information • Geostatistics (spatial GLM) • State-space model (Bayesian processing) • Spatial stock assessment (production models, VPA and integrated models) • Analyses of currents and tides	• Surfer • Spherical trigonometry for the globe (to compute accurate area and distances)

Note: ADCP = acoustic doppler current profiler; CPUE = catch per unit effort; CTD = conductivity, temperature and depth; EEZ = exclusive economic zone; GLM = generalized linear model; GPS = global positioning system; IUU = illegal, unreported and unregulated; MPA = marine protected area; SST = sea surface temperature; VMS = vessel monitoring system; VPA = virtual population assessment.
Source: Adapted from ESL (2008).

the FSF. Some freeware and open source software may need to be purchased and this is fine as long as the user retains the right to copy and change the software as required.[58] 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 data that form "the foundation of a learning society where we share our knowledge in a way that others can build upon" (FSF, 2008).[59] So, both types of software, as well as providing access to free or very inexpensive GIS capability, come with a source code that can be modified and then passed on to others, or it may have simplified licensing arrangements and the user is not tied into the sometimes restrictive demands of the proprietary GIS software suppliers. The discussion that follows does not generally discriminate between freeware and open source GIS software.

The growth of FOSS has also spawned the creation of recognized subdivisions within the world of FOSS GIS, including strong support mechanisms. Thus, as well as the groups who are developing the software itself, there are groups interested in "libraries" (catalogues of projects and/or programs that are classified as FOSS), plus groups interested in Web-serving requirements for the online delivery of data and software. Ramsey (2007) also notes that groups within the FOSS GIS community can be subdivided according to the programming languages that they are working in, and with respect to the types of organizations that are promoting FOSS, e.g. government agencies, universities and/or research establishments, commercial companies and individual enthusiasts. Since 2006, the Open Source Geospatial Foundation (OSGeo) has been in operation and its mission is "To support the development of open source geospatial software, and promote its widespread use",[60] and Sveen (2008) claims that the FOSS GIS community is now centred around this OS Geospatial Foundation, which serves as a host for several projects. Additionally, there are now moves by the International Cartographic Association to achieve professional and technical operating standards for the development of free and open source geospatial software.[61] Although organizations are trying to pursue the rights for more users to have access to freeware,[62] on the other hand, many scientific institutions are trying to facilitate the exchange of information among the community of researchers and managers, and they may see the need to retain existing "conformist" proprietary GIS software. The balance between opting for conformity and choosing to migrate to cheaper experimental or developing GIS may be difficult to achieve. However, Steiniger and Bocher (2009) outline the enormous rate of expansion in the use of FOSS since 2006, with a 6 percent rise in two years in the number of FOSS GIS projects listed on the www.freeGIS.org Web site, and with some companies experiencing a 45 percent increase in free GIS downloads over the last three years. Taken together with the emerging support groupings,[63] plus the fact that 750 participants attended the FOSS4G (FOSS for Geospatial Conference) in 2007 in Victoria, Canada, and 869 attended the 2010 conference in Barcelona, Kingdom of Spain, this all points to the healthy nature of FOSS GIS developments. Table 2.4 summarizes the major advantages and disadvantages of FOSS compared with proprietary GIS.

[58] There are a number of free GIS software products that cannot be classified as FOSS because of their licensing conditions - Google Maps and Google Earth are examples.

[59] For initiatives that focus especially on the free availability of geodata, see FreeGIS: www.freegis.org.

[60] For further details, see OSGeo: www.osgeo.org/content/foundation/about.html.

[61] See details at: http://ica-opensource.scg.ulaval.ca/index.php?page=home.

[62] See, for instance, www.fsf.org.

[63] Support is also available for most applications on mailing lists, discussion forums, wikis, search engines, etc.

TABLE 2.4
Major differences between proprietary and free and open source software

	Proprietary software	Free and open source software
Advantages	• Products are under warranty • All components should work together • Software is usually well documented • Pool of trained workers in some GIS brands	• No licence fees • No limit on the number of installations • No update enforcement • Support of open standards • Support usually available from several providers • Customization at API level • A wide range of unique functionalities • Access to source codes
Disadvantages	• Software price and maintenance fees • High training costs • Maintenance tied to specific licensed companies • Customized development can be difficult due to available resources from vendors • Support only as long as software company exists	• Installation and integration know-how necessary • Training costs • Software developments likely to be more tenuous

Source: Adapted from Weiss (2006).

The range of GIS software under the FOSS heading is vast, varying from complete GIS packages to small applications that just perform a selected task. Table 2.5 gives brief details on some of the main GIS FOSS packages,[64] and the project developer's Web sites should be consulted for further details. If users of FOSS are thinking of adopting such software for future use in order to maintain the long-term viability of the software, it

BOX 2.5
Questions to ask of any open source software projects

Evaluations of projects using open source software (OSS) should ask:
- Is the project well documented? Does the availability of the software provide direct access to both the source code and documentation about the internals of the code? Is there tutorial-level documentation for all three user categories (user, administrator, programmer) to enable people to work with the software quickly?
- Is the development team transparent? Is it clear who the core development team is? Is the development team mailing list public? Is the current development version of the code available online? Is membership in the team attainable via a merit-based process?
- Is the software modular? Is there a clear method to add functionality to the project that does not involve reworking the internals? Is this method documented clearly with examples? Is there a library of already contributed enhancements maintained by the wider user/developer community?
- How wide is the development community? Are multiple organizations represented in the core development team? Are core team members financially supported in their work by sponsoring organizations? Is the development community national or international? How large is the user mailing list? How large is the developer mailing list?
- How wide is the user community? What organizations have deployed the software? What experiences have they had?

The more of these questions that are answered in the positive, the healthier the OSS project is.

Source: Modified from Ramsey (2007).

[64] For a more detailed description of the evaluation criteria, please see www.spatialserver.net/osgis.

TABLE 2.5
A selection of major free and open source desktop GIS projects

Project/software (year founded)	Evaluation criteria					
	Application focus	User level**	Supported operating systems	Development platform	Development by	Software licence***
GRASS (1982) (http://grass.osgeo.org)	Analysis and scientific visualization, cartography, modelling and simulation	Good novice to expert	MS-Win, Linux, MacOSX	C, Shell, Tcl/Tk, Python	Research institutes, universities, companies, volunteers worldwide	GPL
QGIS (2002) (www.qgis.org)	Viewing, editing, GRASS-graphical user interface	Novice to research	MS-Win, Linux, MacOSX	C++, Qt4, Python	Universities, companies volunteers worldwide	GPL
uDig (2004/05) (http://udig.refractions.net)	Viewing, editing, analysis	Novice to research	MS-Win, Linux, MacOSX	JAVA (Eclipse RCP)	Companies, organizations, volunteers	Core Eclipse RCP is EPL
gvSIG (2003) (www.gvsig.org/web)	Viewing, editing, analysis	Novice to research	MS-Win, Linux, MacOSX	JAVA	Companies, universities, government	GPL
Kosmo (2005) (www.saig.es)	Viewing, editing, analysis	Novice to expert	MS-Win, Linux	JAVA	Companies (project driven, utilities, etc.), government	GPL
SAGA (2001/02) (www.saga-gis.org)	Analysis, modelling, scientific visualization	Novice to research	MS-Win, Linux	C++ (MS Visual C++)	Universities	LGPL (API), GPL
ILWIS (1985) (www.itc.nl/ilwis)	(Raster) analysis	Novice to research	MS-Win	MS Visual C	Universities, companies	GPL
MapWindow (1998) (www.mapwindow.org)	Providing core GIS and GUI functions, developing decision support systems	Novice to research	MS-Win	MS Visual Studio .NET (C++, C#, VB.NET)	Universities, companies, volunteers worldwide	Mozilla Public Licence Version 1.1
JUMP/OpenJUMP (2002/3)* (www.openjump.org)	Viewing, editing, analysis	Novice to research	MS-Win, Linux, (MacOSX)	JAVA	Volunteers worldwide	GPL

* There are various versions of JUMP that are now being developed by private companies.
** User levels: novice (viewing), experienced (editing, simple analysis), expert (analysis), research (scripting, programming).
*** Licences: often software use different libraries resulting in a mix of different licences; therefore, only the software-core licences are listed.

Note: GPL = general public licence.
EPL = Eclipse public licence
LGPL = library general public licence
RCP = rich client platform

Source: Modified from Steiniger and Bocher (2009).

is important to verify the background to the software developers, and in particular to ask the questions shown in Box 2.5. Valavanis (2002) suggests that the main criteria to look for when choosing any GIS software are the learning curve, ease of use, hardware platforms, networking capabilities, the amount and formats of data that they can process and their connection abilities with other external packages, e.g. statistical and visualization software. Moreover, when considering the use of FOSS, it is essential to see the exact range of functionality that is contained within the softwarepackage or application. For instance, of the software listed in Table 2.5, the only fully-fledged GIS packages would be GRASS and ILWIS, i.e. they could be compared with the proprietary packages covered in Table 2.2. Other applications in Table 2.5 have a more limited range of functionality. Beyond those listed, there are hundreds of smaller GIS applications and even smaller "plug-ins" that collectively perform a huge range of spatial analysis tasks. It is likely that most people involved in marine and fisheries GIS are using powerful GIS packages (proprietary or FOSS) as their main data servers and a series of peripheral applications and plug-ins (usually FOSS) for specific tasks (Valavanis, 2002). Sherman (2008) agrees that those who opt for the FOSS software route are essentially assembling a toolkit of loosely coupled FOSS applications rather than hoping to depend on one major software package to do all of the work.

Readers wishing to obtain up-to-date books covering all practical aspects of FOSS for GIS may refer to Kropla (2005) or Sherman (2008). For those who may wish to try out FOSS GIS without making a physical investment, this can be done using a live DVD or pen drive link. Thus, "OSGeo-Live 4.5 is a self-contained bootable DVD, USB pen drive or Virtual Machine based on Xubuntu, that allows users to try a wide variety of open source geospatial software without installing anything." (from http://live.osgeo.org/en/index.html). Readers wanting a good practical paper covering some of the numerous software issues confronting their use in a fisheries environment, may refer to Pierce, Wang and Valavanis (2002). The following Web sites provide additional information and more detailed listings of GIS freeware and open source software.

- FreeGIS Project: http://freegis.org;
- Open Source GIS: www.opensourcegis.org;
- Spatial Server.net: www.spatialserver.net/osgis;
- Government Open Source Software Resource Center: www.gossrc.org/geographical;
- GeoCommunity: http://software.geocomm.com;
- Spatial Analysis Online: www.spatialanalysisonline.com/SoftwareFree.pdf.

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

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3.1 INTRODUCTION

This chapter first looks at the types of data needed for fisheries or aquaculture GIS work; it then describes the main characteristics of geographic data and how they are recorded in map form. An examination is also made of issues surrounding data quality and data standards, and the chapter concludes with the important subject of data sources and data collection. Aspects relating to the preparation of data and mapping for GIS use are examined in Chapter 5. For any GIS work, the quality of the data that can be acquired (captured) will have a major bearing on the success of the project, and the main aims of this chapter are to make certain that the GIS user fully understands data requirements in order that success can be achieved in terms of having the appropriate inputs for any GIS project.

Here, data are defined as "purposeful observations that have been recorded and stored", and data differ from information in that the latter represents data (or other material) that have usually been summarized, organized and processed.[65] As mentioned in Chapter 1, data now represent the largest cost element in a GIS project, where the often repeated figure of 80 percent of project costs is given (Clark, 1993; Bernhardsen, 2002). Data for use in fisheries-related work (especially marine fisheries) are frequently more expensive than data used for terrestrial projects because there may be major expenses in gathering data at sea (e.g. vessel purchase or hire, crew costs) and additional costs related to the 3D or 4D environments (vertical and horizontal data needs). There is also the sheer size of marine areas over which data may need to be gathered. Additionally, marine or river environments are mobile in terms of both the water and the objects in them, and this may create a need for more frequent data collection.

The format in which data has been traditionally obtained has undergone a rapid transition during the last two decades. Until the end of the 1980s, virtually all data were procured in a hard copy format, usually paper. This consisted of data represented by maps, tabular and graphical data, and numerous data obtained from a range of documents and reports. For much of the world, the move to digital information systems has entirely reversed this situation, so nowadays it is rare to obtain data that are not in a digital format. However, in this technical paper hard copy is discussed because some data are still collected and stored in this format in many developing countries and thus there is a legacy of existing data that may need to be converted to a digital format.

3.2 EVALUATING DATA NEEDS FOR FISHERIES OR FOR AQUACULTURE GIS PROJECTS

In Section 1.2 some background was provided on the use of GIS and it was made clear that GIS is a tool for allowing the various spatial aspects of a project to be combined for a variety of analytical purposes. The GIS project itself might be ameans of ensuring success for a proposed future activity, or it might be used to improve

[65] Readers who require knowledge on marine or fisheries information and information systems (rather than data) should peruse any Internet search engine under "fishery" or "marine" information systems.

the management of existing capture fisheries or aquaculture in a particular area, or fishery, or with a particular species. Essentially, GIS is being used as a tool to aid the planning, managing or monitoring of fisheries or aquaculture in order to bring about improvement and success. It is important to keep in mind that "success" for any production activity ideally needs to be measured in terms of four criteria:

- Economic. The activity might aim to minimize costs or to maximize profits.[66]
- Social. The activity should aim to best foster the social ideals of those participants in the production activity. This is best thought of in terms of successful social well-being and cohesion, including health, education and job satisfaction.
- Physical/biological. The activity needs to consider production in terms of successfully meeting physical and biological input requirements to the production process.
- Sustainability. The production activity needs to function successfully in combination with other activities for the indefinite future.

It is apparent that there is likely to be a clash in perceptions of "success" between these four criteria. Thus, profit maximization as a goal for success is quite likely to be incompatible with the goal of sustainability, at least in the short term. It is of interest to note that in Meaden and Kapetsky (1991), a forerunner of this present publication, it was noted "we must take profit maximization as our production rationale since failure to aim for this objective will mean that there is no point in seeking suitable locations for aquaculture or inland fisheries, i.e. with enough capital it is possible, through the manipulation of production functions, to produce almost anything anywhere." (p. 7). However, in 1991 sustainability was not a concept underlying much production activity, but since then there has been a flowering of sustainability ideals in many facets of productive life. With the demise of fisheries, as outlined in Chapter 1, it is now recognized that the only way in which the activity can have an assured future is to place sustainability as the core rationale (or modus operandi) for all fisheries-related activities. Profit maximization as the rationale for fishery production is, therefore, being replaced by concepts of sustainability, and it is hoped that sustainability will be achieved through the ecosystem approach to fisheries (EAF) (FAO Fisheries Department, 2003) or the ecosystem approach to aquaculture (EAA) (Soto, Aguilar-Manjarrez and Hishamunda, 2008; FAO, 2010b).

In terms of data needed for any GIS-based project on capture fisheries or aquaculture, what is required are data on how to ensure that any production activity thrives bearing in mind four criteria for success (economic, social, physical/biological and sustainability), or, in other words, bearing in mind the EAF or EAA approaches. In practical terms, for any capture fishery or aquaculture GIS project, it is likely that the people identifying and organizing the project will need to convene meetings with relevant "participants" to identify a number of project parameters.[67] For instance, initially, careful attention should be given to the extent and boundaries of the geographic (spatial) area[68] and the scale (resolution or detail) at which the study is carried out (scale and resolution are examined in detail in Section 3.3.5). Box 3.1 gives some recent suggestions on spatial area and scale for potential GIS applications in aquaculture.[69] It will also be essential to decide on project partners and to decide on work partitioning. It will then be necessary to identify what the spatially based production functions are which in combination can best lead to success. Here, "production functions" are defined as those factors or variables that, in various combinations, influence the success

[66] Whether cost minimization or profit maximization is aimed for may depend upon the nature of the political economy of the country, society or the individuals who are organizing the production activity.

[67] "Participants" here might include local or national experts in the field of concern or perhaps a focus group of local fishers or aquaculturists.

[68] In EAA or EAF terminology, the first phase of the ecosystem approach is to "define ecosystem boundaries".

[69] It is also important to note that the data needs of any project might be dependent on the issue being addressed, e.g. assessment of aquaculture potential, zoning and site selection.

BOX 3.1

Scales and levels of analysis for potential GIS applications to aquaculture

When evaluating data needs for fisheries and aquaculture, an important first step is to define the ecosystem boundaries. In this regard, important considerations are (i) the scales and (ii) the levels of analysis.

Scales

Experts at the FAO workshop on "Building an ecosystem approach to aquaculture (EAA): initial steps for guidelines" (Soto, Aguilar-Manjarrez and Hishamunda, 2008) identified four scales and/or levels of EAA application: the farm; the waterbody and its watershed; the aquaculture zone or region; and the global, market-trade level.

Kapetsky, Aguilar-Manjarrez and Soto (2010) demonstrated that EAA scales are easily accommodated by GIS, remote sensing and mapping as applied to aquaculture because GIS is capable of being applied at any scale. Practically, many spatial applications in aquaculture primarily deal with a natural or an artificial waterbody in its entirety or in part. Otherwise, the geographic extent of many applications is often defined by some extranational, national or subnational level of administration, or national level of administration, or subnational clusters of administrations (see the following "scale definitions"). The scale chosen will dictate data needs and will have a direct influence on the selection of an appropriate methodology and on the level of effort and costs for data purchasing and processing.

Scale definitions

Scale	Scale description
Local	Generally, a natural or artificial ecosystem or a third-level administrative area
State or province	The second level of administration below national
Region within a country	Generally, an area occupying an appreciable part of a country and/or including more than one state or province
National	An application covering the entire country
Region among countries	Covering two or more countries
Continental	Covering all of the countries of a continent
Global	Including all countries with aquaculture

Levels of analysis

Here, the consideration is with differing degrees of assessments that dictate a number of characteristics of data needs. Common levels of analysis from an aquaculture viewpoint are: assessments of the potential for aquaculture; local zoning of aquaculture; siting of aquaculture; and monitoring of aquaculture operations. Assessments of the potential deal with data at relatively low resolution using a few key data sets to generate indicative results, while siting and monitoring require more detailed data at higher resolutions and are aimed at producing more accurate results.

An important point is that there are no hard and fast rules on the numbers and kinds of data at any scale or level of analysis; one uses as much as one can to achieve the desired objective.

Source: Kapetsky, Aguilar-Manjarrez and Soto (2010).

of the production activity.[70] Section 1.4 gave clues to the likely production functions that controlled aquaculture success in the Democratic Socialist Republic of Sri Lanka. These will obviously be production functions that relate to the specific functioning of the fishery or aquaculture activity in a particular area and at a particular scale – no two areas are likely to have the same set of production controls. Some of the functions may be "one-off" considerations that only need apply when, for instance, a site is

[70] It is also important to note that the data needs of any project might be dependent on the issue being addressed, e.g. assessment of aquaculture potential, zoning and site selection.

being acquired for aquaculture facilities. This would be synonymous with fixed costs such as land purchase. Other functions will be akin to operating costs as their consideration may be continual, e.g. access to markets. Production functions may be highly variable within an area or region (e.g. soil suitability, bottom sediment types or population density), while others will be much more uniform in their distribution (e.g. water temperature, salinity and some climatic factors). Increasingly, functions are able to be manipulated in the sense that deficiencies can be overcome. For instance, if there are no electricity supplies nearby, then a mobile generator may be employed, or the deficiencies in oxygen supplies to water can be redressed through artificial oxygenation. However, overcoming function deficiencies can add significantly to costs.

The various production functions will each have their own degree of importance and, if only fairly crudely, it is essential that these can be ranked or measured for specific locations[71]. Practising fishers or aquaculturists are often the best people to do this. Table 3.1 shows the production functions that pertain to cage culture in the Mediterranean Sea, the Kingdom of Spain (Forget, Stuart and Platt, 2009), and it can be seen that both objective and relative suitability are indicated. The importance of measuring the relative importance of production functions relates to the fact that an "importance score" (or "weighting") can be incorporated into GIS-based scoring systems that might be utilized in the search for optimum production locations. Box 3.2 outlines the main production functions that apply to most inland aquaculture. As well as the functions listed, there may be others that apply to individual locations and functions that are less important.

TABLE 3.1
Production functions for fish cage site selection and environmental monitoring in the Mediterranean Sea, Spain

Production function	Good	Medium	Bad
Coastal exposition	Partial	Sheltered	Non-sheltered
Wave height (m)	1 to 3	<1	>3
Water depth (m)	>30	15–30	<15
Water current speed (cm/s)	>15	5–15	<5
Pollution level	Low	Medium	High
Max. temperature (°C)	22–24	24–27	>27
Min. temperature (°C)	12	10	<8
Salinity (average)(L’)	25–27	15–25	<15
Salinity fluctuations (L’)	<5	5–10	>10
Dissolved oxygen (%)	100	70–100	<70
Turbidity/suspended solids	Low	Moderate	High
Sediment type	Sand/gravel	Mixture	Mud
Water classification	Oligotrophic	Mesotrophic	Eutrophic
Fouling	Low	Moderate	High
Predators	No	Few	Abundant

Source: IOCCG (2009).

[71] It should be mentioned that it is often impossible to obtain data on all production functions, but data on at least the main functions should be included in the GIS project work.

BOX 3.2
Main production functions applying to inland aquaculture

- **Land availability** – Usually refers to so-called "greenfield" sites that might be available for development.
- **Topography** – Flat sites are far cheaper to develop, though they can be liable to flooding.
- **Water temperature** – Most species are only tolerant to fairly narrow ranges of temperature.
- **Water quality** – Salmonids are far less tolerant of poor-quality water than, for instance, cyprinids.
- **Water quantity** – Most culture systems require a turnover of water to ensure oxygen availability and to dilute certain chemical parameters.
- **Water access rights** – Access rights to, and availability of, sufficient water is becoming an increasingly important spatial consideration. Aquaculture may be competing with other water users.
- **Soil chemistry and structure** – Many species cannot, for instance, tolerate high or low pH values, and porous soils may be unsuitable for pond construction and for water retention.
- **Adjacent land uses** – Certain neighbouring land uses may be adverse for aquaculture facilities.
- **Proximity to supporting infrastructure** – It is advantageous to be near to essential suppliers or sources of advice, e.g. feed suppliers and veterinarians.
- **Access to roads** – Most inputs and outputs must be brought in or out by road transport.
- **Climatic disturbance** – Care and consideration must be taken in areas subject to tropical cyclones, hurricanes or other severe weather factors.
- **Population density** – People living nearby can provide a workforce and market outlets, but they also provide a source of disturbance or poaching.
- **Distance from other fish farms** – This can be positive (for sharing resources), but negative from a disease-spreading perspective.
- **Access to electricity** – Electrical supplies may be vital to certain production activities.
- **Environmental constraints** – Increasingly, environmental constraints to aquaculture developments are being applied, e.g. mangrove clearance for shrimp ponds has mostly been prohibited.
- **Access to main markets** – It will be important to establish the main markets for output initially, though these might vary over time. They could be wholesale or customer direct.
- **Availability of fertilizer or agricultural by-products** – These are often used to obtain maximum productivity in freshwater ponds.

Source: Adapted and updated from Meaden and Kapetsky (1991).

The spatially variable production functions that influence fisheries are far more varied than those that exert a control on aquaculture, and they vary enormously from fishery to fishery according to, for example, whether the activity takes place in a developed or less-developed country; the species being targeted; and the size of the fishing vessels being used. An additional factor adding to a complex situation is that, whereas most GIS used for aquaculture projects are for optimizing site selection or for monitoring the aquaculture environment (see Table 8.1), in capture fisheries the uses to which GIS are put are far more varied (see Table 10.1). There is, therefore, a far wider variety of production functions about which data might need to be collected. Box 3.3 gives some pointers to the range of spatially variable production functions that may influence the relative success of marine fisheries. For inland fisheries, the production function list would be similar except that some of the water quality factors would vary, the functions would generally be much more crucial to fishery success, and there are likely to be seasonal variations, e.g. in water quantity. The functions shown in Box 3.3 have been ordered to show a progression from natural physical functions, through biological functions, and on to economic and then social functions.

BOX 3.3
Some important spatially variable production functions influencing marine fisheries

Only a limited range of the more important functions can be illustrated here. The functions controlling fisheries on larger inland lakes will be similar to those influencing marine fisheries.

- Bottom sediments – The distribution of many demersal and benthic species is defined by bottom sediment types. This will affect the types of fishing gear used.
- Bathymetry – Different species are physiologically adapted to live at different water depths.
- Salinity – Different species are also adapted to different salinity levels, though some living in tidal zones can tolerate wide variations.
- Chlorophyll – The abundance of these algae can be a good indicator of water productivity.
- Bed shear stress – This indicates the current speeds on the seabed and it strongly influences marine benthic assemblages.
- Water temperature – Again, physiological adaptations are made to water temperature. Seasonal variations can encourage migrations.
- Thermal fronts – These occur where bodies of relatively warm water meet colder water. High productivity along these fronts encourages feeding by pelagic species.
- Species distributions – These are highly variable both spatially and temporally, and will affect the distribution of fishing effort.
- Nursery or spawning grounds – Once identified, it is often essential to give some protection to these areas.
- Marine vegetation – Kelp forests, seagrass beds, coastal mangroves, etc., may all offer unique and important habitats.
- Migration routes – Species at higher trophic levels often make major migrations in response to water temperatures, spawning and/or food needs.
- Predators – Some areas have significant numbers of bird, fish or mammal natural predators, e.g. seals and marine sea birds.
- Distance from port – Fishers will try to minimize fuel costs by fishing as close as possible to home ports. Some ports act as major markets.
- Fishing systems – These may vary greatly at macro- and microscales.
- Fishing effort – The amount of fishing taking place in a given area over a given time period. It may be measured in fishing days at sea, or engine capacity, etc.
- Catch distribution – This is typically measured by species per unit area for a temporal period.
- Fish values – Prices for different catch species may vary significantly and this can affect the fish species targeted.
- Prevailing regulations – Most marine fisheries operate within defined areas that have prevailing regulations that may significantly affect fishery activities.
- Conservation areas – Various by-laws will operate in these areas that will usually restrict fishing effort and catches.

Box 3.4 examines production functions in marine cage culture. As this is a rather specialized activity, it is restricted to a fairly narrow range of potential sites, although in total a considerable marine area has the potential for cages to be sited, especially if consideration is given to aquaculture using submerged sea cages. The functions controlling successful production are much more restricted for this activity. It should be remembered that production functions will also control a range of other aquatic culturing activities, most of which are carried out on a very small-scale in highly selected locations, for example, mussel culture, seaweed culture, and culturing of sponges, sea cucumbers, crabs and lobsters.

BOX 3.4
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 storrn 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 aware of local biodiversity, waste deposition and benthos issues.
- Distance from other cage farms – Because of disease problems, cages are preferably 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 in 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.

This section has discussed in some detail the spatially variable production functions determining the success of fisheries or aquaculture as productive activities, and it is clear that it will be the spatial data that can best describe the disposition of these functions that will be needed as source data for any GIS work. It will be the job of the project personnel (e.g. IT staff, aquaculturists, fishery experts) to decide on what production functions are essential to achieving success for the fishery or aquaculture planning, monitoring or management project. This is an extremely important task in GIS project planning, as the nature of the data to be gathered will depend on it.

3.3 SOME CHARACTERISTICS OF DATA FOR GIS USE

For GIS purposes, all data must minimally have five facets: (i) be temporal (indicate a date); (ii) be thematic (relate to a theme or an attribute); (iii) have a quantity (a number of data objects or events); (iv) be spatial (have a georeference or location); and (v) it will be important that scale and resolution are relevant to the tasks being undertaken. There are other facets relating to data captured for GIS purposes, but these will not be essential requirements with respect to data collection.[72] There is also the important GIS consideration of how data are mapped, but this will be looked at in Chapters 5 and 7. Each of the main facets of data can now be briefly examined.

[72] Examples of other data facets include accuracy, temporary or permanent, data classes – some of these facets are examined later.

3.3.1 The temporal facet

The first facet, temporal, needs little explanation. Knowing when data were collected is both important and useful. Data gradually age and knowing their age is highly relevant in both an absolute and a sequential or relative sense. Because different natural or human processes operate at hugely varying temporal rates, the user may wish to allocate differing time spans over which different data sets retain their usefulness, though the user may constantly face a dilemma over the costs versus benefits of when data sets should be updated. The great majority of data can be used for time series analyses, which themselves point to rates of change or temporal trends within or between thematic areas.

3.3.2 The thematic facet

The second facet of data, thematic, refers to what it is that the data are concerned with. This may be in the form of a thematic area, subject, object or a process and/or event. Themes may be perceived in a wide, general sense (e.g. "marine", "fisheries" or "aquaculture"), or they may be much more specific (e.g. "freshwater fish of the Federal Republic of Nigeria"). There can also be a hierarchy of data within a theme, for example:

- marine fauna
- fish
- demersal fish
- plaice
- female plaice
- juvenile female plaice

Any hierarchy may be important when it comes to setting up a database of associated objects (see Section 5.4). As well as being hierarchical, themes can be simply subdivided into a range of different classes (or classifications). Data can be collected on areas, themes, objects or process and/or events at the same time. For instance, in the sphere of fisheries (theme), data may be collected on the number of salmon (object) in British Columbia, Canada (area) passing a counting station (event), or the number of times a fisher (object) casts a net (event or process) per day. For all thematic data, the main subclassifications (or categories) are referred to in GIS as attributes. So the salmon could be juvenile or mature; large, medium or small; coho, pink, chinook, chum, or sockeye, etc.; and the net being cast could have various dimensions, various mesh sizes, be made of various materials, etc., or it could be undergoing various activities, such as mending, storing, repairing and changing. Although it might be useful with respect to sourcing data, it is beyond the remit of this technical paper to explore all the possible themes that data being used for fisheries or aquaculture work might take. It is suggested that the use of an Internet search engine will be the most convenient means of locating whether data on specific thematic areas exist or not.

3.3.3 The quantitative facet

For the third facet of data, all thematic data (about objects or events) can be quantitative as well as descriptive. This simply means that they can be counted or measured. It is essential to know that counting or measuring can be carried out at various levels, as explained in Box 3.5. It is also important to mention here that quantitative factors relative to data should include a consideration of precision or accuracy – these are discussed in Section 3.4.

BOX 3.5
Levels of measurement that can be assigned as an attribute of collected data

On most occasions, data collection will involve counting or measuring (i.e. quantitative data will be recorded), and these numerical data become an attribute of the objects or events being sampled or surveyed. There are basically four "levels of measurement", as follows:

- **Nominal** – This really only signifies the name given to an object or to a class of objects. It can, however, include numbers, e.g. a fishing vessel registration number. Arithmetic operations cannot be applied to these numbers.
- **Ordinal** – This measurement characterizes objects or events by their rank or order in a sequence. For instance, the suitability of soils for the construction of aquaculture ponds in any area could be ranked from best to worst. Although arithmetic operations cannot be performed on ordinal data, it is possible to establish the median and/or the rank.
- **Interval** – This measurement derives a scale along which readings relative to the object can be placed. Data on water temperatures are measured on an interval scale. But note that there may be no absolute zero on this level of measurement (though there may be an arbitrary zero), and that, for instance, a temperature of 20 °C is not twice as hot as 10 °C. A wider range of arithmetic operations can be applied to interval data.
- **Ratio** – This measure is where an absolute zero is possible, such as the number of fish in a particular aquatic area. It is called "ratio" because it is possible to say that 50 fish is exactly twice as many as 25 fish. Ratio data are the most useful for statistical work.

Source: Adapted from DeMers (2009b).

3.3.4. The spatial facet

The fourth facet of data, i.e. spatial, is a record of where an object is located on the planet or where an event took place, and from a GIS perspective this is arguably the most important facet of data.[73] The spatial facet of data refers to a location that may be specific, for example, a point, or it may be more widespread, for example, an area such as a county. Points are frequently located in terms of a georeference,[74] and there are various methods of georeferencing. For spatially locating exact points on a map, it is common either to record the latitude and longitude for that point or to use a Cartesian coordinate system whereby a grid reference is assigned that is based on an artificial placement of parallel "x" and "y" grid lines across a flat map. Figure 3.1 shows the familiar earth coordinate system provided by lines of latitude and longitude. Lines of latitudes are measured as being from 0 degrees at the equator to 90°N or –90°S at the North and South Poles, respectively. Lines of longitude are measured from the 0° line (meridian), which passes through Greenwich, London (the Prime Meridian), and are recorded in degrees from 0 to 180°E or from 0 to –180°W. For greater precision, both latitudes and longitudes can be divided into degrees, minutes and seconds. Thus, a georeference using latitude and longitude might state that the Statue of Liberty near New York is located at 40° 68' 92"N and 74° 04' 45"W. Computers usually store latitude and longitude data in a decimal format.[75]

[73] All facets of data are important, but it is the spatial facet that distinguishes data as being suitable to be employed in a GIS. The other four facets of data mean that the data could be employed for other purposes but not by themselves for GIS analyses.

[74] A georeference is usually an alphanumeric means of giving a location on a map.

[75] For details on converting degrees, minutes and seconds to decimal degrees, see de Graaf *et al.* (2003) (available at www.fao.org/DOCREP/006/Y4816E/y4816e0e.htm#bm14). For conversion tools, see GPS Visualizer "calculator" (www.gpsvisualizer.com/calculators).

FIGURE 3.1
Illustration of lines of latitude and longitude

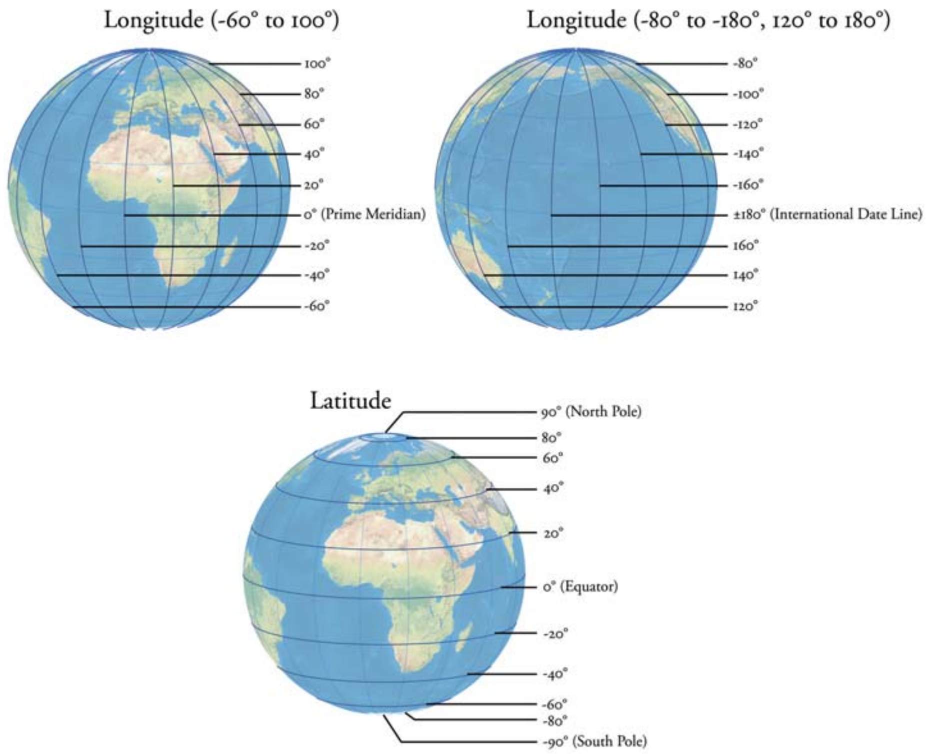


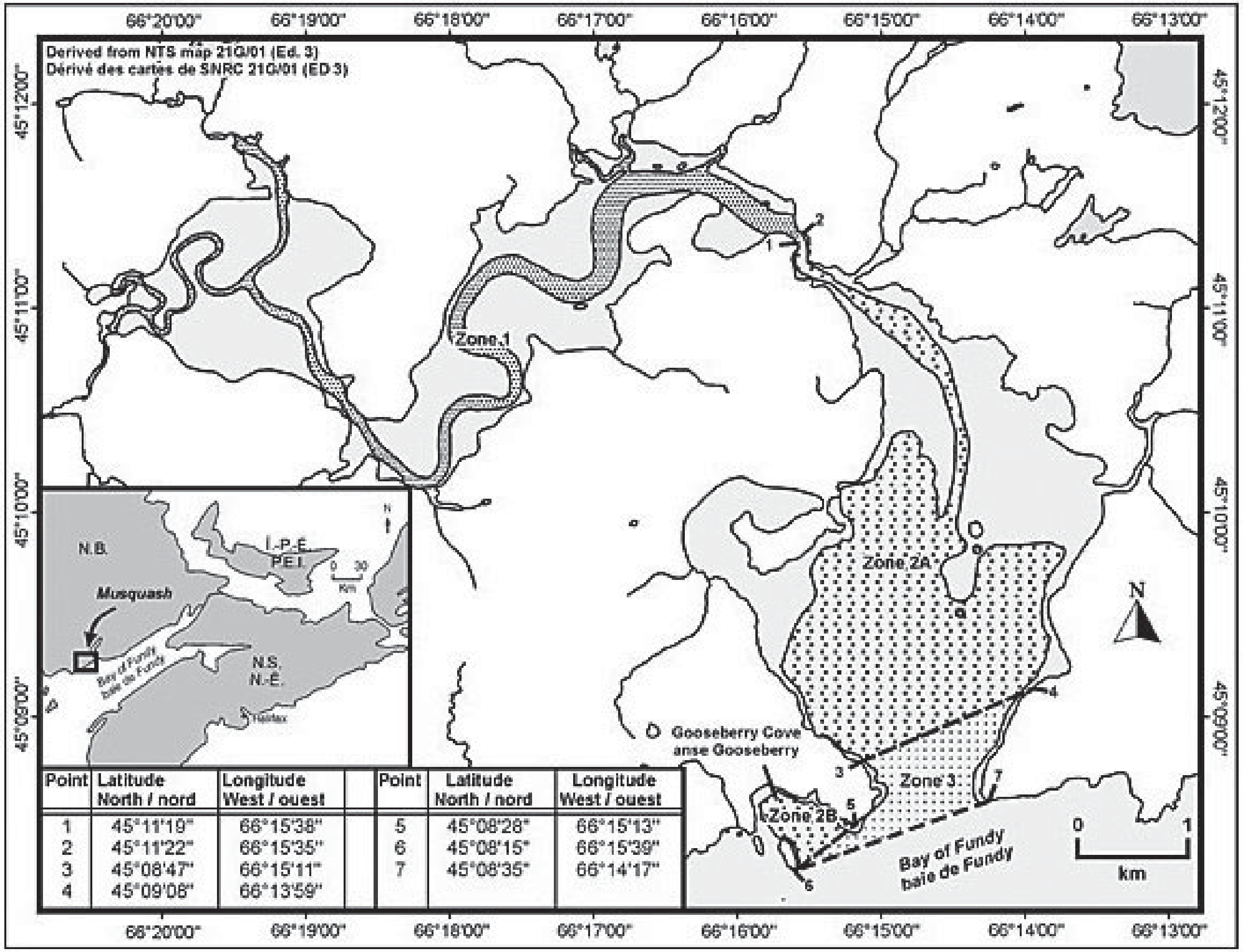
Figure 3.2 shows an example of the use of latitude and longitude designations on a map illustrating a newly designated marine protected area in eastern Canada (Canada Gazette, 2005). Here, the map border uses latitude and longitude designations in degrees, minutes and seconds (to the nearest one minute), though in the legend individual points on the map are shown as latitude north and longitude west to the nearest degree, minute and second.

Although exact latitude and longitude georeferences are readily obtained, e.g. from GPS, and they are useful as points from which to measure exact distances or directions across a curved surface, they are not always used in GIS work. This is because many technologies and mediums for working with geographic data are inherently flat, e.g. paper, square grids, and because the grids (graticule) produced by latitudes and longitudes are non-standard in size. Because people are used to viewing maps, plans, atlases, etc., displayed as flat surfaces, it is necessary to transcribe the ellipsoid shape[76] of the earth onto a flat surface. This requires the use of a so-called "map projection", which is an attempt to convert a spherical shape into a flat surface. There are many different map projections,[77] but none of them can give a true representation of the actual surface of the earth. Different projections have advantages or disadvantages in terms of how accurately they portray mapped shapes, areas, directions or distances, and Table 3.2 gives the best projection for each. For a single GIS project, it is important that all the data sets used conform to the same projection, but most GIS software have the ability to accept a wide range of projections and projections can be readily changed when required. Detailed information on map projections can be obtained from Robinson *et al.* (1995) or Harvey (2008).

[76] An ellipsoid resembles a flattened sphere. The earth is slightly flattened, such that the diameter across the equatorial axis is 23 km more than the diameter across the polar axis. The ellipsoid itself is not smooth having various bumps and hollows that depart from the smoothed average surface by up to 60 m, and on top of this irregular ellipsoid mountains or valleys may be imposed.

[77] For a range of examples, see Robinson *et al.* (1995).

FIGURE 3.2
The Musquash marine protected area in New Brunswick, Canada



Source: Department of Justice, Canada (2012).

TABLE 3.2

Suitable map projections for highlighting different map attributes

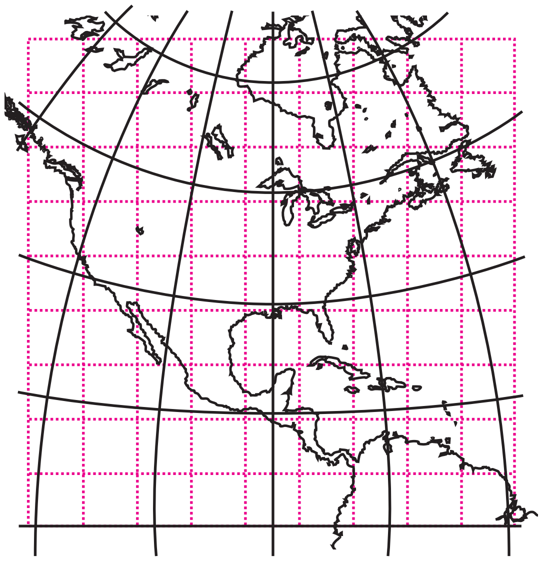
Attribute preserved	Projection	Applications	Examples
Area	Equal area	Many thematic maps use an equal area projection. Maps of the United States of America commonly use this projection.	- Albers Equal Area Conic
Shape	Conformal	Useful for navigational charts and weather maps. Shape is preserved for small areas, but the shape of a large area such as a continent will be significantly distorted.	- Lambert Conformal Conic - Mercator
Distance	Equidistant	No projection can preserve distances from all points to all other points. Instead, distance can be held true from one point (or a few points) to all other points or along all meridians or parallels. If using a map to find features that are within a certain distance of other features, an equidistant map projection should be used.	- Equidistant Conic
Direction	Azimuthal	Projections preserve direction from one point to all other points. This quality can be combined with equal area, conformal and equidistant projections.	- Lambert Equal Area Azimuthal - Azimuthal Equidistant

Source: de Graaf *et al.* (2003).

Once the projected map has been produced, it is still not in a convenient form for georeferencing. This is because the projected latitudes and longitude lines may not be evenly spaced, the lines may curve and the lines may not be parallel. To circumvent these problems, plane Cartesian coordinates are used. This means that a regular square grid is superimposed on the projected map such that the "y" axis is pointing north, or strictly speaking, to the top of the map (Figure 3.3). The most commonly used map projection upon which Cartesian coordinates are used is the Universal Transverse Mercator (UTM). This projection, at least for smaller areas, keeps distances, directions, shapes and areas reasonably accurate. The UTM system has a unique alphanumeric referencing system that allows any location in the world between latitudes 84°N and 80°S to be allocated to a numbered zone to allow for more detailed grid-referencing (Figure 3.4 shows the UTM alphanumeric referencing on the x and y axes[78]). The regular plane coordinate square grid can now be used as the basis for giving georeferences (commonly called grid references) based on linear measurements along the "x" and "y" axes. If any single project is using a variety of mapping sources, it is important that all map layers are utilizing a common georeferencing system.

[78] The yellow arrow in Figure 3.4 identifies the UTM grid cell discussed in Box 3.6.

FIGURE 3.3
A plane coordinate grid (dotted lines) superimposed onto a projected map



Source: U.S. Geological Survey (2012).

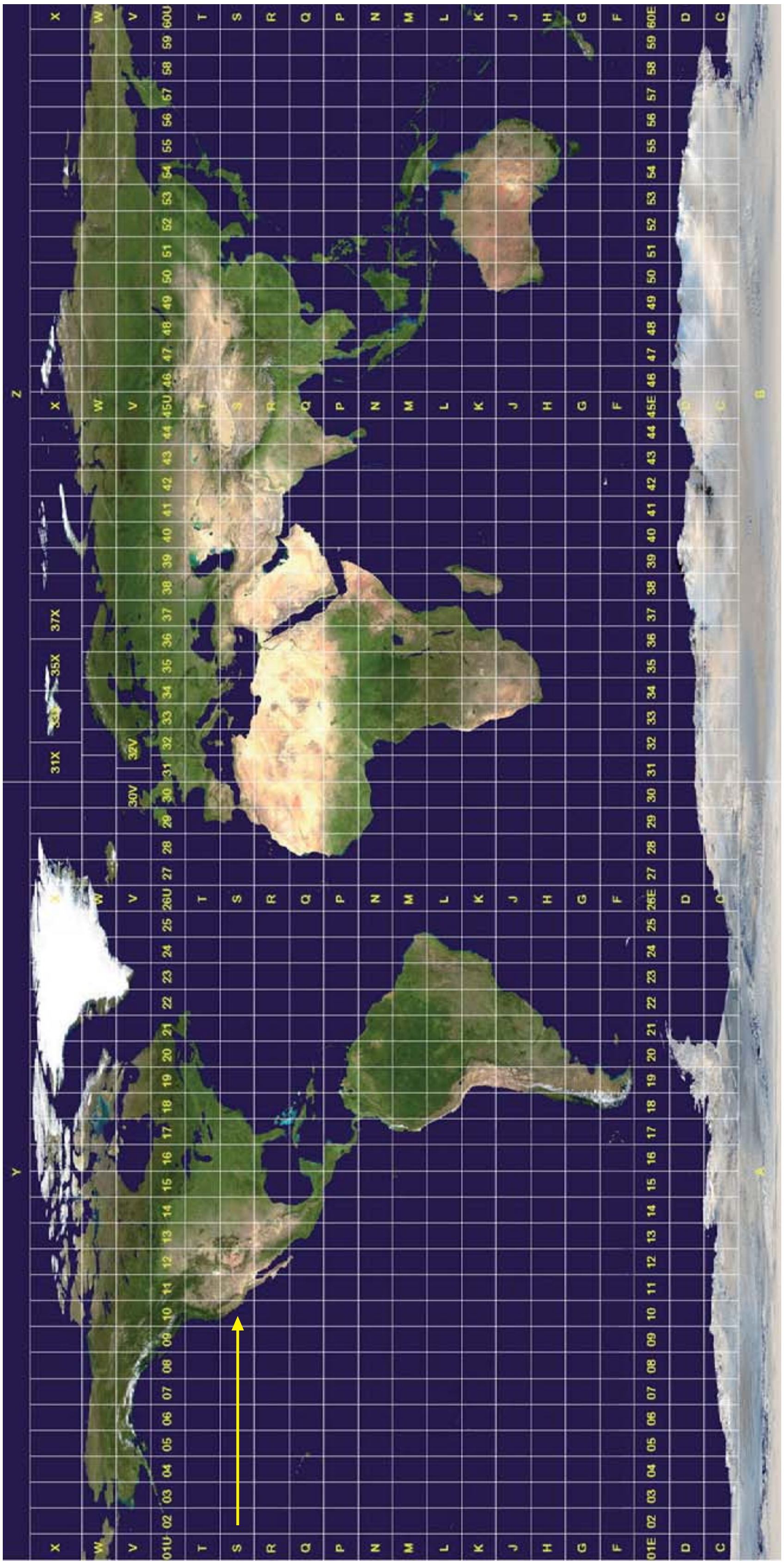
When collecting most geographic data, it is essential that the user knows the basics of reading grid references, even though this task is now usually done by the use of GPS. Box 3.6 explains how a grid reference is derived for the red star located in a small section of a United States of America topographic map.

As well as recording the spatial facet of data through the use of grid reference coordinates, a named area or descriptive code can be used. These codes would normally be allocated to polygons, i.e. spatially extensive or non-point locations such as a county, post code area or census enumeration district. The GIS will have the ability to, for instance, draw a map of county boundaries and then match any data collected for each county to the correct county area. Just as thematic facets of data are stored in a hierarchical referencing system, so too are the descriptive codes given to spatially extensive polygons. For further details on the principles of mapping and georeferencing, see Butler *et al.* 1987; Robinson *et al.* (1995); Van Sickle (2004); Harvey (2008), Petersen (2009) or Crampton (2010), or the following Web sites:

- Harvard University, Graduate School of Design, Boston, United States of America: (www.gsd.harvard.edu/gis/manual/data_basics/index.htm);
- Free Geography Tools: (http://freegeographytools.com/2009/google-earth-coordinate-system-grids)
- University of Colorado, Boulder, Colorado, United States of America: (www.colorado.edu/geography/gcraft/notes/coordsys/coordsys_f.html)

Readers who do not feel confident about handling, finding, interpreting and using geographic information should refer to Johnson (2003).

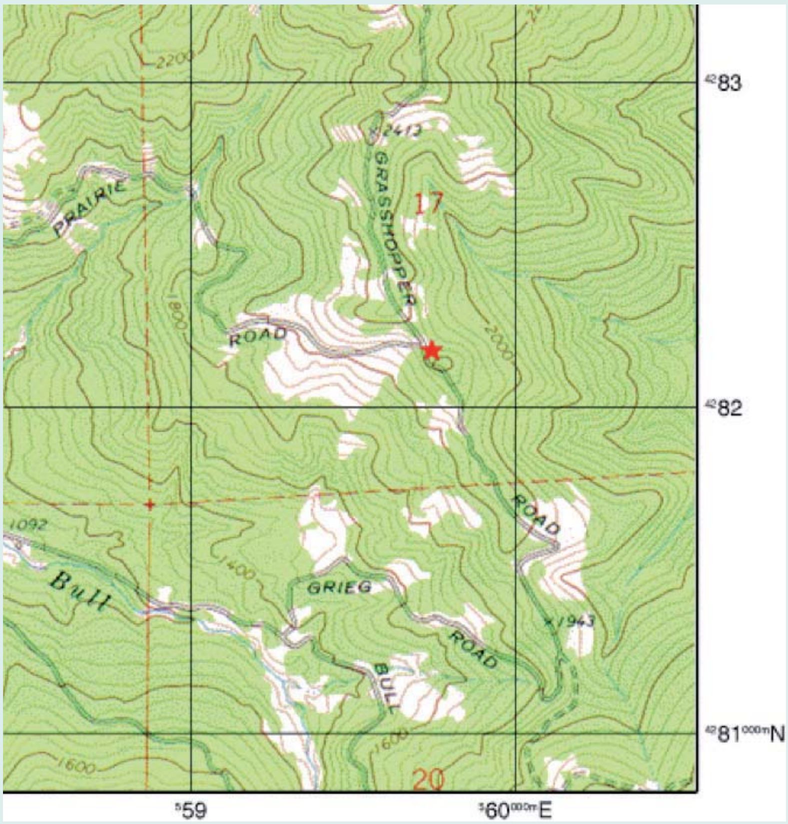
FIGURE 3.4
The basis of the Universal Transverse Mercator grid zone designations



Source: Rambler-Info (2012).

BOX 3.6

How to read a grid reference from a topographic map



Standing at the road junction marked with a red star on the section of a United States of America topographic map shown here, a very precise grid reference using Cartesian coordinates based on a Universal Transverse Mercator (UTM) projection would give a location of:

10 S 0559741 (Easting) 4282182 (Northing)

The 10 S represents the UTM zone number (see Figure 3.4) showing zone 10 to pass through the northwest of the United States of America – this is where horizontal zone S is located; this is a unique global zone number.

The number 0559741 shows that the location is 559 741 metres east of the Cartesian based origin line for zone 10 S. The 559 in the metre measurement is read along the bottom of the map, and the 741 in the measurement is an estimation of the number of metres between the 559 and 560 Easting lines on the topographic map, which themselves are 1 000 metres apart.

The number 4282182 represents a measurement of the north/south position within the 10 S zone in metres from the Cartesian coordinate origin line. The 4282 can be read off from the vertical (northing) axis, and the 182 in the measurement is the estimated number of metres between the 4282 and the 4283 northing lines.

So the full UTM coordinate 10 S 0559741 4282182 gives the grid reference for a location on the earth to the nearest one square metre. Some countries use variations on the above coding method to give their full UTM grid reference.

Source: U.S. Geological Survey (2010).

3.3.5 Scale and resolution facets

Although data themselves might not have properties of scale or resolution, these are essential features to consider when the data need to be mapped or used for any type of GIS purpose. First, when data are mapped, the map itself will have to be reproduced at some scale. This means that there must be a proportional relationship between the size of the mapped area compared with the real area being mapped (or the ratio between distance on the map and distance on the ground). Figure 3.5 gives an illustration showing maps from North America at three very different scales. There is no "correct" scale to use and the scale that is chosen will be related to the size of the area that a GIS project is concentrating upon. A scale may be recorded as a statement such as "one centimetre equals one kilometre", or in the form of a linear bar that is marked off in mapped distances, or as a representative fraction such as 1:50 000 – meaning that one distance unit on the map is equal to 50 000 units in the real world.

FIGURE 3.5
Portions of North America at three different scales

More detail	←	→	Less detail
Larger scale			Smaller scale
1:24 000	1:100 000	1:500 000	1:1 000 000

Resolution refers to the degree of detail that can be shown at any specific scale. For instance, in the first map in Figure 3.5, the city of Chicago and its surrounding towns can be generally shown, but this amount of detail could not be shown in the last map because the resolution is inappropriate. If data are mapped using pixels (rasters – see Section 5.8.2), then the real world length of the side of one pixel represents the resolution of the map. For example, a spatial resolution of 30 m means that one pixel represents an area 30 m by 30 m on the ground. If the pixel is rectangular, it will be represented by a length and width dimension (e.g. 50 m × 80 m).[79] Resolution is a very important consideration when using data in GIS. For instance, if measurements were to be taken to compile a surface water temperature map of the Pacific Ocean, a very large number of sampling points would be needed. If data were only obtained from 100 points, then this resolution would be entirely inappropriate, i.e. it would be possible to construct a map but this map would be very unreliable and it would have very low statistical significance. Therefore, when collecting data for GIS use, thought must be given as to how many data samples will be necessary for the production of reliable mapped information.

3.4 DATA QUALITY AND DATA STANDARDS

Before examining the collection of data for GIS, it is imperative that those who are engaged in data collection are familiar with considerations regarding data quality. GIS output will only be acceptable, and thus useful and successful, if high-quality data are input to the system. Many users of GIS output, and of mapping products more generally, readily accept that these products are always of a high quality. Perhaps this is because many maps are sourced from reputable companies or government agencies, most of

[79] For details on scale and resolution, see remote sensing resources at: (http://biodiversityinformatics.amnh.org/index.php?section_id=31&content_id=119).

which do indeed produce qualitative products, but it is also the case that mapping output should be treated with a degree of caution. This section exemplifies various aspects concerning the basic quality of the raw data used to compile mapping output and, hence, hints at the wide range of circumstances that may cause mapping deficiencies.

What are the main components contributing to data being of high, or at least acceptable, quality? Box 3.7 explains the main qualitative components in brief; further information is available in most GIS textbooks. The overriding factors influencing data quality are the resources of money, time and effort that can be put into data collection or gathering, and the amount spent can significantly affect the final quality of GIS output achieved. It is important to mention that data quality is scale-dependent. For instance, any map made at a world scale will be significantly generalized compared with a town map. It would be impossible to zoom into the dot representing a city at the world scale to obtain better quality information or data on that city. Accuracy is mentioned several times in Box 3.7, and it is important to state that there is an important distinction between accuracy and precision. Accuracy expresses how close a measurement is to the real measurement being quantified; greater care taken should result in greater accuracy, though it is very difficult to say how accurate any measurement is. Precision relates to how precise one needs to be in recording the measurement, e.g. to the nearest millimetre, centimetre or perhaps metre. It is also important that data are collected in a consistent manner. Thus, all data collectors should use the same methods, the same degree of precision and the same means of classification, including object descriptions and class boundaries. A further consideration about data quality is that the GIS user should be aware that there are a large number of possible sources of error in geographic data. Because in some ways these are almost infinite, it is not possible or relevant to list them here. However, most GIS texts devote sections to this (e.g. Burrough and McDonnell, 1998; Lo and Yeung, 2002; Bernhardsen, 2002; Heywood, Cornelius and Carver, 2006).

BOX 3.7
Some important factors to consider regarding data quality

The most important factors or measures contributing to data quality are:

- Positional accuracy – This refers to the locational accuracy to which data are placed on a map. Map scale can affect accuracy, e.g. the width of line shown on a small-scale map may of necessity be shown as being a real world width of several hundred metres. Additionally, in crowded areas of a map, it may be necessary to show objects in approximate positions only.
- Attribute accuracy – This refers to the description given to mapped objects. While it may seem obvious what most things are, difficulties may arise, e.g. in defining the edge between one marine ecosystem and another, and frequently two individuals would categorize objects differently. These problems are multiplied when objects need to be classified into numeric classes. This is a particular problem in remote sensing image analyses.
- Data completeness – Have all the required data been collected in a consistent manner across an entire study area? Note that completeness might not require all data if a sampling strategy is employed that only requires a representative sample of data.
- Data timeliness – Timeliness refers to how up-to-date data may be. Some data may only change very slowly, e.g. bathymetry, while other data may be constantly changing, and for these data timeliness may be almost impossible to comply with. This is a particular problem in fisheries where many objects are in perpetual motion.
- Data lineage – Refers to a knowledge of how the data was collected, e.g. the instrument types used, or how the data may have been transformed or treated in some way.
- Data accessibility – This describes where data can be found and obtained. Data may be more or less accessible according to price, copyright, format, etc., and inaccessible data can result in a need to use perhaps lower-quality substitute data.

Given that qualitative data are of great importance to the success of any GIS project, then one means of ensuring quality and consistency is through the establishment and maintenance of certain data standards.[80] Bernhardsen (2002) notes that standards will provide a definition of data structures, data content and rules that will:

- increase mutual understanding of the geographic data among users;
- eliminate the technical problems of exchanging geographic data between different GISs;
- increase integration and combination of geographical data and related information.

The components of geographic data standards include:

- standard data products – whereby many data sets will conform to standard georeferencing systems, projections, legend categorization, syntax, symbolism, etc.;
- data transfer standards – also known as data exchange standards, ensure that data is readily exchanged among different users;
- data quality standards – see Box 3.7;
- metadata standards – see Section 5.6.

International standards are managed by the International Organization for Standardization[81] (ISO) through a series of technical committees (TCs). The ISO/TC 211 coordinates all matters regarding the development and setting of standards on geographic information and geomatics. Many individual countries or regions have their own geographic standards organizations, such as the European Umbrella Organisation for Geographic Information in the European Union[82] or the Federal Geographic Data Committee in the United States of America.[83] A general overview of standards is given on www.opengis.org, and www.isotc211.org provides further details on international geographic standards.

The FAO GeoNetwork open source (www.fao.org/geonetwork/srv/en/main.home) allows spatial data to be easily shared among different FAO units, other United Nations agencies, non-governmental organizations and other institutions. The FAO GeoNetwork has been developed to connect spatial information communities and their data using a modern architecture, which is at the same time powerful and low cost and is based on the principles of free and open source software (FOSS) (see Section 2.3.3) and international and open standards for services and protocols (i.e. from ISO/TC 211 and the Open Geospatial Consortium).

3.5 DATA COLLECTION AND DATA SOURCES

It has been emphasized that at the same time as data needs are established, for each project the geographic boundary must also be agreed. It is often wise to confine projects to national or state boundaries because many data sources will be restricted – obtaining equivalent data for a neighbouring state may be problematic. When assessing data needs, it must also be remembered that many projects, especially those concerned with fisheries or aquaculture, will require data that are collected and registered in four dimensions. A consideration of the scale or resolution for the project also needs to be made. It might be argued that these do not matter, i.e. because the GIS program will contain a zoom facility that allows the user to work at almost any scale. However, if the data have only been collected using relatively few data sampling points, then it will be increasingly inaccurate to zoom into the mapped information. Finally, it may occasionally be necessary to modify the project aims in order to suit data availability - this may theoretically be a poor basis on which to proceed, but it could be the only practical solution for acquiring certain desired information.

[80] GIS "standards" apply not only to data but to other aspects of computing such as applications areas, technology and professional practice. This allows for interoperability and integration among disparate components of the whole IT system. The term "standards" also has two connotations, i.e. that of "quality" and that of "uniformity".

[81] See International Organization for Standardization (www.iso.org).

[82] See European Umbrella Organisation for Geographic Information (www.eurogi.org).

[83] See Federal Geographic Data Committee (www.fgdc.gov).

Given this paramount importance of data to GIS project success, it is important to ask a range of fundamental questions on data – Box 3.8 provides such a list (as obtained from www.gis.com/content/selecting-right-data).[84] Having determined data needs and other essential facts relating to data requirements, the data themselves must be obtained. Basically there are two broad options for collecting data: (i) collecting one's own data; or (ii) securing data that have previously been collected. These types of data are known respectively as primary data and secondary data.

BOX 3.8
Some questions that should be asked of any data to be collected

- What are the data needed for?
- Where the data might come from and is the data source reliable?
- What are the specific geographic features required?
- What attributes of those features are required?
- What scale and resolution are needed for the data?
- What is the geographic extent of the area of interest?
- What is the level of geography to be examined within the area of interest?
- How current must the data be?
- What type of computing environment will be used?
- What GIS software will be used?
- How many concurrent users will be accessing the data, at how many locations?
- When are the data required?
- Will periodic data updates be required and, if so, how frequently?
- Is the plan to start small, and then expand?
- How much might the data cost?

Source: ESRI (2012a).

3.5.1 Primary data collection

Primary data collection will depend on a number of limiting factors such as:

- the time available;
- the capital outlay planned;
- the skills and number of personnel available;
- the availability and usefulness of any existing data;
- the size of the area being studied;
- the equipment available;
- the purpose for which the data are required.

Any primary data collected could be in various formats, e.g. photographic (video or still), written textual, recorded counts or measurements, labelled pictorial, or digitally captured, but, for GIS purposes, all data collected will eventually need to be transformed into digital formats (discussed in Chapter 5). Additionally, almost all data collected will be the result of a sample survey. Thus, it is rarely possible to collect the total data on any aspect of a project, so some kind of sampling strategy (considering mainly sampling frequency and data resolution) will need to be devised, such that data are collected from a representative range of all possible sites within an area under study. As data sampling strategies is a wide topic, it is not covered here, but there are many texts and Web sites covering this theme (e.g. see Gunderson, 1993; National Research Council, 1998; Stamatopoulos, 2002; Gregoire and Valentine, 2004; Sabatella and Franquesa, 2004). The collection of primary data on fisheries and aquaculture can be conveniently examined under the headings of:

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[84] This Web site can provide further detail on these questions.

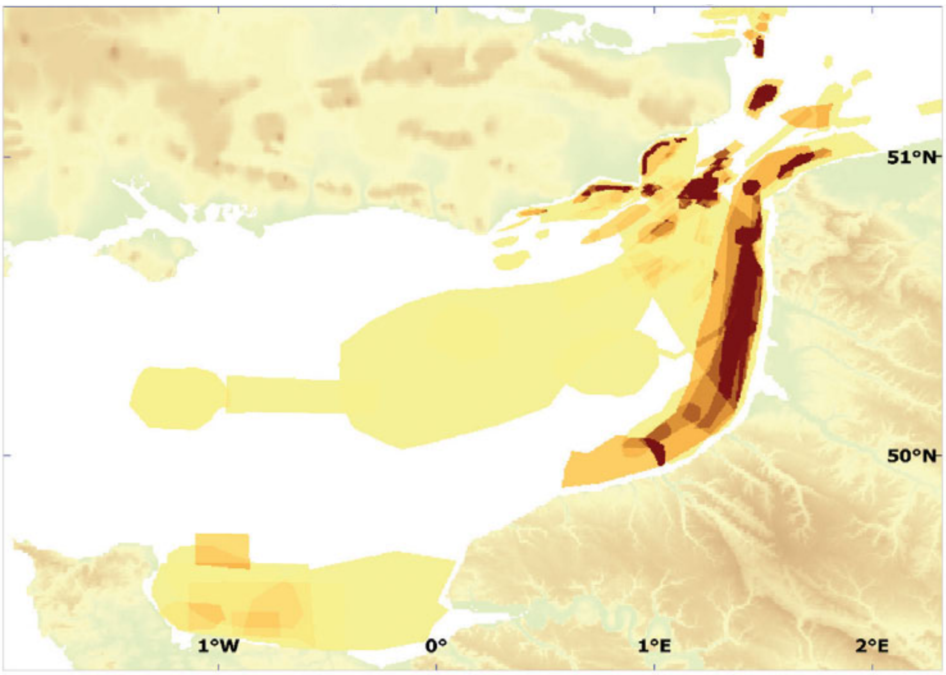
- manual methods using no equipment;
- methods using a variety of equipment.

Manual methods of primary data collection using no equipment

Manual methods of data collection might be conceived as being rather basic but, under many conditions and circumstances, these will be the most practical ways of obtaining the required data. Each of these methods entails varying considerations and complexities – space will preclude a detailed examination of these.

- **Direct sketch mapping**. This will be useful to establish both specific point-based distributions of any variable or more general areas in which an activity takes place. Sketch mapping may also be necessary in instances where available base maps may need updating, and in instances where initially plans are being sketched out, e.g. for the siting of aquaculture facilities. Figure 3.6 shows areas in the eastern English Channel (between the United Kingdom of Great Britain and Northern Ireland and the French Republic) where surveyed local fishers perceive that they mainly fish. Each fisher was given a base map on which to sketch in perceived main fishing areas (perhaps for a particular species), and the results were aggregated to produce this map. Areas of darkest brown show most fishing effort (see www.ifremer.fr/charm, for further details).

FIGURE 3.6
Aggregated fishers' perceptions of their fishing locations for the main commercial species in the eastern English Channel



Source: IFREMER (2011).

- **Interviewing.** Large amounts of data are gathered by face-to-face interviews or by groups of people – often called "focus groups". Data gathered can be both qualitative and quantitative. Interviewing is frequently the only way of obtaining a range of socio-economic information about fisher groups and their activities, and in many areas fishers will have a more detailed knowledge of local conditions than will fishery experts. A potential problem with interviewing is that it may be difficult to ascertain the degree of objectivity prevailing in respect to the data obtained.

- **Questionnaires.** Probably the most common form of primary survey, this usually relies on pre-printed forms. Questioning may be on a face-to-face basis or through the mail or via e-mail or telephone surveys. Questionnaires are very useful for collecting data that may be open-ended or of a preferential response type; aggregations of answers of this latter type can usually allow for statistical analyses. Before carrying out a large-scale questionnaire survey, a small pilot-scale survey should be performed in order to gauge the validity of each question.
- **Form filling.** Many government departments, for instance, have pre-printed forms that are utilized to gather factual data, but any organization can develop forms for any use. Forms are frequently structured so as to allow data to be readily converted into a digital format. Figure 3.7 illustrates typical forms used for recording fishing vessel trips and fishing catch details.

FIGURE 3.7
A basic fishing-vessel logsheet (Form A1) recording details of vessel activity. This may be accompanied by many fishing catch logsheets (Form A2)

FORM A1. TRIP LOGSHEET (LOGBOOK)

Logsheet Serial No:		Vessel ID.:		IRCS:		Trip No:		Date:	
License No:		Vessel name		Logsheets attached		From:		To:	

	PORT	DATE	TIME
Departure			
Arrival			

LANDING PLACE	BUYER	DATE	LANDED QUANTITY (KG)

Captain's signature: ____________________ Date: __/__/__

FORM A2. LOGSHEET (Many A2 forms for each A1 form)

Logsheet Serial No:		Vessel ID.:		IRCS:		Trip No:		Date:	

FILL IN A NEW PAGE FOR EACH DAY, CHART AREA, GEAR OR MESH SIZE FISHED

Chart area:		Gear type:		Quantity gear:		Gear size:	
Mesh size:		No. of hauls/sets:		Average tow/soak time:			

STATISTICAL AREA	SPECIES	LANDINGS (kg)	DISCARDS (kg)

Captain's signature: ____________________ Date: __/__/__

Source: Sparre (2000).

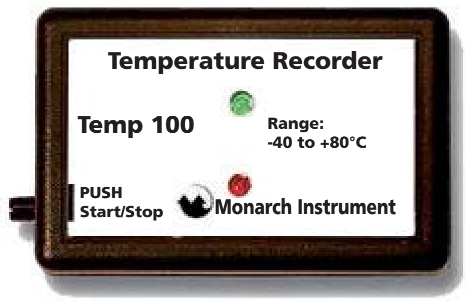
Primary data collection methods using a variety of equipment

A vast range of equipment has been developed for almost every type of data gathering. Over the past few decades this equipment has gradually changed from being mechanically or analogue[85] based to being digitally based, and today very few data are gathered by non-digital means. Fisheries-related examples of data still collected using the more basic, non-digital equipment include the use of various nets to either catch fish samples, or various plankton nets, and the use of simple length measuring devices. In non-fishery fields, instruments such as rain gauges, barometers, soil sieves and clinometers are still in frequent use. Most of this equipment is relatively easy to use, but it is likely that it will be slowly phased out.

In digital data collection, the range of relatively simple instruments is extremely wide and here only a basic range is discussed.[86] The full range can easily be ascertained via the use of Internet search facilities. Here, our discussion is ordered in an approximate hierarchy moving from the more basic towards very complex equipment and systems. The use of an even more complex system – remote sensing – is discussed in Chapter 6.

- **Electronic "read-out" equipment.** This category covers basic pieces of mainly portable equipment that allows the user to read or record measurements on a variety of parameters, e.g. temperature, water-flow rate, pH, weight, humidity and light strength. An Internet search will quickly reveal a more complete range of this equipment. The most basic devices simply give instant readings that could be recorded manually. With increasing sophistication, these devices will record sequences of reading that are typically aligned to time or place. Figure 3.8 illustrates a simple device, weighing only 28 grams, that records temperatures between –40 °C and +80 °C. It can store more than 30 000 readings taken at intervals from 30 minutes to 2 days and to a resolution of 0.1 °C, and these data can be downloaded to a computer for further analysis. There is a close association between functionality and cost and thus care needs to be taken in deciding the quality of the data required.

FIGURE 3.8
Simple electronic device for collecting temperature data



Source: Monarch Instrument (2008).

- **Digital cameras.** These cameras can be usefully employed to capture data on an almost infinite variety of subjects. For instance, McKnight (2009) recently took over 1 500 photographic records showing Pacific oyster densities of this invasive species at sampling points on structures built along the northeast Kent coast in the United Kingdom of Great Britain and Northern Ireland. This baseline information will allow for differential rates of population change to be calculated. The price of cameras has dramatically reduced over the past decade, and their memory storage has exponentially increased. Many cameras have the added capacity of video recording. Airborne digital photography has become a source of huge inputs of data for GIS purposes, and digital underwater photography is capturing increasing data holdings relating to underwater topography, rugosity,

[85] Analogue means electrical output information that is represented by, for example, a voltage reading or a pointer rather than through use of a digital display.

[86] Note that some of this digital data collection equipment was more suitably discussed in Section 2.2.1.

sedimentary structures and vegetation distributions. Airborne digital photographs can be readily incorporated into most raster-based GIS (see Chapters 5 and 6) as an aid to updating mapped data, or as the basis for additional analyses.

- **Data loggers and personal digital assistants (PDAs).** This heading includes a wide range of usually handheld digital devices for communications, basic computing and data capture. Data loggers are handheld, or in situ, devices developed for capturing a range of data on specific themes. They are generally battery powered, portable, and equipped with a microprocessor, internal memory for data storage and sensors. Some data loggers interface with personal computers and utilize software to activate the data logger and view and analyse the collected data, while others have a local interface device (keypad, LCD) and can be used as a stand-alone device. Data loggers are frequently developed and programmed for specific purposes. For instance, nearly all household electricity meter readings are made via a person calling at the house who punches in the current meter readings using a pre-programmed form. Figure 3.9 shows that data loggers may be specially waterproofed (and ruggedized) for use in more hostile natural environments. For all environments (e.g. marine, freshwater and brackish water) for fisheries and aquaculture purposes, data loggers may be deployed to capture data on water quality parameters, on water flow regimes, on fish movements, etc., and instrument deployment may be in the form of free floating or tethered buoys, on instruments attached to vessels, or on a variety of programmed autonomous underwater vehicles, etc.

FIGURE 3.9
A typical waterproofed and ruggedized handheld data logger

Source: MobileDataforce Australia (2011).

  PDAs commonly have colour screens and audio capabilities, enabling them to be used as mobile phones (smartphones), Web browsers, portable media players or computers. Many PDAs can access the Internet, intranets or extranets via Wi-Fi or wireless wide area networks (WWANs). Most PDAs employ touch-screen technology and can be synchronized to a PC allowing for two-way information or data flows. They may be loaded with their own proprietary software, or they may be synchronized with a range of external programs.[87] Figure 3.10 shows a PDA that combines communications functionality with data collection and mobile computing functions. Most PDA-type devices today are pushing the limits on storage capacity, although only a few have so far ventured into the micro-hard drive territory, which greatly expands the storage capacity, making PDAs

[87] An important program that can be loaded to mobile computers is ArcPad. This is mobile GIS software, produced by ESRI, that has been purposefully designed so that field data can be collected in a variety of ways; most include inserting a zoomable backdrop map so that data can be recorded at required georeferenced points as an "overlay" layer to the map. ArcPad also has an integrated GPS, range finder and digital camera (see www.esri.com/software/arcgis/arcpad/index.html).

FIGURE 3.10
An integrated computing and communications-based personal digital assistant

Source: PC Cubed Ltd. (2012).

potentially every bit as powerful and flexible as a desktop PC. There is also a strong demand to increase the integration of functionality so that any one piece of equipment will perform a wide range of tasks. From the data collection perspective, this might be successful, but where there is a need to display and visualize mapped data then a penalty is adopted because of the micro nature of much of the visual display capabilities. However, some PDAs, e.g. Blackberrys, have managed to marginally increase display size. Finally, it is important to mention that developments in this area of data capture equipment are occurring at a very rapid rate, so any PDA equipment purchased may quickly become obsolete.

FIGURE 3.11
A handheld GPS receiver

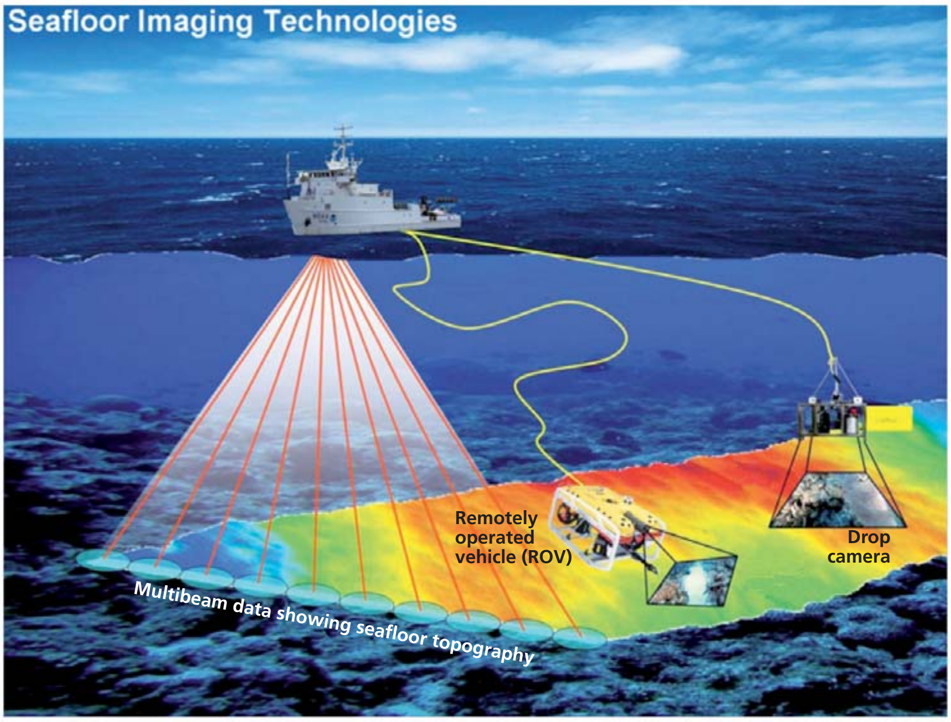
Source: Garmin Ltd. (2012).

- **Global positioning systems (GPS).** Although GPS are complex satellite-based systems, for the purposes of this technical paper it is not necessary to be concerned with exactly how the system works – the concern is simply with the capability of the user segment of the system. Those wishing to find out more details on the total system should refer to Steede-Terry (2000), Kennedy (2005), Taylor and Blewitt (2006) or El-Rabbany (2006). Figure 3.11 shows a typical handheld, battery-operated GPS receiving device. This receiver is used for capturing location information or a georeference at the point where each reading is taken. Along with georeferences, which may be captured as a latitude/longitude set of coordinates or as a UTM-based set of Cartesian coordinates relating to the area and/or region in which the readings are based, GPS receivers can capture and store data on a wide range of variables including route lines, altimetry, travelling speeds and direction, distances and time. This functionality makes GPS a very useful data collection device for any geographic purpose. GPS functionality has now been integrated to a wide range of separate devices or equipment, such as watches, digital cameras, mobile telephones, vehicle navigation systems and in vessel monitoring systems (VMS). Data from VMS are being extensively used to monitor the trajectories of fishing vessels, and it is relatively simple to estimate from the recorded vessel locations and speed of travel exactly where fishing activities have taken place. Handheld GPS may record location accuracy to within 5 m of a precise location, and this is adequate for most fishery and aquaculture purposes. More expensive "differential" GPS equipment can be accurate to approximately 5 cm.[88]

[88] Differential GPS makes use of ground stations having exact known fixed locations to enhance the accuracy of the GPS positions as suggested by any space-based satellites that are fixing the location.

- **Acoustic sonar and other underwater devices.** There is a wide range of acoustic sonar and other devices that capture data relating mainly to depth and to the bottom characteristics of a waterbody, e.g. seafloor substrates or rugosity, or relating to fish locations. There are different types of acoustic sonar that vary according to the trajectories of their scanning functions. The systems work on the principle of having a transducer underwater, which may be mounted on the hull of a vessel, or which may be towed attached to a "towfish", or which may be integral to an autonomous underwater vehicle, or which may be attached to the headrope of a large trawl fishing net. The transducer sends out pulses that, when they encounter objects such as the seafloor or fish, bounce off the object and are echoed back to the transducer. Knowing the time taken for the echoes to be received indicates the distance of objects from the known location of the transducer. Different echo patterns are received on a display unit and this gives an indication as to what the object is. Figure 3.12 illustrates the operation of multibeam acoustic scanning. Here, the remotely operated vehicle (ROV) and the drop camera are being used for ground truthing purposes,[89] but they may be used independently to gather seafloor data.

FIGURE 3.12
Seafloor imaging using multibeam acoustic sonar, a drop camera and a remotely operated vehicle



Source: NOAA National Centers for Coastal Ocean Science (2004)

Sound waves travel differently through fish than through water because a fish's air-filled swim bladder has a different density than seawater. This density difference allows the detection of schools of fish by using reflected sound. While it is difficult to identify individual fish species, it is relative easy to deduce the species of larger shoals that may be present and to estimate the biomass of a shoal. Acoustic technology is especially well

[89] Ground truthing is the process of verifying the captured imagery digital data with what is actually recorded at the site. It enables the captured data to be calibrated so as to aid the interpretation.

suited for underwater applications because sound travels farther and faster underwater than in air and because the use of multifrequencies and omnidirectional sonars has greatly improved the ability to understand the complexities surrounding fish stock behaviour and distributions. Today, larger commercial fishing vessels and fisheries research vessels rely almost completely on acoustic sonar and sounders to detect fish. While acoustic sonar has been mainly used in the sea or large inland waterbodies, Hateley and Gregory (2005) report on the monitoring of fish quantities in freshwater river environments through the use of multibeam sonar techniques. Useful information on acoustic sonar and similar data collection techniques can be found in Simmons and MacLennan (2005) and Foote (2009).

3.5.2 Secondary data acquisition and sources

With respect to both data collection methods and data sources, the acquisition of secondary data has undergone rapid changes over the last few decades. These changes have involved the types of data sources, the form that the data takes, the delivery mechanisms for data and the breadth and volumes of data available. Twenty-one years ago, Meaden and Kapetsky (1991) reported 21 different sources of secondary data, including encyclopaedias, directories, textbooks, reports, maps and atlases. They further noted that the production format of secondary data included written accounts, diagrams, figures, tables, graphs, maps and aerial photographs. Today, very few of their data sources and formats would be considered as applicable. The only sources that still apply are maps, some aerial photography, digitally encoded material and computerized databases, and, in fact, these headings more or less encapsulate all of today's secondary data sources. There has been a move from largely fragmented paper-based data sourcing to more centralized digital data sourcing. Probably more than 95 percent of today's fisheries-related secondary data already exist in digital format, with the main exceptions being some "historical" tabular data held in various paper-based archives and a range of cartographic source materials that have yet to be digitized. The proportion of available digital mapping varies significantly from country to country. A major problem that has been largely overcome in the past 20 years is that of the digital format of any data set obtained. Thus, through standardization of data formats and through the ability to change formats, it is more likely that any digital data obtained will be usable by any GIS software that may be deployed.

Today, secondary data are mostly stored in databases that themselves are held at numerous portals[90] on powerful computer servers awaiting delivery to "clients" via the Internet. Some digital data would still be delivered via CD–ROMs or DVDs, but with the rapid rise of broadband Internet services these delivery mediums would be of decreasing importance. What are the main sources of secondary data? There are a number of major data sources that might be used as initial starting points in any search for marine and fisheries data. These sites include those that supply very general geographic data that could be utilized for cartographic or socio-economic needs, those sites that specialize on broad themes such as the environment or oceanography, and those that concentrate on fisheries (marine or inland) or aquaculture related subjects. Box 3.9 lists some useful starting points. This section does not attempt to list sources of more basic and general data, such as climatic data, soils data, protected areas, administrative regions and biodiversity regions, even though some of these data could well be very useful. Good sources for information on this data are presented in Box 3.10. As well as these major general data repositories, there are a large number of more specific data (and information) sources beginning to accumulate. Some of the means of accessing these are presented in Box 3.10,[91] and Table 3.3 provides an example of the more specific databases that are available for inland fisheries in North America.

[90] Portals are usually access points to the Internet allowing connections to specialized information and data.
[91] The sources listed here represent major FAO compilations.

BOX 3.9
FAO portals to major marine, fisheries and aquaculture data providers

Aquaculture
Kapetsky, Aguilar-Manjarrez and Soto (2010) –
Available at: www.fao.org/docrep/012/i1359e/i1359e00.htm
- Chapter 3: Spatially defined global ecosystems, their issues and their relevance to the ecosystem approach to aquaculture
- Chapter 4: Spatial data to support the ecosystem approach to aquaculture

Kapetsky and Aguilar-Manjarrez (2007) –
Available at: www.fao.org/docrep/009/a0906e/a0906e00.HTM
- Table 4.3: Freely downloadable spatial data and their application to assess marine aquaculture potential: cultured organisms (CO), offshore culture facilities (OF) and transport and maintenance trips from shore facilities to offshore culture facilities (TM)
- Chapter 5: Data availability

Marine and fisheries
Carocci *et al*. (2009) –
Available at: www.fao.org/docrep/012/i1213e/i1213e00.htm
- Annex: Major fisheries and marine data providers on the Internet

Although the material included in general data repositories may cover marine, fisheries and aquaculture data sources, for GIS work directed specifically to inland fisheries or aquaculture it is likely that access will be needed to terrestrial topographic mapping at various scales. Most countries have government mapping agencies that are responsible for map distribution, and the location of these agencies are readily discovered via Web-based searching. Most mapping agencies apply modest charges for paper-based products and much higher charges for the same information in digital formats. However, the latter products will not require digital conversion, a process that can be expensive. On the other hand, paper mapping products can be selectively digitized (see Section 5.2.1) ensuring that only required digital information is obtained. Mapping agencies in some countries provide for interactive map deliveries of cartographic data covering selected areas at selected scales, though this data may only be obtained under certain licensing and copyright conditions.[92] As well as national mapping agencies, many countries have “hydrographic” agencies that can supply charts and other marine information, e.g. bottom sediment, ocean currents, bathymetry, and locations of shipwrecks and other obstructions. As well as government mapping agencies, there are a large number of private companies and other organizations that provide maps or mapped data, with each usually concentrating on specific themes or geographic areas. One such private source of a large range of data is shown in Box 3.10.

[92] See http://nationalmap.govsed or www.ordnancesurvey.co.uk/oswebsite, which provide, respectively, mapping agency data for the United States of America and the United Kingdom of Great Britain and Northern Ireland. Many countries now provide similar mapping services.

TABLE 3.3
Some sources of GIS databases for inland fisheries in North America

Characteristic	Database	Source and Internet address**	Scale	Comments
Geology (bedrock and quaternary)	Geological surveys	Association of American State Geologists (www.stategeologists.org); Geological Survey of Canada www.gsc.nrcan.gc.ca) Global geology (www.portal.onegeology.org)	1:250 000	Small-scale allows for landscape-level analyses
Soils	Soil surveys	USDA, Natural Resource Conservation Service (www.nrcs.usda.gov); Global soil regions (www.soils.usda.gov/use/worldsoils/mapindex/order.html); Agriculture and Agri-Food Canada, National Soils Database (sis.agr.gc.ca/cansis/nsdb/intro.html)	1:20 000 –1:250 000	Large-scale data are useful to characterize the watershed or miscellaneous conditions that influence water quality
Elevation and watershed boundaries	Digital elevation model (DEM); Digital terrain elevation data (DTEM)	USGS, Earth Resources Observation and Science Center (eros.usgs.gov/#/Guides/dem); Natural Resources Canada, Canadian Digital Elevation Data (www.geod.nrcan.gc.ca); NASA, ASTER Global Digital Elevation Model (asterweb.jpl.nasa.gov/gdem.asp)	1:20 000 –1:250 000	Most DEMs currently are small-scale
Hydrography (lakes, reservoirs, streams, rivers)	Digital line graph (DLG); TIGER/line files	USGS, Earth Resources Observation and Science Center (eros.usgs.gov/#/Guides/dlg); U.S. Census Bureau, TIGER (www.census.gov/geo/www/tiger/index.html); Natural Resources Canada, Geometrics Canada; (geonames.nrcan.gc.ca) Global Hydrographic Data GGHYDRO (www.geodiscover.cgdi.ca)	1:24 000 – 1:2 000 000	Provides a base map for planning, mapping and analysis
Dam locations	National Inventory of Dams (NID)	USACE (http://nid.usace.army.mil); Global Reservoir and Dam (GRanD) Database (http://atlas.gwsp.org/)	Not available	A georeferenced database of dam locations in the United States of America and the world
Transportation (roads and railways)	Digital line graph (DLG); TIGER/line files	USGS; U.S. Census Bureau; Natural Resources Canada, the Atlas of Canada (atlas.nrcan.gc.ca/site/index.html)	1:24 000 – 1:2 000 000	Intersections with streams identify access and impact sites; compute road density in watersheds
Land cover/land use	Land use and land cover (LULC); National Wetlands Inventory (NWI); digital raster graphics (DRG); digital orthophoto quads (DOQ)	USGS, Seamless Data Warehouse (seamless.usgs.gov/); USGS, Land Cover Institute (http://landcover.usgs.gov/landcoverdata.php); USFWS, National Wetlands Inventory (www.fws.gov/wetlands/); Natural Resources Canada, the Atlas of Canada (atlas.nrcan.gc.ca/site/index.html)	1:100 000 –1:250 000; 1:24 000	Useful for watershed and riparian analyses; DRGs are digitized topographic maps; DOQs are rectified aerial images matched to DRGs
Place names	Geographic names information system (GNIS)	USGS (nhd.usgs.gov/gnis.html); Natural Resources of Canada, Geomatics Canada (geonames.nrcan.gc.ca); National Geospatial Intelligence Agency, GEOnet Names Server (GNS) (http://earth-info.nga.mil/gns/html/)	1:24 000	Names of physical and cultural places, features and areas

***Acronyms for data sources:* National Aeronautics and Space Administration (NASA); United States Department of Agriculture (USDA); United States Geological Survey (USGS); Department of Defense (DOD); United States Army Corps of Engineers (USACE); United States Fish and Wildlife Service (USFWS).

Source: Modified and updated from Fisher and Rahel (2004b).

BOX 3.10
Online and mobile solutions to GIS mapping from the Environmental Systems Research Institute

The Environmental Systems Research Institute (ESRI) has a number of new and evolving solutions for online and mobile GIS, many of them free that can be used to complement and extend GIS use. These new tools are:

ArcGIS Online provides a common platform to find, share and organize geographic content and to build GIS applications. A wide range of worldwide mapping is available for access and download, and these will be updated twice annually. Online map layers that can be used in your documents include multiresolution imagery, street maps, topographic maps, relief maps and demographic maps. A range of "tasks" is also provided that allows for tasks such as routing, address finding and place locating.

ArcGIS.com is simply the Web interface for ArcGIS. Online, users can access maps, applications and tools published by ESRI and other GIS users, and share their own content with a broad community of users.

Portal for ArcGIS provides the same collaboration and sharing tools as ArcGIS Online, but in the user's own secure environment. It becomes the central repository for authoritative content that users inside an organization can access to quickly create maps and applications using templates and Web mapping APIs*, form groups to collaborate on projects or common activities, share maps and applications with private groups or the entire organization, and embed maps and applications in customized Web pages or blogs.

ArcGIS applications for smartphones allow users to navigate maps, collect and report data, and perform GIS analysis. It is a part of the ArcGIS system and is a new means to discovering content by browsing map galleries from ArcGIS Online or leveraging existing enterprise GIS services. It also displays maps and captured information, develops a custom application or brands own applications specific to business needs, and extends the users GIS to a wider audience.

*Applications Programme Interface.

Source: ESRI (2011a).

Data users will need to check: (i) whether data are free or if they incur a cost; (ii) what the spatio-temporal resolution is; and (iii) what format the data are available in. Data are commonly delivered from any of the Web-based, CD–ROM or DVD data sources in spreadsheet formats that are easy to incorporate into GIS. If the data format is not compatible with the chosen GIS, then conversion to another format may be necessary. The availability of fisheries data tends to be less frequent than marine data mainly because fisheries data are often collected for small-scale projects, where only short time periods are covered, or by a diversity of smaller and perhaps more isolated institutions. Fisheries databases are typically difficult to find on search engines. Valavanis (2002) provides a helpful and extensive commentary on how marine and fisheries data may be integrated and used within a GIS environment.

In order to circumvent any data assembling problems, many groups that are working on fisheries-related GIS projects decide that collection of their own data is beneficial, or they decide that they will only work on GIS projects where they know that good quality appropriate data can readily be obtained. For users, or potential users, of GIS in developing countries, it will be important to check the cost and availability of data before embarking on any GIS work or, indeed, before implementing a GIS per se. Unless the means can be obtained for acquiring appropriate data, then it may not be wise to proceed. However, GIS users could also be encouraged to experiment with data that are readily available, and then to try to assess the viability of any GIS-based analytical output produced against some measure of expectation.

3.5.3 Proxy data

One final means of coping with a deficiency of data needs to be mentioned. This refers to the use of so-called "proxy" data. Proxy data are data that may not be directly related to the exact data required but can nevertheless be a substitute for the real data. For instance, there is plenty of evidence that there is a close relationship between air and water temperatures, certainly in rivers[93] and lakes (Smith and Lavis, 1975; Balarin, 1987), so if average air temperature data can be obtained for a given aquatic site, then these can usually be a good substitute for water temperatures. There are also many relationships between plant and soil types, with all plants showing a preference for more or less acidity, or soils having various structures, e.g. free draining or water retaining. A vegetation map therefore may give clues as to the types of soil prevailing in an area. Much of the GIS-related work on site suitability for aquaculture has been based on these relationships. An example of this work, done by 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 (see: www.fao.org/docrep/w8522e/W8522E04.htm#P951_45085).[94] Whether to use proxy data or not has to be based on a decision involving considerations of the time taken and costs involved in collecting the real data versus the likely accuracy of any intended proxy data. There are also considerations of scale and of the areal extent of the proxy data. Sometimes it might be better to use two or more proxy data sources, e.g. the cost of land might be a function of both population density and of the quality of the soils. In this case, the latter two distributions would need to be combined in an agreed way. Table 3.4 provides some examples of possible uses and sources of "proxy" data.

TABLE 3.4
Examples of possible uses and sources of "proxy" data for aquaculture site selection

Production function requiring data	Possible proxy data source
Soil quality	Distribution maps of particular plant species
Water quality	Distribution maps of various aquatic fauna or flora
Water temperature	Maps or tables of air temperatures
Catering outlets	Listings of hotels or restaurants
Underground water sources	Hydrogeological or geology maps
River water quantity	Annual rainfall maps
Land costs	Population density map
Wholesale market outlets	Distribution of large towns or cities
Fertilizer inputs	Maps of livestock or poultry farms
Availability of capital inputs	Distribution of large towns and cities

Source: Meaden and Kapetsky (1991).

Most of the proxy data shown in Table 3.4 apply to terrestrial mapping of production functions pertaining to aquaculture production and locations. However, it is also possible to use proxy data for developing maps showing aspects relating to capture fisheries, although generally these maps are likely to be less reliable than proxy terrestrial-based maps. This is simply because in the fisheries environment both the

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[93] This relationship may not be the case where the main body of water in rivers is coming from underground (spring) sources.

[94] For details on the main properties of soils for freshwater fish culture, see FAO (1995a) and Meaden and Kapetsky (1991).

environment itself and the fauna in it may be constantly moving both at the micro- and macroscales. Nevertheless, most marine and inland waters can be subdivided into numerous biogeographic realms (at a large-scale) or aquatic habitats (at a small-scale), and both of these are classified on the basis that they are aquatic areas exhibiting collections of integrated species living under specific environmental conditions. So, if the details pertaining to the trophic web of a particular marine biogeographic realm or aquatic habitat are known, it is likely that broad assumptions can be made as to the range of species found there and the likely parameters of local waters (depth, salinity, temperature, bottom sediments, etc.). Much of the recent work done on establishing habitat suitability or essential habitats for aquatic species has relied on these relationships (MacCall, 1990; Rubec *et al.*, 1998; Brown *et al.*, 2000; Leathwick *et al.*, 2006; Fisher *et al.*, 2011; Lauria *et al.*, 2011). An example of this is the work done by Le Pape *et al.* (2003), who showed the direct relationship between the growth of juvenile sole in the Bay of Biscay, in the northeast Atlantic Ocean, and the quality of coastal and estuarine nursery habitats. So, a map of juvenile sole abundance could prove a good proxy for a map of sole nursery habitats. There are, of course, an almost infinite number of similar relationships within the aquatic spheres.

4. Implementation of GIS

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

4.1 INTRODUCTION

Readers who have read or referred to the first three chapters will now understand the importance of GIS to fisheries and aquaculture, and they will appreciate the demands of using GIS in terms of hardware, software and the data that may be required. Thus, they are likely to be suitably equipped to make a decision as to whether and how GIS may contribute to their fisheries and/or aquaculture work, even though they are unlikely to know their precise requirements. If the decision is to move ahead and acquire GIS capability, then the relevant means will be explained in this chapter. It should be noted that this chapter describes GIS implementation procedures required for the management of an average fishery area or for various aquaculture purposes; implementation requirements for a very small or for very large and more complex GIS can be adjusted accordingly.

Some words of caution are needed before embarking on GIS acquisition. Getting GIS properly implemented is an extremely important part of the total GIS adoption process. The lead editor of this technical paper recalls visiting a fisheries organization in a developing country some two decades ago with the purpose of assessing that organization's possible needs and usage for GIS. Some considerable time was spent during the visit trying to establish if other GISs were "up and functioning" in the country; it turned out that many organizations had already purchased systems that covered a wide range of GIS application areas.[95] However, a more detailed investigation of the status of these GISs revealed that in fact only one other GIS was actually working. Most of the other organizations had heard of the potential benefits of this spatial analytical tool and they moved quickly to obtain the software. But insufficient homework had been carried out; for example, little consideration was given to where their data would come from, where local support could be obtained, what the requisite hardware requirements were and who was available to actually work the system. This was a salutary lesson for the author as well as for the organization concerned. As Bernhardsen (1999; p. 321) has noted regarding GIS implementation: "Projects are often technology driven, and technology takes the upper hand, ahead of the tasks it has to perform. The results may be an unprofitable over-investment in hardware and software at the expense of the primary tasks, which remain undone." In a paper, available on the Web at http://spatialnews.geocomm.com/features/mesa1, Hamil (2002) gives an excellent account of why many GIS implementations fail, and Box 4.1 describes some common pitfalls for GIS implementation. It is clear from the information in the box that success for GIS implementation depends upon there being a very interested, cooperative and well-managed computing environment, whose personnel will require a degree of "spatial intuition" as well as task dedication and persistence.

A further introductory point to consider is that the introduction of a complex technology such as GIS into an organization is certain to have repercussions, which may substantially affect current working practices. DeMers (2009b) suggests the following changes that may need consideration:

[95] It is useful to know of other GIS functionality in a local area because this can often prove to be a useful source of support.

- Change in priorities. If GIS becomes productive, then the priorities of the organization might wish to take advantages of any improvements made.
- Change in the organizational hierarchy. According to the success of GIS work, changes might need to be made as to the relative importance of GIS work within the total work ambience of an organization.
- Change in workflow. GIS will cause changes in who does what, how they do it, and when it gets done. People doing the work might need new or different skills. This could lead to changes within the employment structure of the organization.
- Change in the types and amounts of products. Output from GIS may be very different than that conventionally produced, for example, in terms of mapping, animations and reports.
- Changes in training needs. With technological advances occurring rapidly, especially in an area such as GIS, then undoubtedly allowance will need to be made for frequent training updates.
- Change in the financial distribution. GIS cannot be acquired cheaply. The organization needs to understand the budgetary effects and the possible knock-on effects among the existing workers who might not be involved in GIS.
- Changes in working spatial allocation and design. A computing environment means that working conditions and space allocation might be entirely altered.

BOX 4.1

Some common pitfalls contributing to the failure of GIS

Common pitfalls that most often contribute to the failure of a GIS implementation strategy include:

Failure to identify and involve all users. Users in an operational GIS environment consist of operations, management and policy levels of the organization. All three levels should be considered when identifying the needs of users.

Failure to match GIS capability and needs. A wide spectrum of GIS hardware and software currently exist, so it is difficult to make the right choice. The right choice will be the GIS that provides the required performance (no more, no less) for the minimum investment. The success of a GIS implementation is particularly sensitive to the right hardware and software choices.

Failure to identify true costs. GIS acquisition costs are relatively easy to identify. However, they represent a small fraction of the total cost of GIS implementation. Ongoing costs are substantial and include hardware and software maintenance, staffing, systems administration, data acquisition, data updating, custom programming and consulting fees.

Failure to conduct a pilot study. The GIS implementation plan is concerned with many technical and administrative issues and their related costs. Three of the most crucial issues are database design, data acquisition and maintenance, and day-to-day operations. The pilot study will allow the gathering of detailed observations, provided it is properly designed, allowing effective estimations of the operational requirements.

Giving the GIS implementation responsibility to another information technology (IT) department. Because of distinct differences in GIS from conventional IT systems, the GIS implementation team is best staffed by non-data processing types. Specialized skills of the "GIS analyst" are required at this stage. Reliance on conventional IT personnel who lack these skills will ensure failure.

Failure to consider technology transfer. Training and support for ongoing learning for in-house staff and for new personnel is essential for a successful implementation. Staff at all levels should be familiar with the role of the GIS in the organization. Education and knowledge of the GIS can only be obtained through ongoing learning exercises. Nothing can replace the investment of hands-on time with a GIS.

Source: Buckey (2012).

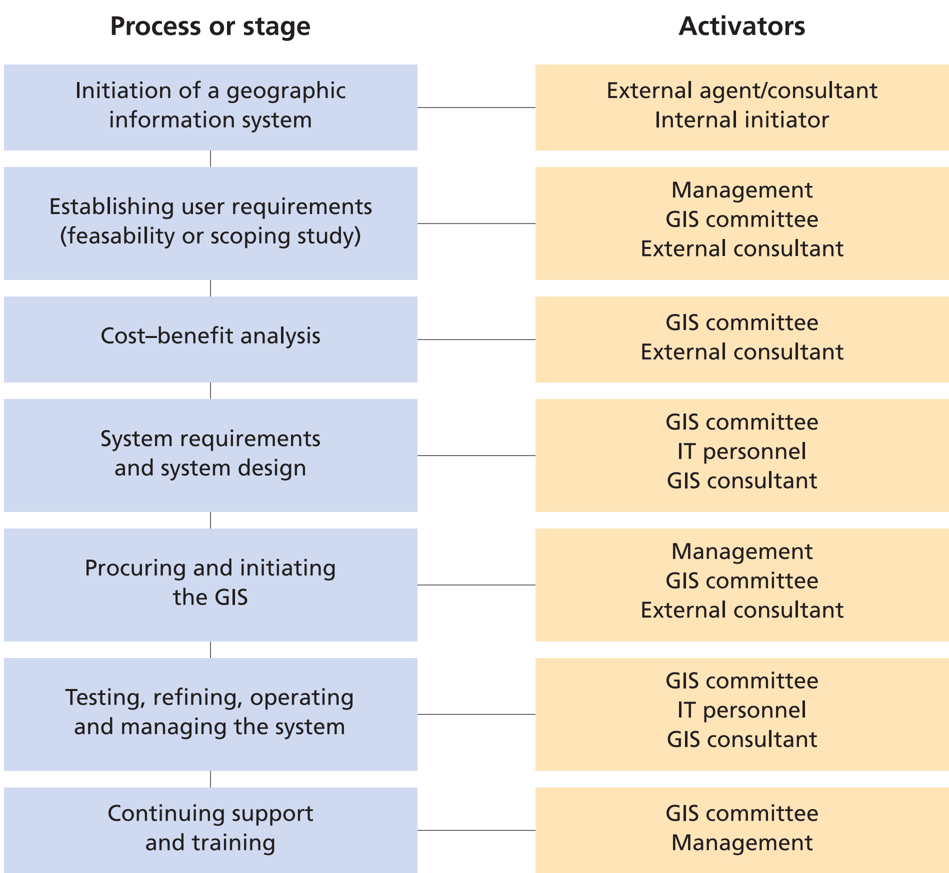
As this list makes clear, people management skills need to be enhanced because human resource satisfaction is vital to any successful organization.

A set of recognized procedures is useful to follow when pursuing GIS implementation, and they are illustrated in various general GIS texts (see, for example, Bernhardsen, 2002; Harmon and Anderson, 2003; Lo and Yeung, 2002; Yeung and Brent Hall, 2007; Longley *et al.*, 2011). Moreover, Ramasubramanian (1999), Taleai, Mansourian and Sharifi (2009), and the following Web sites, also give valuable insights into GIS implementation:

- GISLounge: http://gislounge.com/implementation-of-a-gis;
- Environmental Systems Research Institute (ESRI): http://support.esri.com/index.cfm?fa=projectCenter.gateway&pageID=3&activeTab=1;
- GIS Implementation in the Grassroots: www.urisa.org/files/Siebervol12no1-2.pdf.

More recently, and specifically for fisheries and aquaculture, Aguilar-Manjarrez, Kapetsky and Soto (2010) and Carocci *et al.* (2009) provide some general guidance on GIS implementation to support ecosystem approaches to aquaculture and marine fisheries, respectively. However, to date, there is no single recognized GIS implementation model because this varies enormously between different thematic areas for GIS and between organizations of different sizes or purpose. Figure 4.1 illustrates the main processes (stages) and their activators as currently recognized. It may not be necessary to carry out the processes in exactly the order mentioned and, clearly, some of them can be carried out in parallel. Each of these processes is now discussed in turn.

FIGURE 4.1
The main processes and activators involved in GIS implementation



Source: Adapted from Meaden and Do Chi (1996).

4.2 INITIATION OF A GIS

The idea of using GIS to help resolve problems or challenges in fisheries or aquaculture areas must come from somewhere. The impetus initially comes from an external source. This source may be an article in a journal or trade magazine; it may be from an exhibition or conference; it could be as result of networking or talking to others working in fisheries and/or aquaculture management or research; or perhaps as a recommendation from an external agent such as a consultant or a GIS software house; or, indeed, it might also be from reading a publication such as this technical paper. Whatever the source, there must have been an individual within a group or an organization who perceived the idea of investigating or utilizing GIS as a means of progressing whatever research or management was taking place in their workplace. This individual is called a "champion", i.e. someone who in this case will champion the cause of GIS. A "champion" is usually the person within the organization who initially has the idea of GIS use and adoption and who in some way pursues this and fosters its growth and development within the organization.[96] The champion may be in a managerial position, though it is just as likely to be a middle-level employee who is more involved with the day-to-day practical activities within the group or organization. However, what is imperative is that champions have recognized the potential that GIS has to offer and that they are able and willing to do whatever it takes to promote the future use of GIS. Champions are also likely to know at least some of the potential benefits of GIS and the types of tasks that it could perform, and it is also likely that they will be proactive in that they will be looking for further opportunities to utilize GIS.

At this stage, the full implementation of GIS will probably not have been considered. GIS will be seen simply as an innovative idea to the champion. There are probably many cases where an idea has been perceived but, because the prospective champion lacked the vision or the required impetus, the idea never materialized. But if the champion has vision, then he or she will think about the required actions that need to be taken for promoting the use of GIS. More than likely the idea of using GIS will first be discussed among colleagues, and then sooner or later the idea will make its way to the decision-making level of the organization.

Many readers may note that the GIS initiation process described above is not what occurred within their organization. They probably had GIS imposed upon them, maybe from a senior-level staff member within their group, or perhaps from the distant "head office". In many ways, this situation is undesirable, and it will depend upon how the "imposition" is handled. Thus, when introducing a new and innovative technology, one that will involve substantial changes in working practices, it is vital that management does this with care and consideration and, indeed, it is often good practice to identify a potential "champion" within the workplace, someone who can nurture the future development of GIS within the organization in a way that will be sympathetic to the personnel concerned.

4.3 ESTABLISHING USER REQUIREMENTS (A FEASIBILITY OR SCOPING STUDY)

Once the possibility of using GIS has been "championed", then clearly the feasibility of GIS adoption needs to be determined, i.e. is the use of GIS likely to be a sensible route to take? The feasibility of using GIS varies greatly between organizations in terms of not only their needs, but also according to their familiarity with information technology, the skills of their personnel and management, the resources available, and whether the use of GIS will help attain the goals of the organization or group. Several authors have highlighted the fact that user requirements have been the most neglected aspect

[96] It is likely that a large number of GISs will have been adopted through the enthusiasm of such an individual.

of information system development (Hadzilacos and Tryfona, 1996; Lo and Yeung, 2002). There are various ways of carrying out a needs assessment, all of which might be termed a feasibility (or scoping) study, and which will be variably applicable according to individual situations. Four useful ways of conducting a feasibility study are through:

(i) **A GIS committee.** The champion or a senior manager should establish a small committee of interested personnel who are given the responsibility for investigating the potential that GIS has to offer. One important task will be to consult with other organizations who have successfully adopted GIS, and possibly to invite an expert who can give a talk or demonstration on general GIS capabilities.

(ii) **Survey questionnaire or interview.** For smaller organizations, the champion or management should circulate a questionnaire to relevant personnel to help identify key issues (e.g. aquaculture siting and zoning), and to assess their GIS capacity and their likely needs for GIS. This information might also be gathered in the form of structured interviews.

(iii) **Holding special workshops, seminars or demonstrations.** In most information technology (IT) sectors, special workshops are organized so that any interested party can participate in exploring the idea of adopting GIS.

(iv) **An external consultant.** It can be invaluable to recruit an external GIS specialist who can ascertain the needs for a GIS, and whether a GIS can be afforded and sustained. Although this might be expensive, the specialist should have extensive background and thus be aware of the wide range of considerations to setting up a successful GIS. It is important that the external consultant has both knowledge of GIS and of fisheries or aquaculture. It is likely that a consultant or adviser can point out an additional array of spatially based problems that GIS might resolve.

Organizations can carry out any combination of the methods listed above. Readers can also raise their awareness of GIS potential and GIS needs through reading up on these subjects, either through some of the general texts suggested in Chapter 1 or through searching for information on the Internet. Attending exhibitions or conferences are also advantageous, as they are opportunities to meet people who have knowledge of GIS and of any pitfalls to its use.

What types of general questions need to be asked in undertaking a scoping study[97]? Box 4.2 gives some main areas for questioning and makes clear that there are a large number of areas that need to be researched before a GIS can be considered. A major point to note is that there are various operational alternatives for GIS implementation. These can be briefly explained as:

- **Using a "headquarter's GIS".** Here, GIS is envisaged as an important function that can best be accommodated as a centralized activity at an organization's headquarters. This will usually be as a result of GIS being a major decision-making tool – one that needs to be accessible to management and to offices where data and IT systems reside.
- **Having on-site localized GIS.** In many cases, GIS might be functioning as a tool within a specific department, research station or outlying office. Within a larger organization, GIS might operate on several local sites.
- **Contracting work to a GIS company or consultant.** For organizations where the cost–benefit analysis (see Section 4.4) shows GIS to be of only marginal value, it could be sensible to contract the work out to specialists. For GIS, this might enable considerable cost savings in terms of operating and maintaining the system as well as in some of the capital costs.
- **Sharing or collaborating in the GIS work with a similar organization.** In the sense that there are a large number of minor organizations, small fishery

[97] At this stage of GIS implementation, it will only be necessary to ask general questions concerning GIS adoption, though there should be some knowledge of the types of work to be undertaken.

departments, small research departments, small states or regions, all of which might have a limited amount of fisheries or aquaculture work, a sensible plan might be to work cooperatively and/or to share facilities and support.

There are no right or wrong implementation alternatives and the means chosen will reflect particular local circumstances. Thus, it is important not to proceed with full GIS adoption if there is insufficient demand relative to the costs and effort of establishing GIS capability. The outcome of the feasibility study should be in the form of a short document, with much of the information being transferable to, or incorporated in, the system's design report (see Section 4.5).

BOX 4.2
Examples of questions to be asked in a feasibility study

- What are the key issues relating to the management and further development of the fisheries and/or aquaculture sector?
- Which of these issues are fully or partially spatial?
- What might a GIS reasonably do for the organization?
- What geographic area should be covered?
- Should GIS be shared with others?
- Should the GIS operate across the whole organization?
- What georeferenced data does the organization have?
- What data are needed?
- Will the organization need to use a customized GIS?
- Is there likely to be a longer-term need for a GIS?
- Will there be good access to support and training?
- Will there be time for existing personnel to do GIS work?
- Will existing personnel accept the introduction of GIS?
- To what extent will GIS satisfy information needs?
- Would funding be available for any longer-term GIS work?
- Does the organization have the right methods for doing GIS work?
- Are there better ways of achieving the information that is needed?
- How much will each employee need to learn about GIS?
- Where can reliable external advice be obtained?
- Can a GIS be integrated to the existing IT functioning?
- Who will champion the GIS work in the future?

4.4 COST–BENEFIT ANALYSIS

If it seems likely that the need is there to justify GIS adoption, this should still not proceed until some kind of cost–benefit analysis has been pursued. This basically involves undertaking an exercise that attempts to balance the total costs of acquiring the system against the benefits that will be gained from deploying a GIS, i.e. do the advantages of adopting GIS outweigh the disadvantages? To exemplify a range of capital costs that might be required, Box 4.3 illustrates some recent costs involved in installing the main components of a GIS system in the People's Republic of Bangladesh as part of an FAO field project. This system was able to utilize existing computers, and note that up to five seat licences were acquired to be used by a team of about five people. Although this information exemplifies real capital costs, they will be highly variable according to the scale of the GIS operations envisaged and according to any existing hardware and software that may be available.

BOX 4.3

Example of some costs involved in a recent (2009) implementation of GIS for aquaculture work in Bangladesh

Equipment (for TCP/BGD/3101)	US$	Quantity	Total US$	
HP Colour LaserJet 5550 dn	4 218	1	4 218	
Oki C830 Dn A3 Colour Laser printer	2 165	1	2 165	
Adobe Photoshop CS4 v11, English version (inclusive CD)	397	5	1 985	
Idrisi Taiga (software)	1 250	5	6 250	1 licence
External hard disk GB 250	91	5	455	
Global positioning system (GPS)	105	3	315	
ArcGIS 9.3 ArcView Concurrent Use Licence	1 925	1	1 925	UN price
ArcGIS 9.3 Spatial Analyst Concurrent Use Licence	1 375	1	1 375	UN price
ArcGIS 9.3 ArcView Single Use Licence	825	5	4 125	UN price
ArcGIS 9.3 Spatial Analyst Single Use Licence	1 375	5	6 875	UN price
	TOTAL		**29 688**	

Source: FAO training course on "Use of Geographic Information Systems for Aquaculture planning and Management", held 25–29 October 2009, as part of the FAO field project entitled "Developing a national shrimp seed certification system" (TCP/BGD/3101).

Terminology:

Concurrent use licence. A concurrent use licence permits execution of the software on any computer on the network. A concurrent use licence allows a product to be licensed such that multiple users can gain access to the software concurrently through a shared pool of licences administered by a central licence manager. The number of concurrent licences determines the number of users who can run the applications concurrently. However, each user only accesses a licence when it is needed as a concurrent use licence is not locked to a single computer and, as such, can "float" on a network.

Seat licence. The number used to specify the amount of concurrent instances of the software that can be used at one time. Most often, seats represent users at individual computers. However, seats may also represent the concurrent number of servers or connections in use.

Source: ESRI (2012b).

It is important to note that neither "costs" nor "benefits" can be simply quantified in financial terms; they are likely to be more nebulous "values", such as "gaining access to qualitative maps" or gaining any specific information that will be of value to decision-making. It is widely recognized that true cost–benefit analyses in GIS are difficult to perform in terms of obtaining objective results (Maguire, Kouyoumijan and Smith, 2008).[98] In fact, Obermeyer (1999) suggests that the potential costs and benefits of implementing GIS fall into two categories: tangible (economic) and intangible (institutional). Table 4.1 illustrates Obermeyer's findings. The author suggests that the intangible costs and benefits are generally more important than the tangible, and this makes the adoption decision more difficult.[99] It is also the case that benefits may take a long time to accrue for GIS work, so there may be an initial period where the costs far outweigh the benefits. An additional problem with cost–benefit analysis is that the ratio between the two can vary greatly according to the time period over which equipment is depreciated, and with GIS work the value of the output obtained will vary greatly from project to project. Nevertheless, it is important that these considerations are made because the analysis may provide the best information as to whether GIS adoption should proceed. If the necessary expertise exists, a cost–benefit analysis can be performed internally, but it is often advisable to hire experienced analysts for this task.

[98] A detailed synopsis of this publication can be obtained from http://roi.esri.com; this publication is one of the few attempts to quantify cost–benefits for GIS use.

[99] Because of their subjectivity, cost–benefit analyses can be thought of more as an art than a science.

TABLE 4.1
Summary of main costs and benefits associated with GIS

Category	Costs	Benefits
Economic (tangible)	Hardware	Reduce costs (e.g. of staff)
	Software	Greater work productivity
	Training	Increased revenues
	Additional staff	New market services
	Additional space	Expanded market potential
	Data	Rapid access to output
	Maintenance	Decrease in contracted services
Institutional (intangible)	Interpersonal shifts	Quality visual products
	Layoff of staff	More accurate analytical data
	Staff anxiety	Improved client relationships
	Neglect of other projects	Improved morale of workforce
	Increased vulnerability – computers	Better information flows
		Enhanced sense of achievement

Note: Most reduced costs accrue because the addition of GIS adds to the outputs from staff and equipment, e.g. there will be greater productivity.
Source: Adapted from Obermeyer (1999).

Output from a cost–benefit analysis is frequently in the form of a spreadsheet or a small report. This information may be used by senior management in prioritizing GIS adoption against competing funding needs, or it might allow GIS to be immediately ignored as a non-viable option for that specific organization. Longley *et al.* (2005b) note that there have been surprisingly few cost–benefit analyses published with respect to GIS implementation. This is most likely because it is a difficult task in the sense that so many of the costs and benefits are either intangible or they are difficult to separate out from other costs, e.g. staff may be working on non-GIS tasks, as will computer time allocations. A detailed set of GIS cost–benefit considerations can be found in Bernhardsen (1999), at the NYS GIS clearinghouse (www.nysgis.state.ny.us/coordinationprogram/reports/montana), and at the European Commission (www.gisig.it/best-gis/Guides/chapter9/nine.htm). A cost–benefit analysis is strongly advised because it will allow an organization to get an early feeling for what may be involved with a GIS implementation. If the task is too difficult, then it may be possible to simply produce lists that detail the advantages and disadvantages of GIS adoption.

4.5 SYSTEM REQUIREMENTS AND SYSTEM DESIGN

If the benefits of operating a GIS within the organization clearly outweigh the costs, then the implementation can move to the system design stage. The outcome at this stage should be creating a report entitled "GIS system design", which not only provides answers to the types of questions posed in Box 4.2, but which also demonstrates the conceptual design of the complete system in terms of hardware, software, personnel, data sources and databases, and includes factors such as the architecture of the GIS, where it might be housed and how the management structure might operate. The purpose of the "GIS system design" report is to serve as a comprehensive guide showing that all aspects of GIS implementation have been considered, as well as to inform management of the total intentions and requirements for GIS implementation. It is very important that managers know what the GIS involves. The report can further be made accessible to external suppliers who might be contributing towards assembling the GIS.

The "system design" report can be a major task because it will involve a range of expertise and a wide range of considerations. Thus, the sections on hardware, software and data needs can be extensive and tricky to complete without additional advice. If an in-house GIS expert is not readily available, then it is recommended that external advice be sought. It is recognized that many GISs being implemented for fisheries or aquaculture purposes may be starting at a relatively simple level and, indeed, in most situations this scale of entry to GIS is recommended. This might be reflected in a relatively basic system design document. However, whatever the scale of GIS adoption is, it is still recommended that the main sections of a system design report should include those shown in Box 4.4.[100] If future GIS work is successfully accomplished, there could be a rapid expansion of the system and various allowances must be made for this, e.g. personnel, rooming, additional capitation and software upgrades. For further information on GIS system design, see Lo and Yeung (2002), Harmon and Anderson (2003), Heywood, Cornelius and Carver (2006), Yeung and Brent Hall (2007), or in Peters (2008), which is available at www.esri.com/library/whitepapers/pdfs/sysdesig.pdf and which provides comprehensive information.

BOX 4.4
The main sections of a "GIS system design" report

- **Introduction** – Detailing what the overall objectives for a GIS are, how this might help meet the "mission statement" of the organization and the results of the cost–benefit analysis.
- **GIS accommodation** – Details of rooming requirements and user site location(s) for the system.
- **GIS projects to initiate** – A summary of each of the GIS tasks that are already envisaged for the projected system, possible future projects, how projects might help meet the organization's needs.
- **Personnel requirements** – Including number of personnel, level of appointment, job descriptions, possible training, and possible needs for external help.
- **Data needs and sources** – Include existing data held, data modifications, new data sets required, data sources, database design, data storage, data management and database model to be deployed.
- **Hardware requirements** – To include numbers and specifications of computers, range of peripheral hardware, system's architecture, network communications, possible hardware suppliers, plus a review of existing hardware capacity.
- **Software requirements** – Functions required from software, software proprietary options, range of software required, including operating systems, word processing, spreadsheets, databases, plus the GIS software and software support.
- **Management needs and system's organization** – How GIS will fit into the organization, how it will be managed, work allocation, possible cooperative use of facilities, lines of responsibility and who will receive GIS output.
- **Availability of support** – Accessibility and range of back-up support, documentation and literature, plus support needs.
- **Level of capitation and running costs** – Estimations of all capital costs, estimations of staff and data costs, estimations of ongoing running costs, such as rent, power, peripherals, and possible sources of funding, amortizing period for hardware and software.
- **Constraints, challenges and risks** – Any recognized constraints or risks should be declared at this point (some of these might be indentified in the cost–benefit analysis).
- **Proposed implementation dates** – This might include target dates for each stage of GIS implementation.

[100] It should be noted that the "GIS system design" report is not the same as the "GIS implementation" plan (which is discussed in Section 4.6).

4.6 PROCURING AND INITIATING THE GIS

If following feedback from the GIS system design the decision is made to adopt GIS, then there are fairly standard procurement procedures that ought to be used in order to ensure successful installation of GIS. This stage is concerned with putting together an "implementation plan", which is really an extension of the system design report (Box 4.4). In this way, full GIS implementation can proceed in a structured, planned and efficient manner. In addition to the system design information, the implementation plan will include factors such as the manner of GIS introduction (see boxes below), the geographical area coverage for the GIS, the timing and cost schedule for implementation, quality control, any organizational matters, need for pilot studies, plans for support and training (see Section 4.8), system maintenance and security arrangements. A GIS committee should develop this plan with demonstrable support from management and perhaps with advice from external consultants. Once the plan has received managerial approval, then it can be followed or used as the means of GIS introduction. In order to get a feel for what implementation plans may cover, examples of two actual implementation plans are included as Box 4.5 (a and b). Although both of them involve the introduction of GIS for either departmental or county administrative purposes, they were chosen to illustrate the wide number of matters that could be considered, thus illustrating that there are no hard and fast rules for implementation planning and that it needs to be carried out in some detail. Each of these plans extended to about 30 pages.

BOX 4.5(a)

Example of GIS implementation plan for a fisheries department

EXECUTIVE SUMMARY ....
CHAPTER 1 – OVERVIEW AND METHODOLOGIES ....
CHAPTER 2 – GENERAL SYSTEM DESIGN ....
Database philosophy ....
Graphics definition ....
Interfaces to other systems ....
Recommended commercial off-the-shelf products ....
GIS software ....
Enterprise RDBMS ....
Customized software options ....
Recommended hardware configuration ....
Network considerations ....
Wide area network solution ....
Local area network solution ....
Internet/intranet options ....
Field access data options ....
CHAPTER 3 – PROJECT SCHEDULE ....
System implementation schedule ....
CHAPTER 4 – PROJECT BUDGET ....
Hardware ....
Software ....
Peripherals ....
Data conversion/development/collection ....
Application development ....
Staffing ....
Training ....
Additional consulting ....
Other costs ....
CHAPTER 5 – ADDITIONAL FINDINGS AND RECOMMENDATIONS ....

Source: Baker GeoResearch (2003).

BOX 4.5(b)

Example of GIS implementation plan for county administration purposes

Source: Brown county GIS department (2005).

There are four basic adoption strategies for GIS, plus a number of combinations of these, any of which can occur at very different scales of GIS operation:

(i) In-house development using a "slow-growth" approach. This is likely to be the common approach adopted for most fisheries and/or aquaculture GIS work. Here, a system is simply developed (built up), perhaps from a small beginning. This has the distinct advantage that initial costs may be quite low and that the GIS workers or team can learn as they progress. The early stages of growth may need a lot of external assistance, but GIS development can be "paced" according to needs, funds and personnel available.

(ii) In-house development using a "big-bang" approach. This approach requires that an existing in-house team works on developing the fisheries or aquaculture GIS according to the implementation plan. A date is usually set in advance indicating when the system will be "unveiled", or ready for use. It should be tested beforehand, but from the date that it is unveiled employees will know that the GIS is available as a complete working system.

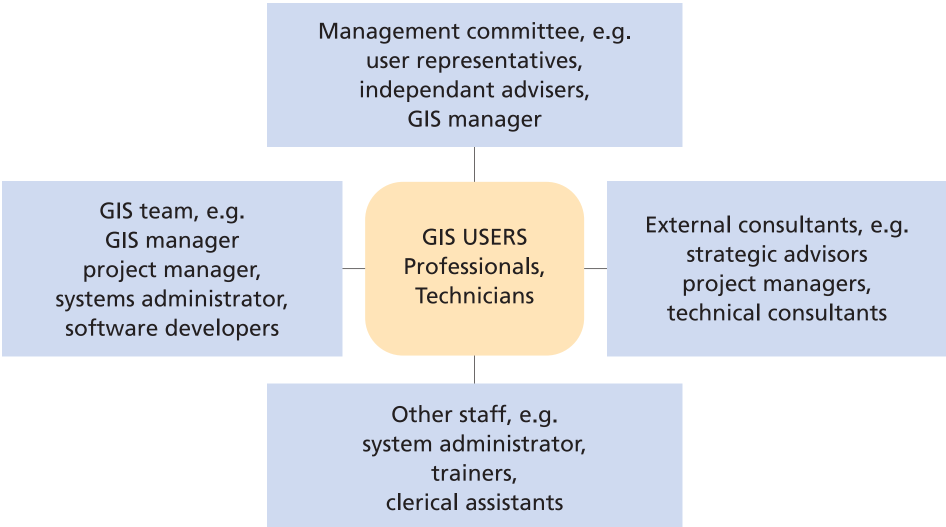
(iii) Contracting out GIS work. As indicated in the preceding paragraphs, it might be considered that there is insufficient GIS work to maintain internal capacity, so the GIS work is contracted out.

(iv) Purchase of a turnkey system. Adoption of this implementation strategy means that the desirability for GIS has been established, but the in-house capacity to implement it is almost non-existent. The organization, therefore, "outsources" its GIS requirements to a specialist external GIS provider that is able to deliver a complete working system to the organization. There needs to be some considerable transition in the sense that the system would need to be explained to relevant personnel via courses of instruction, and a range of other support would be required for periods of up to a year or so. This "turnkey" adoption approach is probably rare today, mainly because there is already a wide degree of IT familiarity and investment in most organizations so the basis for GIS is already established.

If adoption strategies (iii) or (iv) above are selected, then it is clear that GIS will need to be procured from an external source. Most large companies will have official policies for buying, purchasing, ordering, procuring, etc., and the organization's procedures will need to be followed. If the GIS implementation itself is large in scale, then there might be tendering arrangements to be made, i.e. where companies providing GIS might be invited to participate in a bidding or tendering process. As part of this process, the external GIS company may be required not only to provide details on delivery times, system functionality and costs, but it will also be asked to provide sample GIS output to illustrate how its system can best provide materials that help to resolve a spatial problem (or a set task). This process is known as benchmarking, and it is a very useful part of the tendering process. There will also be a range of contractual arrangements to be made, including maintenance and post-supply support.

Whatever implementation plan is followed, it is important that the plan has been carefully considered, that management has given its full blessing, and that a competent individual is in charge of the implementation. This last point is vital because a new "system" will be implemented, and it is one that involves a range of mixed technologies all working properly and efficiently together. As Figure 4.2 illustrates, it may also involve a wide range of staff both within and external to the organization, and within any organization there will be a range of specific procurement and installation tasks that might need to be included that will be organization specific (see tasks shown in Boxes 4.4 and 4.5 a and b). GIS is also an investment that may be expected to show results quite quickly, and these should be seen as positive and genuinely helpful to problem solving within the remit of the organization. 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. Box 4.6 provides a useful checklist of some major issues to consider when implementing a GIS, and Lo and Yeung (2002) give a detailed explanation of the implementation issues. Finally, it should be noted that implementation may be a long and perhaps difficult process. This largely depends on the adoption strategy being used and on the scale of the GIS being implemented. All personnel involved will need to be aware that there are likely to be effects on the organization, and some of them may be quite profound such as institutional restructuring, job insecurity, rationalization and possible redundancies (Bernhardsen, 1999; Heywood, Cornelius and Carver, 2006). Despite these potential negativities, the great majority of organizations will find GIS acquisition to be beneficial.

FIGURE 4.2
Varying staff roles of groups who might be involved in GIS implementation



Note: Figure 4.2 could apply to most types of GIS adoption approach, although only a large organization is likely to have all of these groups.

BOX 4.6
Checklist of important issues when implementing a GIS

- **Plan effectively** – Carefully review GIS goals and objectives, and use available project management tools, e.g. Gantt charts.
- **Obtain support** – Get support from all key stakeholders, and executive-level support within the organization. Carry out public relations exercises within the organization, and arrange meetings of interested personnel.
- **Communicate with users** – Communicate with users from the very start of the GIS project.
- **Supply frequent updates on the progress being made** – Give dates for expectation of results and endeavour to stick to them.
- **Anticipate and avoid obstacles** – Be prepared for any problems relating to hardware, software, data, time frames, funding, training, etc, knowing where to seek support.
- **Avoid false economies** – Pay staff fair wages. Build a team culture so that staff enjoy working at the organization. Cutting down on hardware or software specifications may not pay in the longer term, i.e. as workloads increase. Allow for rapid rates of hardware and software depreciation. Hardware should be amortized over four years.
- **Ensure database quality and security** – Always maintain high-quality data, making sure that it is backed up and secure from corruption or hacking. Have disaster recovery plans ready.
- **Accommodate GIS within the organization** – Manage the GIS work so that it fits in with the working culture of the organization. Try to do all the work in-house if possible so that it can be monitored carefully.
- **Avoid unreasonable time frames** – An underestimation is frequently made of the time needed for GIS to be implemented and for the GIS to achieve valuable results.
- **Do not underestimate funding requirements** – Securing sufficient funds may be a major challenge. Core funding is essential, and to secure this a sound business plan will be necessary. Additional funding needs are liable to be uncertain, i.e. operational budgets can change dramatically over a short time period.
- **Prevent "meltdown"** – There are many reasons why GIS work may dry up completely. Try to work out the causes of this, making sure that workflow planning is well entrenched.

Source: Adapted from Longley *et al.* (2005b).

4.7 TESTING, REFINING, MANAGING AND OPERATING THE SYSTEM

Once the fisheries or aquaculture GIS has been installed, there are a number of procedures that must be put in place to ensure that all parts of the system operate in an efficient manner, procedures that comply with the system design. Here, factors such as testing the GIS are considered in terms of the initial output that can be obtained, making sure that the hardware architecture adheres to its design functions, ensuring that personnel are familiar and content with their roles, having workflow patterns planned and attending to security matters. If the importance of all of this can be acknowledged and acted upon, then it is likely that the system will achieve longer-term continuity (see Section 4.8). Further details on most aspects of operating and managing GISs and GIS projects can be found in several GIS textbooks (see Section 4.8) and Croswell (2009), and at:

- GIS Development: www.gisdevelopment.net/technology/gis/techgi0041.htm;
- ESRI: www.esri.com/news/ArcUser/0205/managinggis.html;
- Current science: www.ias.ac.in/currsci/jan252009/211.pdf;
- Proceedings of the Spatial Information Research Centres 8th Colloquium http://divcom.otago.ac.nz/conferences/geocomp97/cd-rom/sirc96/papers/key1.pdf.

4.7.1 Testing and refining the system

Once the GIS is installed, it is useful to subject the system to some small pilot projects. These should be simple, but designed so that they test as wide a range of the total system as possible. Here, not just the GIS output from each project is considered, but also how the system functions in terms of all items of hardware, including their connectivity; whether data are effectively structured, filed, stored and accessed so that the data are readily accessible and thus contributing to valid GIS output; are staff readily able to fulfil their planned roles; and is the software such that it not only performs what was anticipated but the output achieved is visually and conceptually useful? It should be part of the role of perhaps a small GIS committee to oversee this pilot work, but in the case of a small GIS operation a single GIS operative might do all of these tasks. Even in this situation, the operative should consult with colleagues as to the viability of the output that has been produced. It is almost certain that the pilot work will throw up challenges that need to be addressed, and a good implementation plan will have allowed for this, probably under some sort of contingency planning. It would be fair to say that members of a GIS team must be prepared to face a good deal of initial frustration during the pilot project stage, and learning curves are likely to be sharp and extensive. The extent of frustration can be greatly ameliorated if the GIS team has in place the necessary means of coping with a wide range of contingencies. These would include access to manuals or helplines, technical support from hardware and software suppliers, and access to an external GIS consultant or to more experienced GIS workers at another location. The first few months of GIS operation, therefore, are almost certain to involve constant adjustments and refinements in working practices, and it will be the manager's role to make sure that staff can accommodate and adjust to uncertainties and change.

4.7.2 Championing and managing the system

It would be impossible to conceive that any GIS project could be launched and sustained without enthusiastic backing from either or both of the "champion" (see Section 4.2) and at least one member of the organization's management. It is important to look here at the supporting role that management should make to GIS within the organization: Section 4.8 looks more broadly at the overall support and training required by the GIS team. In effect, there has to be a manager who is willing to take over from the champion. The manager must be an individual who can clearly see the benefits that GIS use will bring and must also be conversant with its use and be willing to strongly support the work of a GIS person or unit within the organization. This support is likely to be reflected in the appropriate time, attention and resources being given to the demands of GIS. Longley *et al.* (2005b) identify the following management support areas that are critical to successful GIS outcomes:

- **Customer support.** A member of the GIS team needs to be designated by management to perform customer support advice and services. In the case of GIS in a fisheries or aquaculture environment, the customers will be both internal to the organization or they may be "upstream", perhaps working at senior government levels. If clear, decisive and cooperative support is given, then customers will be happy, and happy customers give repeat business.
- **Operations support.** Managers need to decide how the GIS operation is to be supported in terms of system administration, maintenance, security, technology acquisitions, etc. Where larger GIS units exist, then someone within the unit will be appointed to fulfil leading and decision-making roles.
- **Data management support.** Managers must be in a position to ensure that access to the best data possible is available. Larger organizations should appoint a database administrator to oversee standards of data accuracy, integrity and compatibility with existing data holdings. The administrator should also be charged with securing future data requirements and with ensuring that adequate storage and database management facilities exist.
- **Applications development and support.** Though most applications will be developed at the start of projects, there are likely to be ongoing and future needs to develop small additions to existing software routines. It might be necessary to secure the technical assistance of external software companies or from an internal IT facility. Care must be taken that languages used are open languages[101] that may have a long lifetime.
- **Project management.** GIS projects may often be complex in terms of both the range of subject matters covered and in terms of the means of executing the work. This is especially the case in fisheries and aquaculture, i.e. as these are multifaceted enterprises that operate in complex environments. The project manager must be able to establish precise user requirements, to participate in systems and project design, and to ensure that projects are completed on time, within budget and are delivered at an acceptable quality.
- **GIS staff.** The exact roles played by staff in a GIS project will vary greatly, mainly according to the size of the institution and the size and scope of the project being undertaken. This means that staff functions will vary in an almost infinite way. Figure 4.2 gives examples of some of the staffing roles. It is usual for senior managers to play an active role in GIS projects, and this is because they should be very familiar with the project aims and be in a position to secure project needs including, importantly, data and staff. The manager should also play a vital role in liaison with external parties and in systems administration. A larger organization may be in a position to appoint a specific GIS manager. Among other things, the manager should be chosen for his/hers "human resources skills" because it is certain that the management of larger-scale projects will need the necessary competence to successfully maintain harmonious working relationships among people who will have a wide range of competencies and experience. Most likely the skills of the manager will be the greatest factor towards achieving GIS project success.

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[101] Open computer languages provide a uniform programming environment for software developers to write efficient, portable code for high-performance computer servers, desktop computer systems and handheld devices.

4.7.3 Working patterns and task allocation

In the situation where GIS is operating at a very small-scale, with perhaps only one or two people being involved directly with GIS, then considerations of work patterns and task allocation are almost non-existent, i.e. one person does everything or two people decide who does what dependent on their skills, time, availability, etc. It is almost inevitable that in a small department each employee will soon need to become multiskilled and adaptable. As soon as a department employs three or more people, then much more thought has to be given to appropriate allocation of task resources. A normal pattern in these situations would be to have a leading person who is multifunctional – someone who knows quite a lot about almost everything – and this person could be the one who liaises with customers,[102] plans work schedules, supervises data processing, writes up reports and who generally directs operations. The other two or three staff will typically take on specific roles, such as: (i) an information technician/technologist and GIS operative who is responsible for actually doing the GIS work; (ii) someone in charge of data acquisition, compiling, database management, etc.; and (iii) someone who does the clerical work for the leading person.

An essential element to GIS project work is project flow and work pattern arrangements. GIS can be capital intensive and can incur high running costs, mostly in terms of labour, rent and other overheads. This being the case, it is essential to ensure continuity of work while trying not to incur work overload. To maintain project flow at a satisfactory level takes a great deal of careful planning, but a steady workflow situation can rarely be maintained. This is a problem that affects GIS possibly more than most other business routines because projects can vary enormously in their scale, data can be very hard to secure quickly, and in certain situations many of the software routines can be challenging to execute smoothly. On top of this, there are inevitable workflow interruptions such as staff sickness, staff redeployment, staffing changes, plus the fact that output demands from the GIS projects can keep changing as a greater range of circumstances is investigated and the fact that urgent requests are frequently made. The difficulties of maintaining satisfactory project flows can never entirely be overcome, but experience shows that many jobs take much longer than anticipated; therefore, it is useful if possible to build in at least 20-30 percent "over-run" timing when planning project workflows. If the time is not required, then there is always the backlog of training, reading, experimenting, etc., to be done, and data sets are in continual need of updating or extending.

4.7.4 System safekeeping and security

It is well established that in computing environments the business of data security is a vital ingredient of the operation. Despite this, most readers will have heard of stories or occasions where data have not been secured. For example, data may have been lost, IT systems may have been "hacked into" (illegally entered), data may have been passed on to unauthorized people, and equipment may have been lost or stolen. The costs and consequences of a breakdown in security can be vast in terms of data losses, time wastages, leaks of confidential information and actual financial losses. Thus, it is necessary to continually reinforce the message about safekeeping and system security.

The causes of data loss are varied and they include system failures, operational faults, and deliberate and illegal activities. Electricity blackouts are probably the most frequent system failure and thus the single largest cause of data loss. However, with the range of electrical and/or electronic equipment being used for GIS, there are also certain to be computer and other system failures at some point and these may also include fire damage. There will be occasions where data have not been filed correctly and where data have been unintentionally deleted. Older data can simply deteriorate

[102] "Customers" could be other departments, aquaculturists, fishery managers, etc, i.e. anyone who might be commissioning the GIS work.

through materials decay or data cannot be easily transferred from one media to another. Operational faults (usually human errors) may be unexpected, but over a period of time they are almost certain to occur. Illegal activities can occur when unauthorized persons gain access to data, mainly because passwords have been deliberately passed on or because "hackers" have managed to gain entry to computers.

To safeguard GIS files and other data, a number of measures are, or should be, put into place. Most people know that to log onto their computer a password is required. However, most people do not change their password periodically and, therefore, their password can become known by others through various means. Frequent changes in password are advised, and many organizations have systems in place that require monthly password changes. Sometimes, this is particular to certain software systems e.g. to e-mail, or various network connections require their own passwords to enter their system. To prevent data loss from non-deliberate events, a number of precautions should be taken. As mentioned in Section 2.2.2, there are various hardware devices for the storage of back-up files and data e.g. external hard drives, CD–ROMs, DVDs, memory sticks, and back up of all important work and data should become a regular routine. Systems are available that allow for continuous back-up of all computer generated work. To prevent losses from power supply interruptions, an uninterruptable power supply device should be installed. If useful old files are being retained that are stored on potentially degradable media, then these should be urgently copied to more modern and convenient back-up devices.

As well as the forms of security and data mentioned above, measures might need to be taken to ensure that access to certain information is only allowed among designated personnel, and management will usually make arrangements for this via adjustments to the computer operating systems. It will be important that a regular agenda item for any GIS committee meeting will be security arrangements. It might also be worth investigating the costs of insuring against equipment or data losses, as replacements can be very expensive.

4.7.5 System maintenance

The use of GIS means that those operating the system are likely to spend the great majority of their time undertaking a range of GIS projects, in this case projects involving fisheries or aquaculture. However, if the GIS operative were only to give attention to the practical GIS work, then the hardware or software systems themselves may eventually experience difficulties when the systems start to malfunction. As with almost any other practical system, GIS needs to be maintained in optimum working order.[103] System maintenance refers to the range of activities necessary to sustain the ability of the system to function as required, and it is a task that may involve the whole GIS team including outside technical support. It is normal for any organization to build system maintenance routines into the work schedule for its GIS. A system that is well maintained is likely to suffer from far fewer error problems, and the system will, therefore, retain a far higher productivity rate. Lo and Yeung (2002) calculate that system maintenance may now significantly affect GIS operating costs.

Basically, there are two approaches to systems maintenance: reactive and proactive.

(i) **Reactive maintenance.** This is maintenance that occurs as a reaction to something that has gone wrong. From a GIS perspective, it is imperative that arrangements are in place to cope with a malfunction. Clearly, this may be unforeseen and it can affect any part of the system. Personnel within the organization should be tasked with responsibility for overseeing different segments of the system, though with respect to a small organization one person is likely to have to manage all

[103] This is analogous to having a vehicle regularly serviced. If the vehicle were to be driven for long periods of time, the mechanical systems would eventually start to break down. Periodic servicing helps to prevent this.

contingencies. Typically, reactive maintenance involves GIS users trying to correct malfunctions themselves; asking for assistance from colleagues; knowing who to make contact with externally in respect to every part of the system (hardware and software); and knowing what alternatives might exist to circumventing the problem – perhaps on a temporary basis until any fault is remedied.

(ii) **Proactive maintenance.** Because systems will inevitably break down eventually, it is sensible to make provision for this before any malfunction occurs. This is typically done through the signing of service agreements (or maintenance contracts) with hardware and software suppliers. Under these agreements, there may be annual servicing provision for hardware, but for software there are a wider range of agreements that include free provision of software upgrades, and perhaps a limited period in which assistance is freely given for software problems. As well as securing against GIS malfunctions, some proactive maintenance will be deployed in making adjustments to the system that may be caused through changing technology and user requirements – this is known as adaptive maintenance (Pressman, 1997). And additional proactive maintenance will be directed towards improvement and enhancement of the functionality of the GIS. Effective proactive maintenance requires that at least one GIS person must be kept thoroughly up to date with GIS and its trends and developments.

As well as systems maintenance to hardware and software, the maintenance of data must be considered. This must be an ongoing task to which someone is permanently assigned. The extent of data maintenance will depend on the data storage capacity or capability of the GIS. Maintenance of data may include a number of tasks:

- systematic error editing;
- temporal updating of data;
- matching of data sets to the management spatial area and to time/space resolution requirements;
- seeking additional data from a wider range of sources;
- reviewing database structures or storage systems;
- metadata upkeep (see section 5.5).

As the GIS work moves from project to project, there is inevitably going to be demands for additional data. This means that storage capacity will quickly grow, but it also means that data sets will accrue, which may not be needed for some time. Decisions need to be taken on what to do with these data. Personnel in charge of data will find that data management tasks can rapidly expand and allowances should be made for this with respect to costs and timing provision.

4.7.6 Coping with organizational change

As with the introduction of most new technologies, the introduction of GIS will bring a period of change. This change can impact on internal organizational structures as well as the organization's relationship with external suppliers and customers. More specifically, Heywood, Cornelius and Carver (2006) report the following main changes that may affect an organization following GIS introduction:

- Changes in job descriptions as employees are obliged to take on different roles. While the organization may recognize that this is bound to impact on job satisfaction, it is often difficult to ensure that any staff redeployments will be in the best interest of each person concerned. There may inevitably be winners and losers in new staffing structures and in staff reallocations.
- Levels of responsibility are certain to be affected. Some people may get job promotions that might not seem fair to other employees.
- The functioning of GIS may positively act to break down barriers in an organization, as its procedures encourage personnel involvement from a wide cross-section of the organization.

- GIS can foster increased contacts with the wider external community. This is because the demands of GIS are such that assembling the inputs of hardware, software, personnel and data makes essential demands in terms of networking and establishing a wide circle of contacts and customers.
- The relationships between different departments within an organization may change as GIS finds its own level and makes more or less demands on each department. The effect can be so great that the whole organization may have to change in order to accommodate GIS.
- Where GIS has literally "taken-off" within an organization, internal restructuring has often been dramatic. In some cases, the rate of change has led to insecurity and uncertainty about the future.

The complex interplay of technical, human and organizational factors will almost certainly have both positive and negative effects and the extent and manner of these effects will involve very careful management if GIS is always to be viewed in a positive light. It will certainly be necessary to be very open with all employees, explaining in detail what is involved and who might be affected. Box 4.7 provides details on "Eason's principles" (Eason, 1988), which represent means of easing the introduction of new technology into existing organizational structures.

BOX 4.7

Eason's principles for introducing new technology into an organization

- **Serve the organization's needs rather than just provide technical support.** Make the introduction of GIS a fully integrated part of the functioning of the organization rather than a peripheral activity.
- **Give employees the ability to make the system work.** Allow employees to feel that they can each contribute to the system if they so wish. If not, they may be unwilling to support the introduction.
- **Integrate the new technology into a planned organizational workflow change.** Because organizations typically have their own structure, structural changes should produce as little disruption as possible.
- **Make employees stakeholders in the system.** For example, individual employee objectives or responsibilities can be tied to GIS success. Employees who benefit from innovation are likely to support it.
- **Ensure that the system meets the organization's goals or solves a problem.** Incorporating new technology because it is perceived as "trendy" may cause the organization to stray from its stated mission.
- **Meet the needs of individual employees.** The system will have a greater chance of success if it makes the workload easier and reduces stress. The workplace becomes a more enjoyable environment.
- **Provide education and training for management and other employees.** Managers need to be very conversant with the technology. The more that employees know about GIS, the more that they can understand and integrate with it.
- **Plan a progressive form of evolutionary growth.** Because GIS adoption may bring new technological and software innovations, plan for the changes in an evolutionary way so as to avoid major disruptions in workflow patterns.
- **Complement existing design principles and organizational change methods.** The more closely the new approach functions like the old, the more quickly both management and employees will adapt to change.

Source: Adapted from Eason (1988) and DeMers (2009b).

4.8 CONTINUING SUPPORT AND TRAINING

The stage has now been reached when the implementation of the GIS has been explained and the system tried and tested to make certain that everything is functioning correctly. But the account of GIS implementation is not finished here because the GIS will need to continue to function into the indefinite future. This section is concerned with keeping the whole GIS team up to date with progress and developments in GIS and knowing where team members can turn to for help and guidance. It is assumed that lead members of the team have basic knowledge of GIS, probably at a university-degree level. 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. FAO provides a number of hyperlinks to formal training, such as commercial training and on-campus training (www.fao.org/fishery/gisfish/id/1035). However, shorter GIS courses that individual team members may need are discussed. It will also be important to realize that most of the support will come in terms of aids to informing and improving the GIS work being completed, though much support may be needed in terms of the fisheries and/or aquaculture side of the work.[104] This section concentrates almost exclusively on the former, though some mention is made of "fisheries GIS" support materials. Basically, support, training and guidance can be thought of in terms of four main perspectives:

- **Needs for support and training.** This refers to the purpose of the support and training, and it may involve the need for GIS users to update themselves in terms of getting to know a new version of a software package or of a hardware device, etc.; this could mean taking a refresher course. It may also include the need to expand the range of GIS-based knowledge in terms of acquiring a wider range of GIS and other skills, or it may frequently refer to the need for specific problems to be addressed and resolved.
- **Sources of support and training.** This refers to the types of organizations or individuals who are in a position to deliver support and training. Here, there would be a wide range of sources, including those listed in Box 4.8.

BOX 4.8
Some main source categories for GIS guidance and support

Examples of sources for support and training for GIS include:

- **Software houses** – Most leading software houses provide a wide range of additional back-up and help, including online courses, upgrade information and case studies. Some categories of support may need to be paid for.
- **Universities or colleges** – These institutions typically may provide varying length courses on a range of GIS topics.
- **Publishers** – Provide information on new books, journals, etc.
- **Non-governmental organizations** – For example, FAO provides varying forms of GIS guidance through both hard copy publications and its GIS portals, e.g. GISFish (www.fao.org/fishery/gisfish).
- **Professional GIS organizations** – Many countries have GIS organizations whose remit is to disseminate knowledge on GIS and this is done through many of the mediums discussed in this section.
- **Consultants** – For specialized tasks, consultants may prove to be a valuable source of GIS guidance.
- **Equipment suppliers** – There will inevitably be problems associated with any of the hardware and peripheral equipment used for GIS, so sources of advice are essential.

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[104] If GIS technicians are not guided by fisheries and/or aquaculture experts, they may not be able to analyse or interpret the results from any GIS output.

- **Medium of delivering support and training.** The concern here is with how support and training is provided or given. This will include a range of delivery methods, e.g. via manuals, the Internet or in person, some of which form the subheadings used in the rest of this section.[105]
- **Types of support and training needed.** It is clearly in the GIS user's interest to know the range of different types of support that may be available.

This section is only concerned with support and training that is specifically aimed at GIS functionality, i.e. support will also be needed and available for hardware and for the peripheral software packages, such as database management systems, but space precludes consideration of these. It will be vital that users know exactly where (and what) support can be obtained for any part of the GIS system.

4.8.1 Instruction manuals and exercises

The manuals that are applicable to GIS generally and those more specifically aimed at fisheries or aquaculture are both considered in this section. Although most manuals are originally supplied in hard copy formats or on CD–ROMs, they can now be downloaded either from the software house itself or from other suppliers.[106] Manuals are aimed at providing both instructions on the use of GIS and for resolving problems that users might experience while attempting specific functions. FAOs Fisheries and Aquaculture Department Aquaculture Branch (FIRA) Global Gateway to Geographic Information Systems (GIS), Remote Sensing and Mapping for Fisheries and Aquaculture site (www.fao.org/fishery/gisfish) is a rich resource of information on publications and case studies demonstrating the benefits of these tools to resolving issues in fisheries and aquaculture. Aguilar-Manjarrez, Kapetsky and Soto (2010) provide a description of selected case studies illustrating a range of such virtual tools. Previous issues of the FAO Aquaculture Newsletter[107] describe activities on GIS, remote sensing and mapping at FIRA.

This heading includes a range of different types of published material:

- **GIS hardware and software manuals.** All manufacturers of hardware components for GIS use will provide instruction manuals that are model specific. Each proprietary software house produces an instruction or operating manual that aims to show how the software can be used,[108] with some software producers now only supplying manuals online, e.g. IDRISI (Clark Labs). Manuals are typically very extensive and the user invariably becomes familiar with only a small proportion of the total content. The software will usually have a "Help" facility that aids the learning process. For GIS users who opt to use open source software, details on supporting this software may be found in Neteler and Mitasova (2008) or Kropla (2005).
- **GIS software "illustrative" manuals.** Some of the software houses, for example, Clark Labs (IDRISI) and ESRI, have produced manuals that are in addition to the basic operating instructions. These mainly recount GIS case studies and/or the main GIS functionality that together usefully illustrates potential applications for their own software. The following are examples of these manuals and/or workbooks: Mitchell (2005); Brewer (2005); Allen (2009); Warner and Campagna (2009); Kennedy (2009); and both the GeoNetwork (http://geonetwork-opensource.org/) and BostonGIS (www.bostongis.com/?content_name=spatialite_tut01)

105 It is clear that the type of training needed may be delivered from any of the range of persons or organizations involved, by any of the mediums of delivery.

106 See, for instance, Free eBook Download (www.ebooksquad.com/search/arcgis+user+manual+download) and WareSeeker.com (http://wareseeker.com/free-idrisi-andes-manual-pdf).

107 Electronic copies of the FAO Aquaculture Newsletter (FAN) are available at www.fao.org/fishery/publications/fan/en. See examples of GIS related activities at FIRA in: FAN 35, pp.13–19; FAN 37, p. 33; FAN 38, pp. 32–33; FAN 41, p. 11; FAN 42, pp. 24–25, pp. 36–38; FAN 44, pp. 8–11; FAN 46, pp. 8–9; pp. 36–37; FAN 47, pp.24–25; FAN 48, pp.14–15, p.20, pp. 48-49, p. 55; FAN 49, p. 39).

108 See, for instance, Eastman (2003).

Web sites provide details of tutorials, documentation and software relating to open source software. Box 4.9 provides information on a useful set of workbooks (based on ESRI's ArcGIS software) that start from a very basic level.

BOX 4.9
Instruction manuals in ESRIs "Our World GIS Education" series

Environmental Systems Research Institute (ESRI) has produced a book series designed to enhance GIS learning for students at all levels. The books provide detailed information about GIS; suggested curriculums for teaching; worked exercises; and a range of other resources. Books in this "Our World GIS Education" series include:

Thinking Spatially Using GIS: Our World GIS Education, Level 1 Spatial thinking concepts and skills are cultivated and basic GIS software skills are taught including map reading and pattern recognition skills.

Mapping Our World Using GIS: Our World GIS Education, Level 2 Investigation and geographic inquiry is explored while basic GIS software skills are solidified.

Analyzing Our World Using GIS: Our World GIS Education, Level 3 The geographic inquiry and analysis skill set is extended to include data acquisition with a lesson using ArcGIS Spatial Analyst.

Making Spatial Decisions Using GIS: Our World GIS Education, Level 4 Students undertake more independent study as they analyse real-world issues using GIS project workflows to ultimately draw informed conclusions.

Source: ESRI (2011b).

- **GIS exercise or tutorial manuals.** These manuals are produced for most of the main proprietary GIS software, though some software houses include exercises in their operating manuals. For these manuals, the accent is on working through prescribed, logically ordered exercises. For instance, ESRI has produced a range of exercise manuals covering each release of ArcView or ArcGIS, e.g. see Gorr and Kurland (2009) and other GIS exercise books are available, e.g. Clarke (2010). Access to general GIS tutorials, exercises or manuals can be found on many Web sites, for example:
  - Intergraph Security, Government and Infrastructure Forum: http://userforums.intergraph.com/support;
  - ESRI: www.esri.com/news/arcuser/avmodel.html and http://webhelp.esri.com/arcgisdesktop/9.2/index.cfm?TopicName=Tutorials;
  - Software.informer: http://software.informer.com/getfree-download-gis-tutorial-exercise;
  - GISLounge: http://gislounge.com/raster-tutorials/#more-654;
  - ESRI Conservation Program Resources: www.conservationgis.org/training/ConsStartKit.html.
- **Fisheries or aquaculture GIS manuals and exercise manuals.** A few GIS manuals and exercise manuals have appeared that specifically cover marine, fisheries or aquaculture related topics – see Table 4.2. In this table, only publications that show the user "how to use GIS" are listed, i.e. it does not list books or manuals that tell readers "about" fisheries or aquaculture GIS – these are shown in Section 4.8.3. Some of the manuals are becoming dated, though they still offer much useful background information. Some exercise manuals may be developed for specific versions of GIS software, so the user must be aware of this before ordering them.

TABLE 4.2
GIS manuals and exercise manuals specifically related to marine and inland fisheries or aquaculture

Author	Title	Publisher	Comments
Kapetsky, McGregor and Nanne (1987) www.fao.org/fishery/gisfish/id/gf92	A Geographical Information System to Plan for Aquaculture: A FAO-UNEP/GRID study in Costa Rica. FAO Fisheries Technical Paper No. 287.	Rome, FAO	Illustrates how GIS was used to identify optimum areas in Costa Rica for shrimp farms.
Meaden and Kapetsky (1991) www.fao.org/DOCREP/003/T0446E/T0446E00.HTM	Geographical Information Systems and Remote Sensing in Inland Fisheries and Aquaculture. FAO Fisheries Technical Paper No. 318.	Rome, FAO	Describes how the emerging technologies of remote sensing and GIS could be used to benefit inland fisheries and aquaculture.
Clark Labs (1996) www.clarklabs.org/products/unitar-workbooks.cfm#CoastalZone	Explorations in Geographic Information Systems: A Workbook Series. Vol.3 – Applications in Coastal Zone Research and Management	UNITAR, Geneva, Switzerland	Provides eight case studies showing GIS use in various marine and coastal environments, including marine fisheries and aquaculture
Meaden and Do Chi (1996) www.fao.org/DOCREP/003/W0615E/W0615E00.HTM	Geographical Information Systems. Applications to Marine Fisheries. FAO Fisheries Technical Paper No. 356.	Rome, FAO	Describes how GIS is being applied to marine fisheries. Includes case studies.
de Graff, *et al.* (2000) www.nefisco.org/GIS_table_of_contents.htm de Graff, *et al.* (2000)	Fish GIS: An Introduction to the Use of Geographical Information Systems and Remote Sensing in Fisheries Monitoring, Analysis and Management	Nefisco Foundation, Amsterdam, The Netherlands	Worked GIS exercises covering a range of fisheries and aquaculture topics based on Bangladesh. Uses ArcView GIS.
Verbyla, D.L. (2002)	Practical GIS Analysis	Taylor and Francis, London, United Kingdom	Using worked examples, the various analysis tools in a GIS, and the concepts behind them are explained.
Kam *et al.* (2008) www.worldfishcenter.org/rdproject/	Recommendation Domains for Pond Aquaculture. WorldFish Centre; Studies and Reviews 1848.	The WorldFish Centre, Penang, Malaysia	Provides aquaculture project outputs and GIS modules, including exercises and data on a DVD.
de Graff, *et al.* (2003) www.fao.org/docrep/006/y4816e/y4816e00.htm#Contents	Geographic Information Systems in Fisheries Management and Planning: Technical Manual. FAO Fisheries Technical Paper No.449.	Rome, FAO	Demonstrates, for biologists and fishery managers, the use of ArcView GIS for a range of inland fisheries and aquaculture purposes.
Jenness, *et al.* (2007b) www.fao.org/docrep/010/a1170e/a1170e00.htm www.fao.org/docrep/010/a0907e/a0907e00.htm	African Water Resource Database. GIS-based tools for inland aquatic resource management. CIFA Technical Paper. No. 33, Parts 1 and 2.	Rome, FAO	Includes some 5.5 GB of data, plus a set of data and custom-designed GIS-based tools, covering many aspects of inland fisheries and aquaculture. Uses ArcView 3.x. Concepts, application case studies and a technical manual and workbook are provided.
NOAA Costal Services Center (2006) www.csc.noaa.gov/training/	Coastal Applications Using ArcGIS	NOAA, United States of America	Includes problem-solving exercises to address a variety of real-world coastal issues using ArcView 9.1 technology.

4.8.2 Practical training courses

For many GIS participants, the preferred method of learning and enhancing their GIS skills is through "hands-on" or practical training. Fortunately, the means of acquiring skills in this way has greatly increased over the past decades and there is now a range of ways of acquiring GIS "hands-on" skills that should satisfy most people's requirements. Here, only shorter more specific GIS training courses are discussed, i.e. not undergraduate degree-type courses. Courses will either be focused on GIS more generally or on specific aspects of GIS, and there may be a few opportunities to attend GIS training courses specifically directed towards fisheries or aquaculture GIS. It is very important when selecting a course to make certain that the course not only meets training content requirements but that it also is delivered at the correct academic level.

Perhaps the most useful way of subdividing GIS training is through the two categories of "face-to-face" instruction or "online" instruction.[109] Although clearly the methods of delivery will be quite different, the material covered can be very similar, and it will be up to individuals to choose the method of training to suit their circumstances. Both types of courses are typically offered by colleges or universities and by the main software houses, though sometimes larger government organizations or private training agencies run courses. A myriad of courses are available ranging from those covering basic GIS principles to advanced analytical techniques. Table 4.3 gives examples of face-to-face and online training courses for both general GIS and for fisheries- or aquaculture-specific GIS.[110] More details on each of these training delivery methods are as follows:

- **Face-to-face instruction.** The chances of receiving face-to-face instruction depends almost entirely on either where you live or whether the time can be obtained for attending courses that are residential. Therefore, training courses are typically held in capital or larger cities where viable attendee numbers may be attained or assembled. This method of instruction has the significant advantage that individual guidance can be more easily delivered, something that greatly favours certain trainees. Face-to-face training is usually quite expensive, with some of the software houses charging about US$500 per day in developed countries, and in addition, most courses are specific to certain software. A major problem with some intensive training courses is that too much information is given in a fairly short amount of time and thus makes retention of course material difficult.[111] Fisheries- or aquaculture-specific GIS face-to-face courses are quite rare, though FAO has offered courses since 1985 and some larger specialist institutions (e.g. the University of Stirling, Scotland, and the National Oceanic and Atmospheric Administration, the United States of America) incorporate fisheries and/or aquaculture GIS into existing degree-level courses or they occasionally offer specialist GIS courses.
- **Online instruction.** An increasingly popular way of obtaining GIS-related training is through delivery of courses over the Internet. These might be thought of as "distance learning" courses, though distance learning itself predates the Internet. Online courses have been largely developed to meet the needs of working professional people. The sources of online training are usually the same as those for face-to-face training. Online instruction has the disadvantage that genuine face-to-face interaction is not usually possible, but it has the huge advantages that instruction can be received in the trainee's own home or place of work and that courses can be undertaken in the trainee's own time and at their own pace. From the training delivery point of view, there is also the advantage that, except for the marking or course assessment viewpoint, almost any number of students can be enrolled in a course. ESRI offers online training through their Virtual Campus,where dozens of courses on numerous topics can be accessed at the user's

[109] Sections of either type of training may also have instruction via manuals, video, CD–ROM and include a fieldwork element.

[110] Some of the fisheries-specific GIS courses are one-off courses that were run in the past. The demand for fisheries- or aquaculture-based GIS courses is too small to allow for any regular courses to be established.

[111] If possible, it is better to choose courses where instruction is spread over a longer time period (weeks or months).

TABLE 4.3
Examples of GIS and fisheries GIS training courses

Source/country	Type of GIS course	Uniform resource locator (URL) of training course
General GIS training		
FAO Aquaculture Branch and Marine and Inland Fisheries Branch; FAO, Italy	Provides a number of links to formal training opportunities and Internet training	www.fao.org/fishery/gisfish/id/1035 www.fao.org/fishery/gisfish/id/1032
NAACCR GIS Committee GIS training-related Web sites; United States of America	Wide miscellany of GIS-related training courses published by the North American Association of Central Cancer Registries	www.naaccr.org/filesystem/pdf/GIS%20 Training%20Web%20Sites.pdf
Sir Sandford Fleming College Web GIS Development; Canada	A one-semester Internet-delivered course on Web-based GIS delivery	www.webgisdev.com/home.htm,
ITC in association with United Nations University, University of Twente; The Netherlands	Distance learning GIS and remote sensing courses at various levels	www.itc.nl/study
Intergraph training course GeoMedia/ GeoMedia Professional training course; United States of America	A web-based course designed to teach Intergraph's Geomedia GIS	www.intergraph.com/training/ courseprofiles/tmap2117.aspx
Geo-Informatics and Space Technology Development Agency; Bangkok, Thailand	Organization of remote sensing and GIS training courses, seminars, workshops and conferences at national and international levels	www.gistda.or.th/en/index. php?option=com_content&view=articl e&id=15&Itemid=37
NYS GIS Clearinghouse. Training and Education; United States of America	Listing of general GIS training available	www.nysgis.state.ny.us/outreach/ training/
The US National Center for Geographic Information and Analysis; United States of America	Clearing house listing GIS training opportunities	www.ncgia.ucsb.edu/education/ projects/univ/unipubs.php
UNIGIS; International	Worldwide information on GIS distance learning courses	www.unigis.org/
GeoData Institute; United Kingdom	Range of scheduled or bespoke GIS courses – most are "face-to-face"	www.geodata.soton.ac.uk/ geodataweb/technologies/ gis/?link=subtheme.php&id=1050
University of Leeds; United Kingdom	Range of online distance learning courses	www.geog.leeds.ac.uk/odl/short-courses.htm
ASKEDU – Schools, certificates, courses, workshops; United States of America	Search facilities for locating appropriate GIS training courses worldwide	www.askedu.net/training_topic/k_ GIS_1.htm
Manifold; United States of America	A range of online video training courses for Manifold GIS	http://gisadvisor.com/index.html
Examples of fisheries or aquaculture training		
*FAO Aquaculture Branch and Marine and Inland Fisheries Branch; FAO, Italy	Provides a number of links to FAO manuals and courses conducted by FAO	www.fao.org/fishery/gisfish/id/1038 www.fao.org/fishery/gisfish/id/1020
2008 World Fisheries Congress; Japan	Two-day training on fisheries GIS	www.congre.co.jp/5thwfc2008/GIS_ courseB_agenda.pdf
Department of Fisheries and Aquaculture (Malta), in collaboration with University of Plymouth (United Kingdom) and COPEMED (FAO); Malta	Four-day course on fisheries GIS in 2001	www.faocopemed.org/old_copemed/ reports/gis/maltaCourse/day4.pdf
Northwest Environmental Training Center; United States of America	Three-day course on use of ArcView GIS for fisheries and wildlife purposes	http://nwetc.org/FILES/gis-400_10-08_oakland.pdf
University of South Florida; St. Petersburg, United States of America	A self-paced workshop teaching various fishery topics using ArcGIS.	www.stpt.usf.edu/gisWorkshop/PDF/ Self_Paced_fishery_I.pdf
National Oceanic and Atmospheric Administration (NOAA); United States of America	GIS courses on a range of marine and coastal issues	www.csc.noaa.gov/training/ coastalapps/
CARIS; Canada	CARIS offers extensive GIS training courses at its Canadian headquarters, plus a catalogue of other international courses	www.caris.com/training/catalogue.cfm
Mappamondo; Italy	GIS instructor-led training courses, some of which are fisheries based	www.mappamondogis.it/training.htm

* The FAO Aquaculture Branch and Marine and Inland Fisheries Branch conducts some GIS training, but only one to three times a year in different countries around the world to support a few FAO field projects when requested and when funds are available. The participants of the courses are usually those who are directly involved in an FAO project.

leisure. Additionally, ESRI offers "webinars", or seminars over the Web, and students can watch short demonstrations of GIS technology and ask questions to the instructors.

It can sometimes be difficult to locate GIS training courses. For general GIS training, it is most useful to consult the Web sites of the major software houses or the sites of universities where geography features as an important subject. In many countries, there are GIS organizations (see Section 4.8.5 below) that frequently publicize courses. The most successful way of locating training courses, however, is through the use of online search facilities. Training that is more specifically based on fisheries or aquaculture GIS is quite rare, and worldwide there are few courses each year. However, this is likely to change over the coming decade and readers are advised to consult the FAO GISFish Web site for details on future training opportunities.

Regardless of whether a person has used GIS before or has been a practitioner for years, education and training are the keys to creating or maintaining the skills necessary to be a proficient GIS operator. Each person has a preferred method of learning, whether it is Web-based training, classes taught by an instructor face-to-face, or by the student learning on their own. All are valid methods of education and vendors and academic organizations now offer all of these methods to the GIS community.

4.8.3 Other published information

As well as various manuals and exercise books that deal directly with GIS, there is a range of other publications that can provide invaluable support. While most of this support material will be in a book or hard copy format, some will be online versions of books and others will be in the form of CD–ROMs or videos and DVDs. The major focus in this section is with GIS materials rather than any material relating to fisheries or aquaculture. There are a number of main forms of published information, including textbooks, academic journals, trade magazines and conference proceedings. Here, the material is summarized under three headings:

- **General GIS books.** When the forerunner of this present manual was first produced in 1991, the total number of GIS books available was 14 (Meaden and Kapetsky, 1991). Typing "geographic information systems" into the "Books" section of www.amazon.com reveals that in mid 2012 there were more than 16 000 results listed – such has been the very broad and intensive growth in this subject area. However, a large proportion of these books are now "topic specific" and cover all the major GIS applications areas shown in Box 1.3. Readers seeking to gain a more comprehensive knowledge of GIS should look at the recommended introductory texts on GIS listed in Box 4.10. These books only provide a general summary of GIS, and therefore for people already working in GIS it is more likely that they will want to consult the manuals discussed in Section 4.8.1.
- **Fisheries or aquaculture GIS publications.** As mentioned in Section 1.4, the first fisheries and/or aquaculture GIS publications emerged in the mid-1980s. Since that time, there have been an increasing number of publications in this subject area, many of which could give important support to any GIS work. As well as the manuals listed in Table 4.2, any of the publications listed in Box 4.11 could prove useful. Table 4.2 lists manuals on "how to do fisheries and/or aquaculture GIS", whereas the publications listed in Box 4.11 tell the reader "about fisheries and aquaculture GIS" and not how to do this work. As well as complete publications on these subjects, there are other publications that devote single chapters to fisheries or aquaculture GIS.
- **Journals and trade magazines.** There is a wide range of professional, academic and trade publications that users can access to further their GIS knowledge. As with books, these sources mostly originate from the GIS software houses, from academic journal publishers or from a range of individual sources, and they can be in hard copy or digital formats. Academic publications on GIS tend to focus on the theory and emerging trends within GIS technology, and they provide a glimpse

into research that is shaping the field. However, it should be noted that most papers published in GIS-related academic journals are fairly sophisticated and they tend to be overwhelmingly devoted to GIS-based research topics. Trade magazines offer information on a wide range of trends as well as reports on the GIS industry as a whole. They are a resource for finding information such as reviews of new software releases as well as opinion articles on the state of the industry. Papers and articles about the use of GIS for fisheries or aquaculture research or management may appear in a wide spectrum of fisheries, ecosystems, marine or other journals, and these articles are much more likely to be both relevant and comprehensible. Box 4.12 provides a selection of journals and trade magazines that frequently have articles covering GIS applications to aquaculture. Access to journals can be difficult because they often involve quite expensive subscriptions, though individual papers (articles) can be bought for a fee. Some journals are free and the best way of ascertaining their access is through an online search.

BOX 4.10

Some introductory textbooks covering general GIS

Bernhardsen, T. 2002. *Geographic information systems: an introduction*. Chichester, United Kingdom, Wiley.
Bolstad, P. 2008. *GIS fundamentals: a first text on geographic information systems (3rd edition)*. Ashland, Ohio, United States of America, Atlas Books.
Chang, K-T. 2009. *Introduction to geographic information systems*. New York, United States of America, McGraw-Hill.
Clarke, K.C. 2010. *GIS Exercise workbook for getting started with geographic information systems.* Upper Saddle River, New Jersey, United States of America, Prentice Hall.
Crampton, J.W. 2010. *Mapping: a critical introduction to cartography and GIS*. Chichester, United Kingdom, Wiley.
Delany, J. & Van Niel, K. 2007. *Geographical information systems: an introduction*. South Melbourne, Australia, Oxford University Press.
DeMers, M.N. 2009a. *Fundamentals of geographical information systems (Fourth Edition)*. Hoboken, New Jersey, United States of America, John Wiley & Sons.
DeMers, M.N. 2009b. *GIS for dummies*. Hoboken, New Jersey, United States of America; Wiley Publishing Inc.
Harvey, F. 2008. *A primer of GIS: fundamental geographic and cartographic concepts*. New York, United States of America, Guilford Press.
Heywood, I., Cornelius, S. & Carver, S. 2006. *An introduction to geographical information systems (3rd Ed)*. Harlow, United Kingdom, Pearson Education Ltd.
Konecny, G. 2002. *Geoinformation: remote sensing, photogrammetry and geographical information systems.* London, United Kingdom, Taylor & Francis.
Lloyd, C. 2009. *Spatial data analysis: an introduction for GIS users*. Oxford, United Kingdom, Oxford University Press.
Lo, C.P. and Yeung, A.K.W. 2002. *Concepts and techniques of geographic information systems.* Upper Saddle River, United States of America, Prentice Hall.
Longley, P.A., Goodchild, M.E., Maguire, D.J. & Rhind, D.W. 2011. *Geographic information systems and science.* Chichester, United Kingdom, John Wiley and Sons.
Madden, M. 2009. *Manual of geographic information systems*. Annapolis Junction, Maryland, United States of America, ASPRS.
Obermeyer, N.J. & Pinto, J.K. 2008. *Managing geographic information systems.* New York, United States of America, Guilford Press.
Schuurman, N. 2004. *GIS: A short Introduction.* Malden, Massachusetts United States of America, Blackwell Publishing.
Skidmore, A. 2002. *Environmental modelling with GIS and remote sensing (Geographic Information Systems Workshop).* London, United Kingdom, Taylor & Francis.
Wing, M.G. 2008. *Geographic information systems: applications in natural resource management.* New York, United States of America, Oxford University Press.
Wise, S. 2002. *GIS basics*. London, United Kingdom, Taylor & Francis.

BOX 4.11

Examples of books published in the last decade on fisheries and/or aquaculture GIS

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

Breman, J.,eds. 2010. *Ocean Globe.* Redlands, California, United States of America, ESRI Press.

Breman, J. & Convis, C., eds. 2002. *Marine geography: GIS for the ocean and seas.* Redlands, California, United States of America, ESRI Press.

Carocci, F., Bianchi, G., Eastwood, P. & Meaden. G.J. 2009. *Geographic information systems to support the ecosystem approach to fisheries.* FAO Fisheries and Aquaculture Technical Paper No. 532. Rome, FAO.

Fisher, W.L. & Rahel, F.J., eds. 2004a. *Geographic information systems in fisheries.* Bethesda, Maryland, United States of America, American Fisheries Society.

Green, D.R. & King, S.D., eds. 2003. *Coastal and marine geo-information systems: applying the technology to the environment.* Dordrecht, The Netherlands, Kluwer Academic Publishers.

Hall, M.K., Walker, C.S., Weeks, J.A., Kendall, L.P. & Jenness, J.S. 2006. *Exploring the ocean environment: GIS investigations for the earth sciences, ArcGIS Edition.* Florence, Kentucky, United States of America, Brooks Cole Publishing.

Kapetsky, J.M. & Aguilar-Manjarrez, J. 2007. *Geographic information systems, remote sensing and mapping for the development and management of marine aquaculture*. FAO Fisheries Technical Paper No. 458. Rome, FAO.

Nishida, T., Kailola, P.J. & Hollingworth, C.E., eds. 2001. *Proceedings of the First International Symposium on GIS in Fishery Science.* Saitama, Japan, Fishery GIS Research Group.

Nishida, T., Kailola, P.J. & Hollingworth, C.E., eds. 2004. *GIS/Spatial Analyses in Fishery and Aquatic Sciences (Vol.2).* Saitama, Japan, Fishery-Aquatic GIS Research Group.

Nishida, T., Kailola, P.J. & Caton, A., eds. 2007. *GIS/Spatial Analyses in Fishery and Aquatic Sciences (Vol.3).* Saitama, Japan, Fishery-Aquatic GIS Research Group.

Nishida, T. & Caton, A., eds. 2010. *GIS/Spatial Analyses in Fishery and Aquatic Sciences (Vol. 4).* Saitama, Japan, International Fishery GIS Society.

Travaglia, C., Profeti, G., Aguilar-Manjarrez, J. & Lopez, N.A. 2004. *Mapping coastal aquaculture and fisheries structures by satellite imaging radar: case study of the Lingayen Gulf, the Philippines.* FAO Fisheries Technical Paper No. 459. Rome, FAO.

Valavanis, V.D. 2002. *Geographic information systems in oceanography and fisheries.* London, United Kingdom, Taylor & Francis.

Valavanis, V.D., eds. 2008. *Essential fish habitat mapping in the Mediterranean.* Dordrecht, The Netherlands, Springer-Science.

Valavanis V., Wright, D., Georgakarakos, S. & Kitsiou, D. 2011. *Marine geographical information systems: theory and applications (advances in geographic information science).* New York, United States of America, Springer Science.

Wright, D.J., eds. 2002. *Undersea with GIS.* Redlands, California, United States of America, ESRI Press.

Wright, D.J., Blongewicz, M.J., Halpin, P.N. & Breman, J. 2007. *ArcMarine: GIS for a blue planet.* Redlands, California, United States of America, ESRI Press.

Wright, D.J. & Bartlett, D. 2001. *Marine and coastal geographical information systems.* London, United Kingdom, Taylor & Francis.

Wright, D.J. & Scholz, A.J. 2005. *Place matters: geospatial tools for marine science, conservation and management in the Pacific Northwest.* Portland, Oregon, United Statesof America, Oregon State University Press.

BOX 4.12
Journals and trade magazines having GIS applications in aquaculture

The following are examples of publications that may feature articles illustrating how GIS has been applied to aquaculture research or management:

- Anatolia
- Aquaculture
- Aquacultural Engineering
- Aquaculture International
- Aquaculture News – University of Stirling
- Aquaculture Research
- Aquaculture and Fisheries Management
- Coastal Management
- Ecology of Marine Aquaculture
- Estuarine, Coastal and Shelf Science
- GIS World
- Hydrobiologia
- InterCoast Online
- International Journal of Remote Sensing
- Mapping Awareness and GIS Europe
- Revista AquaTIC

Source: Updated from Institute of Aquaculture, University of Stirling (2012).

4.8.4 Conferences, workshops and exhibitions

For many participants in practical GIS work, a more conducive form of support and training is through verbal or visual approaches rather than reading manuals or working through exercises. This is where conferences, workshops and exhibitions come to the fore. In these surroundings, participants are able to explore a wide variety of ideas, often at their own pace, and there is more or less complete freedom to delve into subjects of their own choosing and to the depth that they need. There are outstanding opportunities to gather and learn about emerging trends in GIS and to see how others are applying GIS technology in their organizations. For these reasons, especially conferences and exhibitions, they have become very popular in a wide cross-section of subject areas.

Attending general GIS conferences can be highly beneficial, though these mainly take place in major cities in developed world countries. Most conferences include exhibitions because the various vendors need to exhibit their latest software or hardware offerings, and it is largely through the exhibitions that conference attendance prices can be minimized. The authors believe that these exhibitions may provide the ideal platform to establish strengths and weaknesses of individual GIS components. The conferences typically offer a wide range of GIS-based papers, though many of them will have vendor specific content. Although many purchasing deals might be done at conferences and/or exhibitions, they should be the source of ideas rather than hasty purchases. Some of the larger conferences also include workshop sessions, which often take the form of introductions to specific vendor products.

As well as general GIS conferences, there are a number of either "user"[112] promoted or "vendor" promoted conferences that are typically based on a specific software or, indeed, on open source software. These can be particularly useful to GIS users who are committed to using the software that was decided upon during the implementation

[112] "User" groups will be either groups of GIS users that concentrate around a specific GIS software or are based in a specific geographic area.

planning. Conferences also provide the ideal venue for the extension of ideas and possibilities and for learning better ways of achieving desired GIS outcomes. They are sometimes based on a particular theme for each conference, and some conferences are aimed at an academic audience rather than the general public. As there are too many conferences to list, the reader should review Box 4.13, which gives examples of Web site information for both "user" and "vendor" promoted GIS conferences. For the most part, conferences are overwhelmingly held in the United States of America, though the "general conference" listings do cite many international and non-United States events and a Web search by continent reveals that a significant number of GIS conferences are promoted worldwide.

BOX 4.13

Web sites giving information on general and vendor-based GIS conferences

• **General conference listing**	http://gislounge.com/events www.conferencealerts.com/gis.htm www.unigis.org/resources/gisconf.htm http://gisandscience.com/category/conferences www.geo.uzh.ch/en/units/giva/events/conferences www.isotc211.org/events.htm
• **General GIS conferences in Canada**	http://canadiangis.com/events.php
• **Specific biannual conference**	www.ncgicc.com/CurrentActivities/NCGISConference/tabid/158 Default.aspx
• **Specific annual conference**	www.urisa.org/calgis/info www.pagisconference.org/ www.cartogis.org/autocarto
• **Combines remote sensing with a GIS conference**	www.igarss2010.org
• **Manifold users conference**	http://gis4everyone.com/Manifold2009/Presentations.htm
• **Intergraph vendor's conference**	www.intergraph2010.com
• **ESRI vendor's conference**	www.esri.com/events/uc/index.html
• **Open Source GIS conference**	www.opensourcegis.org.uk
• **The 2010 Open Source conference**	http://2010.foss4g.org
• **International academic GIS conference**	www.giscience2010.org

Conferences devoted solely to fisheries or aquaculture GIS are rather rare. One important series of fisheries GIS conferences is the one promoted by the Fishery-Aquatic GIS Research Group, based in Saitama, Japan. The first conference was held in Seattle, Washington, United States of America, in 1999, and since then there have been triennial conferences in Brighton, United Kingdom of Great Britain and Northern Ireland (2002), Shanghai, the People's Republic of China (2005), Rio de Janeiro, the Federative Republic of Brazil (2008), and in Wellington, New Zealand (2011). These important symposia cover all aspects of fisheries and aquaculture GIS, they attract an international audience, and conference proceedings are produced (the latest published is Nishida and Caton, 2010). A number of more local fisheries or aquaculture conferences or workshops have been organized, but they tend to be smaller scale, one-off events.

4.8.5 Other GIS users and professionals

The final source of support and training are various persons or groups that specifically aim to offer advice either freely or on a paid basis. They are a miscellaneous group comprising consultancy services, user support groups, software vendors and professional associations.

- **Consultancy services.** Consultancy is usually provided by individuals who either work privately for themselves or who may be hired on a temporary basis by larger organizations. They are usually experts in specific areas that are either quite broad or highly specialized. GIS consultants often provide rather broadly based advice and other services, though typically many of them now concentrate on individual GIS applications areas. GIS consultants can best be found through business and trade directories or through the professional GIS associations. Some examples of services that a consultant might offer include:
  - needs assessments;
  - system design and architecture;
  - data conversion;
  - data quality assurance and control (e.g. metadata preparation);
  - project management;
  - application development (e.g. database design and development, processing, analysis, modelling, and decision support);
  - mapping;
  - surveying;
  - technical support (software and/or hardware);
  - reporting (analysis, methodologies, etc.).
- **User support groups.** There are two main types of user support groups, i.e. GIS software dependent groups and more general discussion groups or forums. Nowadays, both groups operate via the Internet, and generally users need to register through an online log-in process. With either of these groups, the user basically becomes part of a network of GIS users who communicate freely by basically posing questions, providing answers and entering into discussions (forums). The groups are an excellent medium for problem solving because advice is usually volunteered freely. Examples of user or discussion groups are shown in Box 4.14. A search on Google using "GIS user groups" reveals a large number

BOX 4.14
Examples of GIS user and discussion groups

Manifold users directory	www.manipedia.eu/index.php?title=Main_Page
Manifold users forum	http://forum.manifold.net/forum
Intergraph user support group	http://userforums.intergraph.com/supportL
Listing of GIS discussion groups	http://home.earthlink.net/~rpminfonet/gislist.html
Online discussion lists	www.unigis.org/resources/gisdisclists.htm
Lists ArcGIS user forums	http://support.esri.com/index.cfm?fa=forums.gateway
IDRISI regional support centers	www.clarklabs.org/resources/resource-centers.cfm
Detailed listing of GIS support services	www.gisuser.com/content/view/3006/53
Listing of various GIS forums	http://forum.gislounge.com
Range of discussion and other support	www.geocomm.com
Online GIS discussion forum	www.diva-gis.org/forum/1
GIS India discussion group	http://bestdiscussiongroups.com/gr_gisindia_p1.htm
Wide range of international ArcGIS groups	http://groups.yahoo.com/phrase/esri-gis
GRASS user groups	www.ces.iisc.ernet.in/grass/community/usergroups.php

of such groups, with the great majority located in the United States of America. However, it does not matter where user group members are located, though larger user groups sometimes hold their own conferences or workshops, which usually take place in the United States of America.

- **Software houses.** This heading is included to remind readers that the software houses (vendors) should be a major source of support for all GIS work. Not only do they give advice regarding the use of their software, but it is also likely that users will take out some sort of time-limited contract during which questions can be submitted to the vendor, (this is back-up support in response to functional problems that may arise). As indicated above, vendors also offer support through organizing user groups for their products, through publishing a range of supporting and training materials, and through organizing or attending various conferences or exhibitions. Clearly, the range of support offered by each software house will vary greatly and this should be checked prior to investing in a GIS.
- **Professional GIS organizations.** There are a large number of professional and academic societies and associations that have emerged to act as a voice for the GIS community in their respective regions and/or internationally. These organizations (or associations) provide a range of services or activities, such as issue publications, reports and newsletters, provide GIS certification, conferences, consultancy, advice to government, support and training, and networking opportunities. They may also help the profession to maintain and improve standards. Professional GIS organizations exist in many countries worldwide, and joining one can be advantageous from career, influence and participation viewpoints. A sample of such organizations is listed in Box 4.15.

BOX 4.15
Professional GIS organizations

- American Society for Photogrammetry and Remote Sensing (ASPRS) – United States of America
- Asociación Española de Sistemas de Información Geográfica – Spain
- Association for Geographic Information – United Kingdom
- Association for GIS Professionals – United States of America
- Association of American Geographers (AAG) – United States of America
- Canadian Institute of Geomatics – Canada
- Conseil National de l'Information Geographique – France
- European Umbrella Organization for Geographic Information – European Union
- Geospatial Information and Technology Association (GITA) – United States of America
- Grupo SIG–FAM – Sistemas de Información Geográfica – Chile
- International Association of Chinese Professionals in Geographic Information Sciences – China
- International Society for Photogrammetry and Remote Sensing – United States of America
- Management Association for Private Photogrammetric Surveyors (MAPPS) – United States of America
- Open Geospatial Consortium – International
- Open Source Geospatial Foundation – International
- Organización de los Proyectos de Sistemas de Información Geográfica Territoriales – Cuba
- Pakistan Society of GIS – Pakistan
- Society of South African Geographers – South Africa
- Syndicat Professionnel de la Geomatique – France
- The Korean Geographical Society – South Korea
- Tokyo Geographical Society – Japan
- Urban and Regional Information Systems Association (URISA) – United States of America

5. Preparing data for GIS use

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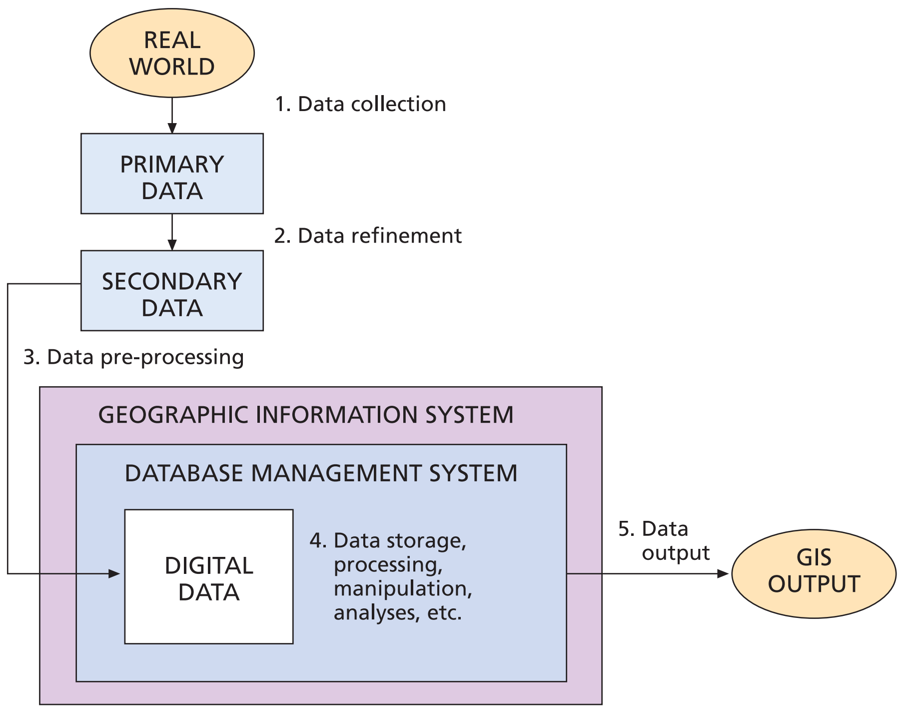
5.1 INTRODUCTION

GIS data can be collected using a variety of primary and secondary data collection methods, as discussed in Chapter 3. The next stage is to assemble and prepare both primary and secondary GIS data to support the GIS-based project.[113] Usable fisheries or aquaculture data come in many forms and formats. Some data exist via "cyberspace", i.e. online at a Web site but not yet downloaded. Other data are stored on digital data collecting devices, and yet other data are in the form of paper-based maps or tables, with some primary data written down in the form of a list. Whatever the data form, the data need to be prepared so that they are permanently accessible to the GIS software in an appropriate digital format. Many workers in the GIS field would agree that getting the data entered in a suitably formatted way, and having these data well edited and stored securely in a database, is the most important (and often time-consuming) task of the whole GIS project. This qualitative concern with data is one primary theme of this chapter, a concern that can be conceptualized by looking at the flow of data through a GIS from the "real world" to the "GIS output" (Figure 5.1).

FIGURE 5.1
Stages in data transformation when used for GIS purposes



[113] It will occasionally also be necessary to identify and collect "proxy" data (see Section 3.5.3).

Figure 5.1 illustrates the five stages at which some transformation of the data will occur; in this chapter, the focus is on the first three stages (data collection, data refinement and data pre-processing), plus some preliminaries of stage four[114] (data storage, manipulation, analyses, etc.). The other main focus of this chapter is to show how data can best be modelled and structured so that a GIS can properly function, i.e. so that the GIS software can use and present the data in a meaningful way. A consideration of how data is stored in databases and how databases function via database management systems is also made, and a brief look is taken at metadata – which is, essentially, information about data.

5.2 METHODS OF DATA INPUT

The methods of data input will vary according to the form or format in which raw data are held. This section examines scanning and digitizing, keyboard data entry and digital data transfer, and also addresses the types of information that need to be recorded, etc. It is important to mention data formats. Format refers to the way that data have been coded and stored in a data file or database. Whatever data that are input to any GIS, they have to be in a format that is readable by the GIS software. Although many GISs handle several formats, some will have their own formatting requirements. Some data formats will require special tools to import data into the GIS. Any specific data format will have strict rules on matters such as how a georeference should be stated (see Section 3.3.4), the range of values that are permissible and the number of decimal places to be recorded. A large number of data formats have evolved, mainly because data are collected for many different purposes. Over the last two decades, attempts have been made to standardize data formats, and much progress has been made on this (see Section 3.4 on Data Quality and Standards). There are now a range of software applications that convert data between formats.[115] Methods of handling remotely sensed imagery data are discussed in Chapter 6.

5.2.1 Scanning and digitizing

Scanners were discussed as one form of useful hardware for GIS in Chapter 2. The overriding purpose of scanning as an aid to GIS is to create digital map images. A simple A4-size scanner can easily create a digital copy of a paper map, aerial photograph, or any printed or hand-drawn diagram. Typically, these digital images will be recorded at resolutions of 200 to 400 dots per inch (dpi) on a flatbed scanner.[116] The resulting captured image can then be displayed on the computer monitor and the size of the image can be adjusted according to the degree of detail required. The scanned image per se cannot be used directly for GIS purposes because it lacks "intelligence". Thus, the scanned image is simply a copy of what was scanned, with the screen image consisting of rows of pixels to match the original paper map image. The information at each pixel point lacks any georeferencing or other information such as colour, attribute and line thickness and, therefore, the scanned image is incapable of being manipulated in any meaningful way. However, the scanned image is an essential prerequisite for digitizing. It should be noted that the accuracy of the scanned image also depends on the condition of the paper being scanned; for example, it may be creased, warped, torn or contain stains. Many of these problems, however, can be resolved in the editing process (as described in Section 5.3.1). After the image has been georeferenced, i.e. assigned real world coordinates so that the GIS knows exactly what area the image represents, the image can be used for either digitizing any selected features or as a background image to any overlaid map (see Section 7.3).

[114] Stage 1 (data collection) includes an array of methods as described in Chapters 3 and 6.

[115] See: Safe Software (www.safe.com) if information is required on converting data between formats.

[116] More detailed scanning of 500 to 2500 dpi can be obtained via the use of more sophisticated drum scanners.

Digitizing is a method of adding intelligence to data so that the data can be usefully used for GIS work. Chapter 2 discussed the use of a traditional large digitizing table for digitizing; however, today, almost all digitizing is carried out using so-called "heads-up" digitizing directly on the computer monitor,[117] using specialized on-screen digitizing software or, more typically, the digitizing function available in most popular GIS software. Whatever features of the scanned map (or image) are required, it is necessary to first georeference the image so that every point on the map can be accurately referenced to a coordinate (see Section 3.3.4). This can either be done "manually" by referring to the paper source or it can be done by overlaying the scanned image onto some other georeferenced data set. Digitizing itself is accomplished by progressively moving the on-screen cursor along any desired map outline and clicking on the mouse as digitizing proceeds. Digitizing procedures allow the user to record details of what has been captured, including feature names/types, registration positions, line thicknesses or colour (see Section 5.8.1 for further details). The digitizing program will build up a series of files containing all of the lines (or points) digitized, including their georeferenced locations and any attributes about them that need recording.

All maps and analyses performed later in a GIS project depend on the accuracy and precision of these data and it is, therefore, critical that the person doing the digitizing takes great care to perform the digitizing operations as accurately as possible. For greater accuracy, especially in areas where the map may be complex, it is possible to zoom into the scanned image while digitizing. As was shown in Figure 2.4, dual or split screens can be used so that both the original map and the already digitized lines can be viewed. In this figure, the green (woodland) areas have been digitized from the original map on the left. Use of the digitizing function within a GIS software package will ensure that the digital map data have been captured in a suitable format for that software.

5.2.2 Keyboard data entry

If data have been collected manually using no equipment, they are likely to be in a written, hard copy (or analogue[118]) format (see Section 3.1). Transforming these data to a digital format typically requires manually typing the information via keyboard entry, although in some cases it can be scanned and converted to text using optical character recognition (OCR) software. Data can be entered into a spreadsheet or into a database that has been designed for a specific purpose. For example, a typical fisheries or aquaculture survey should have a database set up with all the predetermined attributes listed (see Figure 5.2). Use of a spreadsheet is simple with each line (row) representing data from one sampling point, and the columns representing different attributes of the data. For GIS purposes, it is essential that one (or two) column(s) contains a georeference for each sampling point, using actual coordinates or a coded reference to a place name, zip code or some other areal unit. Any data entered manually must be saved as a file in a format suitable for accessing to the GIS program being used (see Section 5.5.1). GIS software will either contain its own inbuilt database program that allows the user to enter data directly to the GIS, or it can connect to a proprietary database or spreadsheet package such as Microsoft's Excel or Access. The keyboard will also be used to edit data in existing files as and when necessary.

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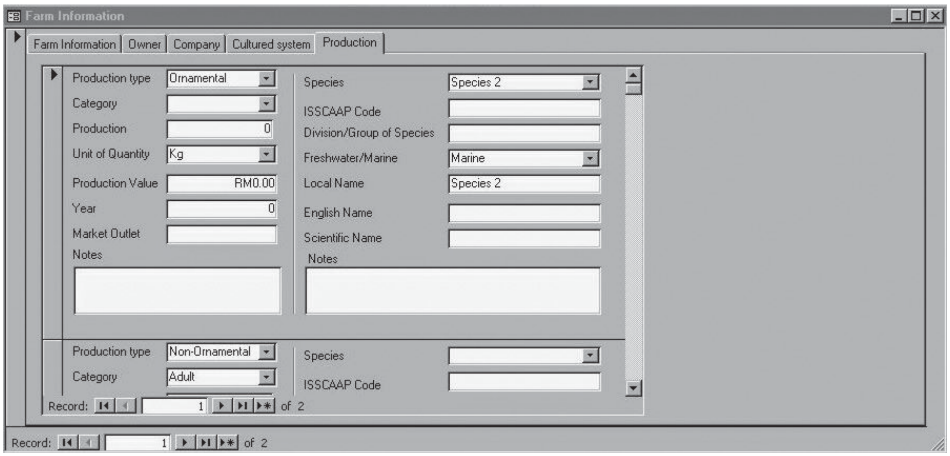
[117] It should be noted that there are other forms of digitizing that may use specially prepared "colour separate" map sheets, or which may rely on automated line following technology. However, these are unlikely to be appropriate in fisheries or aquaculture GIS tasks.

[118] Analogue format can include text, numeric or alphanumeric forms.

FIGURE 5.2
Example of a database set up for recording aquaculture production



Source: Sabah Integrated Coastal Zone Management (1999).

5.2.3 Digital data transfer

Although some data will be input to the GIS via scanning and digitizing or via the keyboard, today the bulk of data is likely to already be in a digital form. There are many mediums by which digital data may be transferred, including CD–ROMs, DVDs, data loggers, memory sticks, internal networks or the Internet. Because similar issues arise with all of these mediums, they can be discussed together.

A large proportion of digital data being transferred will not have been collected specifically for a GIS project. This means that data may have been collected in a neutral way by a recognized authority for a census or for topographic mapping, or data may have been collected for an entirely different purpose, so the user must work with the data available. These facts illustrate that some data will be reliable and accurate whereas other data will not be. While circumspect data may be usable, it is likely that the data will need updating, editing, reclassifying, etc., and, moreover, the data may not have been collected at a suitable scale or resolution. For these reasons, care should be taken wherever possible, to source data from reliable providers.

All data acquired will need to be in an appropriate format and, as indicated earlier, it will be essential to know the format(s) acceptable to the GIS software being used. Therefore, data downloaded from a global positioning system (GPS) or a data logger should be stored in the computer or server in the appropriate format, and it may be necessary to obtain conversion software to translate data into that format. Data that are being transferred use a standard file format called file transfer protocol (FTP). This means that a standardized set of rules (the FTP) has been established that allows data to be input to an exchange medium (CD–ROM, DVD, memory stick, the Internet, etc.), to be stored, to be transferred, and to be reassembled by a distant user.[119] Users need to be aware that some data sets that are downloaded over the Internet or available on CD–ROMs can be very large, as, for instance, remotely sensed imagery, and thus digital storage capacity may be an issue. If large data or information files need to be transferred, they can now be sent over the Internet by using a specialist file delivery service such as YouSendIt (www.yousendit.com) or ShareFile (www.sharefile.com). The YouSendIt service enables users to store and send files to others. YouSendIt offers several account types, which fall into the following categories: free, personal and corporate. Free accounts are offered at no charge and up to 100 MB can be sent by

[119] Data being transferred online will use the Hyper Text Transfer Protocol (HTTP).

e-mail. The other account types are subscription services requiring periodic payments (monthly or annually, depending on the account type) for sending larger amounts of data. A detailed description of the service and the features associated with different account types can be found at www.yousendit.com/compare-plans. ShareFile allows the creation of a custom-branded, password-protected area where business files can be easily, securely and professionally exchanged with clients; up to 2 GB of data can be sent by e-mail per delivery. Delivery costs can be low, though they vary quite substantially according to the amount of usage that is made and, therefore, whether a single delivery is paid for or whether a time period subscription is taken out.

Sometimes data sets are simply too large to transfer efficiently over the Internet using the technology most people have. Some data sets are hundreds of gigabytes in size, and the only way to efficiently transfer them is to load them onto a stand-alone hard drive and physically mail or ship the hard drive.

5.3 DATA VALIDATION AND EDITING

The data that have been collected and transferred to a digital format now need to be suitably organized and stored. However, before this is done users should confirm that the data are up to date and accurate and are, therefore, trustworthy. This may require validating, editing and correcting the data, and may also require other manipulations such as data transformations or reclassifications. Ideally, these edits and manipulations should be done before any analysis is performed, although constant reviews of data are always beneficial. Data validation is always a good habit for maintaining good quality data; however, a lack of time and funds often forces users to simply trust the quality of the data sources. As long as users review the data before their analysis they can decide whether to conduct a thorough validation or editing exercise or not. In this section, only the necessary editing and corrections to make sure that the data are trustworthy are considered; in Chapter 7, other optional manipulations are looked at, i.e. that may be necessary to transform data so that the data can be used for specific GIS projects. Additionally, the updating of data is not discussed because the importance of this is self-evident. However, users should know that maintaining current data can be a time-consuming and expensive task.

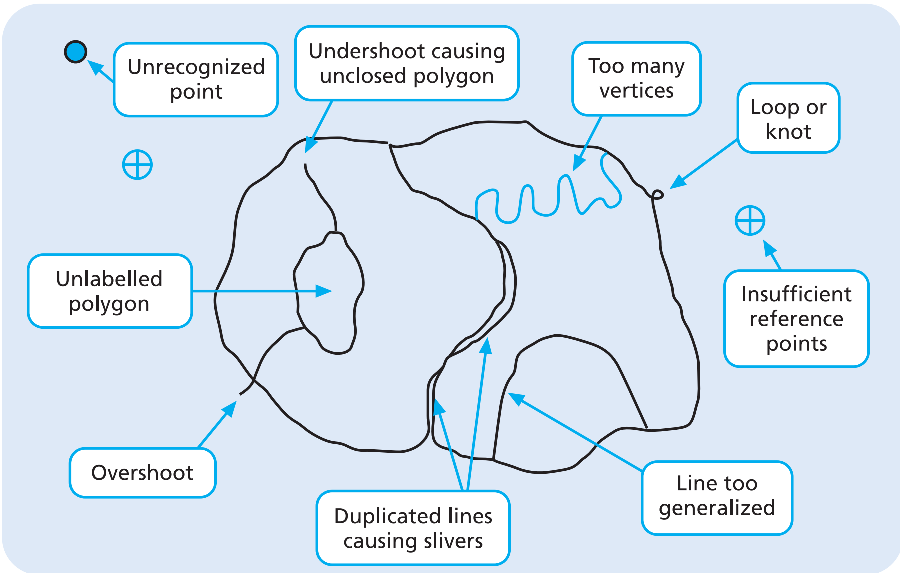
With respect to data entry, the sources of errors are numerous: the source material may have been incorrect or incomplete; mistakes are likely to have been made during the digitizing process; georeferencing might be incorrect or incomplete; data formatting might be unsuitable; and there could be many uncertainties regarding attribute classification and coding. These uncertainties need to be addressed before GIS work starts and before the errors begin to contaminate other data sets. Most GIS packages have their own set of editing tools, ranging from basic functions such as copying and deleting to other more advanced tools such as topological editing and attribute validation tools (see Section 5.8.1). The most comprehensive GIS software allows users to graphically "walk through" and edit the spatial errors. Other GIS software simply identifies the type and coordinates of the error. Some errors can be sorted out before they are input to the GIS, i.e. by means of editing functions within the digital data source such as in image processing software. Because validation and editing is often labour intensive and time consuming, users should consider the error correction capabilities carefully when evaluating any GIS software. Although the software should provide the ability to edit both graphical and attribute data, for many types of editing it may be necessary to do this manually. The editing processes are categorized under two headings: (i) graphical (spatial); and (ii) non-graphical (non-spatial or attributes), though editing may also be necessary if the spatial data are incorrectly linked to the non-spatial data[120].

[120] These mistakes usually occur because an incorrect unique identifier (label) has been allocated during the digitizing process.

5.3.1 Graphical editing

Graphical or spatial editing refers to checking and correcting the digital data that are employed to draw the points, lines and polygons that appear on maps. Data obtained from a national mapping agency are usually reliable, though may require updating. However, data that may have been digitized, usually by a GIS team member, are frequently subject to many errors. Figure 5.3 illustrates some of the errors that typically occur during the digitizing process. When digitizing existing paper maps, it is best to validate graphical data during the data capture process.

FIGURE 5.3
Typical errors caused through the map digitizing process



The most common graphical fault in need of editing are so-called slivers. These usually occur because neighbouring polygons are individually digitized and the common boundaries do not match up exactly, although they may also occur when combining (overlaying) data from different sources. Slivers are easily eliminated through GIS editing procedures. Loops or knots occur when the person digitizing pauses while following a line and fails to restart in exactly the same place. Overshoots and undershoots are common when lines are not "snapped" to link with other lines.[121] It is particularly important to correct for undershoots because polygons will not be correctly identified. And at least four reference points must be used when geo-positioning the map; otherwise, the mapped outline may not be located in an exact position. Many more reference points may be necessary if the data must be mathematically warped or projected to conform to real-world coordinates. Other problems occur when the person who is digitizing forgets to add labels to lines or when the standard of digitizing is insufficiently accurate. Most GIS packages have tools that help identify digitizing errors and once identified the errors can be easily removed.

5.3.2 Non-graphical editing

The focus in this section is with checking and correcting the attribute data that correspond to the mapped features. Errors in attribute data may be caused by a lack of

[121] Users are generally able to select a snapping distance in which the end of a line will automatically snap to join up to the nearest alternative line. This distance will depend on the scale of the work and the accuracy required.

knowledge concerning the classification or categorization of data, in which case they may be difficult to correct, or they may also come from incorrect keyboard entries.

Attribute errors are usually more difficult to detect than graphical errors and, although it may be impossible to verify that every mapped feature has been described correctly, Heywood, Cornelius and Carver (2006) outline a number of methods that can be used to verify the data:

- **Impossible values.** Most data sets contain values that are only within a certain range. Data values lying outside the normal range may need verifying.
- **Extreme values.** These values may need to be checked against the source document.
- **Internal consistency.** Do the data that are in summary tables or that may represent mean or median values correspond with those given in source documents?
- **Scattergrams.** If two or more variables in an attribute table were correlated in the form of a scattergram, do any values depart noticeably from the regression line?
- **Trend surfaces.** Data often exhibits a regional trend, e.g. air temperatures will decrease towards the poles. Are there values that go against the trend?

These data verification methods apply to values that are assigned to attributes, but some of the methods could also be applied to checking the codes given to attributes. For example, Table 5.1 shows part of an imaginary file recording fishing vessel registrations in the Federative Republic of Brazil. The columns headed 1, 2, 3, 4 and 5 are codings given to the previous "attribute" column; in column headed "2", for example, the numbers shown represent a code for the date (year) in which the fishing vessel was registered. It is relatively easy to see that the attribute codes conform to the known range of fishing vessels or the known range of construction dates, etc. Therefore, in Table 5.1, the codings in the column headed "2" may need to be verified because the coding "15" (data row 3) clearly indicates that the vessel was registered in a year ending in "15"; possibly 1915, which means that the vessel is nearly 100 years old yet it is constructed from glass fibre – this is almost certainly a mistake. Similarly, the coding "A" in the column headed "3" indicates a vessel that is not registered in the Federative Republic of Brazil, and this needs to be checked and resolved. Note that, as a means of updating data, it will be simple to add extra rows or columns of data to data sets such as this. A useful way to validate tabular data when they are to be entered manually is to ask two people to enter the same data and then compare the results. Each person is liable to make errors, but they are unlikely to make exactly the same errors. A search is made to find any cases where the two data sets differ, and the correct values can be determined using the source data.

TABLE 5.1
Hypothetical table (file) showing illustrative fishing vessel registrations in Brazil

Registration no.	1	Date registered	2	Home port	3	Overall length (m)	4	Hull construction material	5
RV 1443	43	10.06.97	97	Recife	7	16	16	Wood	1
RV 1447	47	15.07.96	96	Santos	3	31	31	Metal	3
RV 1451	51	23.03.15	15	Recife	7	20	20	Glass fibre	2
RV 1456	56	28.11.01	01	Niteroi	6	28	28	Wood	1
RV 1462	62	04.06.99	99	Montevideo	A	35	35	Metal	3

After the data have been validated and edited where necessary, they can be stored awaiting further use. However, before examining the storage of data in files and databases, it is first necessary to review data modelling. The structure and design of a good data model can be a critical factor in how well data can be used and analysed in a GIS.

5.4 GEOGRAPHIC DATA MODELLING

Initially, some words of caution are needed regarding the confusing terminology that abounds in the areas of data, databases and their associated geographic modelling. Readers might come across the term "data model" being used to portray at least three different concepts:[122]

i. Bernhardsen (1999) discusses "data models" in terms of the ways in which geographic data can best be structured in a GIS so as to represent the real world. This approach is essentially spatial data modelling and refers to the two main models – raster and vector – that are discussed in Section 5.8.

ii. Heywood, Cornelius and Carver (2006) discuss "data models" in terms of the way in which database management systems are structured in order to optimize data handling. This is essentially database modelling and is briefly mentioned in Section 5.5.

iii. Longley *et al.* (2005b) and Wright *et al.* (2007) use "data models" to indicate the ways in which the real world is conceived for digital mapping purposes. This is essentially concerned with the levels of abstraction and visualization required to create industry-specific digital database designs that can best be used within a GIS, and it is this concept of data modelling that is discussed here[123].

In order to create digital maps that will be used in any GIS, it is critically important that a data modelling process has been undertaken. Most GIS users will not be involved in this process because it will already have been undertaken in order that any specific GIS can function as effectively as possible. What is being done in the data modelling process is to undertake a series of steps or stages that create a set of rules allowing for any aspect(s) of the real world to be represented in a digital map form. Modified sets of rules can be used to create a range of geographic data models that can be used for different types of digital mapping purpose, e.g. the creation of topographic maps, marine charts and archaeology maps. Data modelling shows how real world information can be structured in such a way as to allow the portrayal (visualizing) of features on a digital map, or how spatial information can be intelligently structured as the basis for map production in a GIS. It is important to realize that there is no such thing as a "correct" geographic data model; every spatial area or project can be represented with many possible data models. Box 5.1 shows the stages in a hierarchy from the reality of the real world at Stage 1 to the increasingly abstract world of the map at Stage 5.

For many main areas of GIS, data models have already been developed that provide optimum ways of establishing databases. In the area of fisheries and aquaculture specifically, these models have not been developed, though Wright *et al.* (2007) provide evidence of extensive data modelling for the marine environment more generally.[124] Additional information on the rather complex topic of "data modelling" can be found in Bernhardsen (1999), Lo and Leung (2002), Rigaux, Scholl and Voisard (2002), or Manolopoulos, Papadopoulos and Vassilakopoulos (2005), and online information is available at Urban and Regional Information Systems Association (www.urisa.org/node/534).

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[122] Causing even greater confusion is that the same authors often use the term "data model" in at least two of the three ways described here.

[123] For examples of this meaning of data models, see Environmental Systems Research Institute (http://support.esri.com/en/downloadsdatamodel).

[124] See ESRI ArcGIS Marine Data Model (http://dusk.geo.orst.edu/djl/arcgis/ArcMarine_Tutorial/).

BOX 5.1

Levels of abstraction in data modelling for a fisheries or aquaculture mapping scenario

1. The first level is the *real world*, i.e. the way that a vast array of natural and constructed features exist in any real world fisheries and/or aquaculture landscape or seascape.

2. The second *data or conceptual model* level is the abstraction of the real world to include the objects and processes that are seen as important to a particular problem area or theme. For example, if the GIS project was concerned with lake fisheries, special attention may be paid to the fishing vessels, fish markets, preferred species, the shoreline, etc., and little attention needs to be given to the range of tree species around the lake. This step also introduces human bias. Two people developing a data model for the same topic may derive rather different sets of data to be placed in the database, but eventually agreement must be reached. It is also important at this stage to consider the relationship between objects (or entities and attributes), and to keep all considerations completely isolated and independent from the computing environment.

3. The third level is the *data structure or logical model* – sometimes referred to as database design. This is concerned with the organization of data in a way that allows the data to be efficiently stored, managed and manipulated, and the data must also relate to the database software being used and be able to meet user requirements, as expressed in level 2. Here, it will be necessary to work out what sub-themes within, for instance "lake fisheries", will need to have separate files or databases and what attributes will be recorded for each sub-theme. It will also be necessary to work out the symbolism to be used to show all items to be mapped, including colours, fonts and legends.

4. The fourth level is the actual *file structure, or physical model*, referring to how the data are physically stored in the computer, plus the computing environment that will best prevail. This so-called "physical schema" is usually determined by the database management software's data definition language, i.e. the GIS user will have little say in this part of the data model.

5. The final level represents the creation of the *digital maps* that should be possible given that the databases have been carefully designed and structured. If data modelling has been done well, these maps should have the necessary intelligence to be optimally used for GIS purposes.

Note: The names shown in italic are the conventional terms for each stage or level.

Source: Adapted from Longley *et al.* (2001).

5.5 THE STORAGE AND MANAGEMENT OF DIGITAL DATA FOR GIS PURPOSES

As the needs for research into fisheries and aquaculture are being increasingly addressed, it is certain that data will accumulate at an accelerating rate. For maximum efficiency, all data collected need to be appropriately stored, organized, managed and shared, and this is accomplished via the use of files, databases and database management systems (DBMS). Once data are in a database, the data can be added to, edited, searched, ordered, etc. Specific database packages can be linked to GIS software, although major GIS packages now incorporate their own database functionality. This section examines the main factors regarding the storage and management of data.

5.5.1 Data files

As described in Section 5.2.2, data may be collected, stored and saved for future use in the form of files and/or databases. Files are the most basic form of data storage and common examples are text files, tables, shapefiles[125] and images. File-based tables commonly exist as comma- or tab-delimited text files, as dBASE files or as Excel tables.[126] Table 5.1 illustrates the basic structure for tables. The reader will associate this structure as the one adopted in spreadsheets. Each row in a table typically represents one record or one item from all those that are being surveyed or examined. Each column in the table represents an attribute (or field) of those surveyed items. Attributes, which may be numeric or textual, are usually assigned codings (or keys) by the database or GIS software, i.e. as a means of storing the information in an alphanumeric way that can be handled by the software. Columns headed 1 to 5 in Table 5.1 give examples of this. Tables are typically developed for a specific project or survey, though each table might contain records for a particular time period or a particular area. Theoretically, the number of rows or columns is unlimited; however, restrictions exist in the form of data storage and handling capacity, data collection costs, etc. When initially assembled, the records in tables do not need to be in any specific order, but it is essential that tables within a single database are assembled (formatted and structured – see Section 5.2) in the same way. Individual tables do not need to contain the same set of fields (columns), though if tables are to be joined and/or linked they must contain a specific linking or joining field (see Box 5.2) that is common to both tables.

Most tables used for GIS purposes are unique in the sense that they must include a column (or columns) that provides some kind of georeference. Without this, it would be impossible to map the data. The georeference (or unique spatial identifier) in Table 5.1 is shown in the column headed "3", i.e. because this is the only column that contains geographic (spatial) data that could be mapped. Here, the spatial data are in the form of place names, but in some files, tables or databases, the georeference may be in the form of a grid reference or latitude and longitude coordinates. All the files that make up a single database will need to be based on the same georeferencing code so that the files can be linked (see example in Box 5.2). It can be inferred from Table 5.1 that each fishing home port in the Federative Republic of Brazil will have a different number by which it can be identified. The spatial codings in attribute files nearly always refer to points or polygons on a map. Points may be very specific locations, such as a town position, road junction or any other specific feature. Polygons are more spatially extensive areas, such as counties or states, though note that the scale of mapping will affect whether a mapped feature appears as a point or a polygon.

Shapefiles are similar to tables except that they also include a vector object (such as a point, line or polygon) that is paired with each row of data. While a basic table may include a pair of coordinates for each row or a coded value that refers to some spatial location, a shapefile includes the actual spatial object itself. There are other types of files that contain georeferencing information on the locations of point, line and polygon features on a map, such as field boundaries, roads and rivers – this is referred to as topological data and is covered in Section 5.8. It is the georeference unique identifier in files that allows separate files to be intelligently merged, joined or linked.

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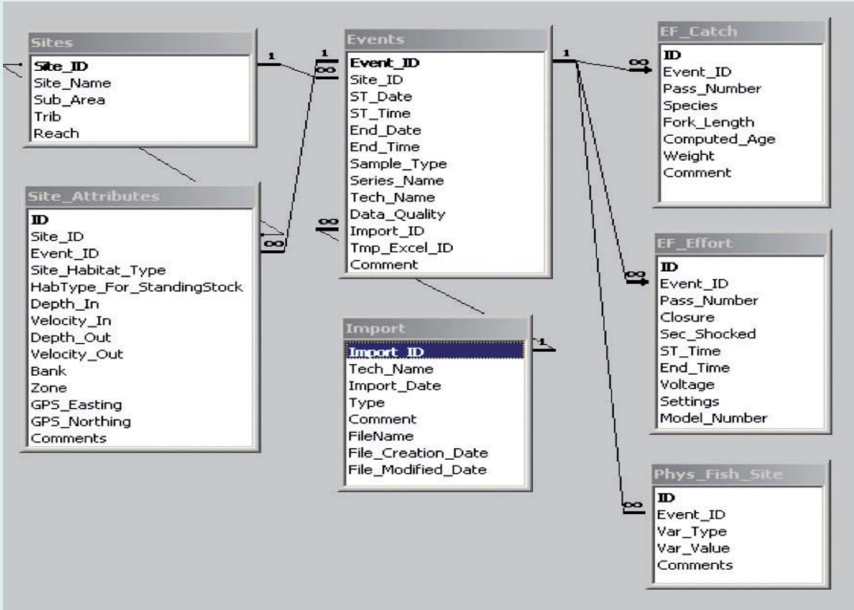
[125] The ESRI Shapefile (or simply Shapefile) is a popular vector data format for geographic information systems software. It was developed and regulated by ESRI as a (mostly) open specification for data interoperability among ESRI and other software products. The Shapefile format was introduced with ArcView GIS version 2 in the beginning of the 1990s. It is now possible to read and write shapefiles using a variety of free and non-free programs.

[126] In this section, the description of files concentrates on tables because they are easy to conceptualize.

BOX 5.2

Part of the database design for a 2007 fish census on the Lower Bridge River, British Columbia, Canada



Source: Lower Bridge River Database (2005).

The fishing authorities in British Columbia contract out regular fish surveys on a number of rivers and the data collected are stored in a relational database. This box shows the seven "internal index tables" that make up one section of the database called "Electrofishing". Each index table shows the file names in that section of the database and the attributes for which data are collected in each file. For instance, the "Sites" file will have the five attribute headings of "Site ID" (possibly an allocated code number); "Site Name" (perhaps the name of a place or a bridge); "Sub-Area" (the name of political areal unit, e.g. a county); "Tributary" (the name of the river); and "Reach" (the name of the particular stretch of the river). Other databases for the same river section include "population estimates", "snorkel surveys", "benthic" and "habitat" data. Together with the "Electrofishing" database shown above, these data sets make up one large database that is continually updated. The linkages show common identifiers (ID) that allow the tables to be connected to one another. For instance, the file "Events" can be connected to "Import" because they both have the common attribute column named "Import ID". It is essential that each index table includes at least one ID that is common to at least one other index table. As this is one of ten databases that make up the complete fish census database for this single river, it is clear that much thought will have been given to the conceptual model that was devised in order to best develop this particular database structure.

5.5.2 Databases

As with "data modelling", the term "database" covers a spectrum of related meanings. At one extreme, Longley *et al.* (2001; p. 18) say that a database "consists of a digital representation of selected aspects of some specific area of the earth's surface or near surface, built to serve some problem solving or scientific purpose". At the other extreme, a database can be seen as a small collection of perhaps half a dozen related files. Whatever the description, a database here refers to an integrated set of data (nowadays usually in digital format) covering a specific subject area. The information stored in a database can refer to: (i) graphical (locational) data, which is digitally georeferenced to show where things are (see Section 5.3.1); (ii) attribute (entity) coding, which is coding to show what things are (see Section 5.3.2); and (iii) relational coding, which shows how features are related to one another. A database that contains locational data is often referred to as a geodatabase. For GIS purposes, the focus is on spatial databases, meaning that they must have georeferencing capabilities. Databases can consist of a collection of data files that are in tabular spreadsheet format (Table 5.1) and/or in special database formats (Figure 5.2), and the collection of files in a single database will all relate to the same topic or theme. Box 5.3 outlines the advantages of using digital databases.

BOX 5.3
Some advantages of using digital databases

For GIS to operate effectively, data need to be organized in databases. This data organization method offers the following advantages:

- All data can be assembled at the same place, thereby allowing efficient data sharing, management and reduction of duplication.
- Maintenance costs can be greatly reduced, and shortcomings in data holdings can be easily recognized.
- Multiple applications will use the same data, so this gives confidence that GIS output will not show conflicting results – it will minimize inconsistencies.
- Security and standards for data and data access can be established and enforced.
- Access to data is controlled and centralized, though non-programmers have a predefined interface to help them.
- Standardized query languages (especially SQL, or "structured query language") are available that allow for efficient posing of a huge range of questions.

Sources: Healy (1991) and Date (1995).

Databases are essential to GIS software packages because they provide the structure for the data stored so that it can be manipulated in a multitude of ways. From a practical viewpoint, database usage may function at different scales. Thus, a very small fisheries or aquaculture institute may hold all of their data in one computer or data server. This is convenient in many ways because one person can easily manage the data in terms of their editing, updating, file ordering and security. However, it is likely that in many regions or countries, fisheries-related GIS data holdings will now be at a larger scale. Here, a special department in charge of database information is common and data are distributed from a central server via the Internet or a LAN. In the case of a departmental database, matters relating to data management, security and upkeep may be operated on a totally different basis than for the small-scale GIS. For instance, because organizations can hire database specialists, they can benefit from economies of scale and thus data can be more easily shared allowing for improved data performance to be recorded.

5.5.3 Database management systems

A database management system (DBMS) is a software package for storing, accessing, modifying, maintaining and retrieving data from databases. There are a large number of DBMS software packages available, but until relatively recently the majority of them lacked the ability to handle spatial data. Until the mid-1990s, GIS-related database management functioned on the basis of external links to separate DBMS, but more recently specialist DBMS vendors have either developed spatial database applications or the GIS software developers have integrated DBMS functions into their packages. DBMS can work with different types of data, they allow databases to be manipulated, to be queried or searched, they provide programming tools, they have particular file

BOX 5.4
The main functions of a database management system (DBMS)

- **Data model** – DBMS include standard general purpose data models suitable for representing several types of themes and objects.
- **Data load** – The provision of tools to load data in standard data types or formats.
- **Index** – An index is a data structure used to speed up searching.
- **Query language** – All DBMS support a standard data query and/or manipulation language called structured query language (SQL).
- **Security** – DBMS provide controlled access to data, e.g. some people have no access rights and others may be restricted to limited sections of the data.
- **Controlled update** – Allows for the management and updating of data sets or databases. This is important when updates affect several different data sets.
- **Back-up and recovery** – In the case of a system problem or failure, such as an electrical failure or incorrect (or accidental) updates or deletions, the data will be recovered.
- **Database administration** – Includes a number of tasks, such as setting up the database schema, creating and maintaining indexes, tuning to improve performance, allocating access rights. Specialized internal software applications conduct this work.
- **Applications** – DBMS include standard general-purpose tools for creating, using and maintaining databases.
- **Programmable API (application programming interface)** – Although DBMS have general-purpose applications for standard use; some specialist applications may require further customization.

Source: Adapted from Longley *et al.* (2001).

structures, and generally they maximize the efficiency in which the data can be utilized for carrying out the whole range of GIS tasks. Box 5.4 provides a more detailed list of the main functions required of a DBMS. It is clear from this information that the average user of a GIS will expect these functions to occur, yet he or she needs to have little knowledge of the functions that are built into the DBMS or the GIS software. In larger organizations, the database manager oversees all the DBMS operations, including adding new data sets or files, regulating access to the system, understanding and adjudicating on legal aspects of data usage, and coping with system problems or failures.

Database management systems themselves can be structured according to four different basic models: networked, hierarchical, relational and object-oriented models. Of these, the relational model has become the most widely used for GIS and for other purposes (Heywood, Cornelius and Carver, 2006) and only this model will be summarized here. Details on the other DBMS structures can be found in Bernhardsen (1999), Longley *et al.* (2011) and in many basic DBMS texts. The structuring of the DBMS relates to the way each database is structured in terms of its efficiency in performing database queries.

The relational database management system (RDBMS) requires that data are organized in a series of tables having columns and rows (as per Table 5.1 or as per a digital spreadsheet). Each cell in the table can contain a "value" that can consist of alphanumeric data having a permissible range of values or meanings. Individual data tables in the DBMS can be linked by common data fields known as "keys". Box 5.2 shows the computer-generated "internal index" tables (the data structure) showing files that make up part of a database that has been developed to record fish surveys in a river in British Columbia in Canada. In the Electrofishing database, the linking "keys" between tables could be "Event ID", "Site ID" or "Import ID", i.e. these "keys" occur in more than one file. Because individual files or databases can be readily linked, the database as a whole can be queried and quite complex questions can be asked. So-called "structured query language" (SQL) has been developed to enable the querying of databases.[127] As Box 5.2 shows, the "Site_Attributes" table is linked to the "Catch" table (via the "Events" table). Based on this link, the user could write an SQL query that would calculate, for instance, the number of fish of a certain weight that were caught in water flowing within a specified velocity range, and through the use of GIS software with its spatial database, this information could readily be mapped. Additional queries can be made on any number of linked tables as required to provide answers, and the queries themselves can be constructed on the basis of Boolean logic.[128] Most proprietary DBMS software generate dialogue boxes providing information on what queries can legitimately be made, and this will depend on what data are stored and whether the data can be linked. Because of the complex tabular linkages that can be created in RDBMS, the system may be inherently slower than other DBMS and efforts have been made to speed operations up through the use of object-relational DBMS.[129]

5.6 METADATA

When collecting data for use in GIS, it is important that the collector has information about the data that are being gathered. This information describing data sets is called metadata. The contents of the metadata will inform the user on whether any data set is worth acquiring – is it reliable to use? Each set of metadata may include a range of variables; for instance, Box 5.5 illustrates the United States Federal Geographic Data Committee recommendations of the major features of geospatial[130] metadata. This list would vary only slightly from country to country, though in many countries metadata quality and standards are still being developed and updated (see Chapter 3).[131] Metadata are stored in a database (a meta-database), and this is intended to be an effective link between the user and the data producer in that they provide relevant information about the various data sets that are held.

From the user perspective, comprehensive metadata have the following advantages:

- Provides a means by which the person(s) producing any data can maintain an overview of what has been compiled over time. This avoids possible duplication of data. Proper documentation creates an institutional record of data holdings.
- Allows the sharing of reliable information with others by allowing for the inclusion of the user's metadata records on metadata clearinghouse servers.
- Helps with the publication and promotion of the data creator's work.
- Reduces workloads in the long run by allowing the creation of templates for an organization's metadata records.
- Helps users to understand the strengths and limitations of the data simply by reading the descriptive information, and helps them to decide whether a particular data set is appropriate for their purposes.
- Helps organizations protect their investment. Data creation or collection is a time-consuming process and it uses resources that could be used elsewhere.
- Documents the process used to create a data set that allows others to replicate that process if the original data collector leaves the organization.

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[127] SQL is a standard computer language designed for accessing, querying and manipulating databases. It allows the user to search for specific information, retrieve it, delete it or add to it, update it and to combine queries.

[128] Boolean logic is commonly used in search engines and it implies the use of delimiting words in queries, such as "and", "or", "equal to", "greater than" and "less than".

[129] See SearchOracle.com (http://searchoracle.techtarget.com/definition/object-oriented-database-management-system) or University of Liverpool (www.csc.liv.ac.uk/~dirk/Comp332/COMP332-ORDB-notes.pdf) for an introduction to object-relational database management systems.

[130] Geospatial tends to be used as a way of differentiating between "geographic" data and data that might be concerned with "space". For simplicity, geospatial can also be referred to as "spatial data".

[131] Other metadata standards include the International Organization for Standardization and the United Nations Environmental Programme standards, plus the standards that are compatible with existing metadata databases, such as the National Aeronautics and Space Administration, Center for International Earth Science Information Network, and the World Conservation Monitoring Centre.

BOX 5.5

Main characteristics of metadata as defined by the United States Federal Geographic Data Committee

- Data set identification – Details on the name, ownership, themes, etc.
- Data quality – How accurate and complete are the data, plus consistency, lineage, timeliness and derived data sources.
- Spatial data organization – The data model used, the number of variables collected and details on non-coordinate methods of location encoding.
- Spatial referencing information – Coordinate system used, plus projection and datums, and what spatial area is being recorded.
- Data exchange format – Information on the structure of the data – how it is stored.
- Entity and attribute information – For each attribute, what information is recorded and any coding used.
- Distribution information – Where and from whom can the data be obtained, including available formats, online or other availability, copyright details and costs.
- Metadata reference information – Contact address for organization producing the data. Responsibility for data upkeep.

Source: Adapted from Federal Geographic Data Committee (2012).

As a GIS user, the first thing that should be done when collecting primary geospatial data is to create metadata about this data.[132] Metadata should always be reviewed when collecting secondary data and, if no metadata are present, then the user should give serious consideration as to whether to use the data or not. Can the user have confidence in its reliability? With inadequate metadata, there is no assurance that the data were collected with enough accuracy or precision to use in a serious project. More information on metadata can be found at the following sites:

- Federal Geographic Data Committee (www.fgdc.gov/metadata);
- Open Geospatial Consortium, Inc. (http://opengeospatial.org);
- Environmental Systems Research Institute (ESRI) (www.esri.com/library/whitepapers/pdfs/metadata-and-gis.pdf);
- International Organization for Standardization (www.iso.org/iso/catalogue_detail.htm?csnumber=26020).

5.7 FROM REAL WORLD FEATURES TO A MAPPED WORLD

A brief look at geographic data modelling was made in Section 5.4. The focus now is to look at the basics of digital mapping before exploring in more detail four important data models that have evolved for operational GIS. From the GIS perspective, at its most basic level, geographic data are nothing more than an electronic representation of real world features. For the GIS technicians who will be creating spatial data and using data created by others, it is vital that they understand the process of generating mapped information from real world features. It is incumbent upon them to try presenting reality as accurately as possible when data are created. This means that GIS technicians must have a good understanding of the features that they are trying to represent as geospatial data (maps), and this can be quite difficult to achieve.

Figure 5.4 illustrates how real world features (as detected from a remotely sensed image) might be represented as mapped data; it is clear that to derive the map from the real world a series of decisions must be made – this decision series is shown as the five levels of abstraction in Box 5.1, and this modelling is described in more detail in Bernhardsen (1999) and Lo and Yeung (2002). Box 5.1 clearly illustrates that the mapping processes involve considerable generalization and classification. Thus, the real world is complex compared with the mapped world, and the art of the cartographer is to identify the important information that needs to be displayed

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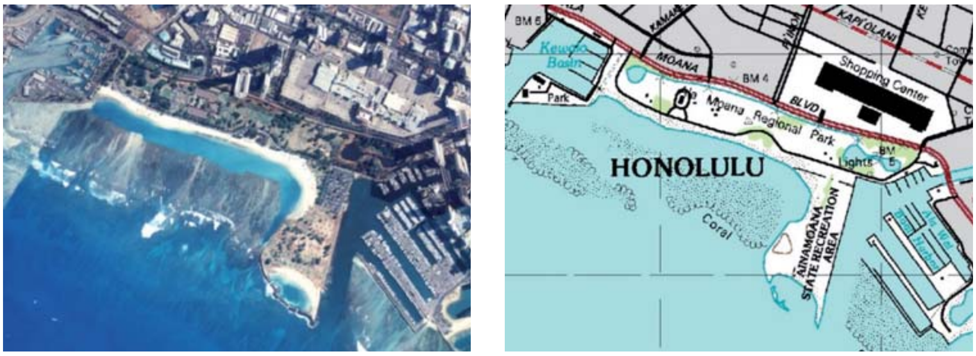
[132] It will also be necessary to update the metadata whenever editing or updating of any data occurs.

FIGURE 5.4
Real world spatial features represented as geospatial (mapped) data

Realworld space **Spatial representation**

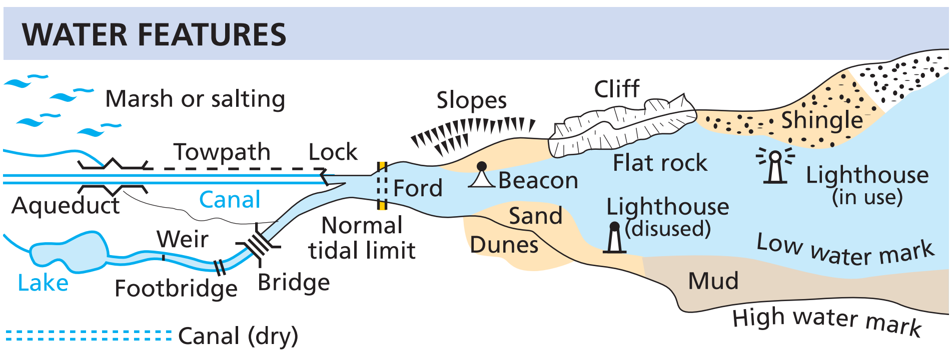


Source: Feinholz and Walker (2007).

and to establish ways of symbolically representing this important information.[133] The process of generalization in GIS is a recognized (and quite skillful) means of simplifying reality while at the same time maintaining as much as possible the true position and shape of the features to be mapped.[134] Cartographic classification forms an associated process, i.e. how best to classify groups of similar objects (entities).

For instance, in the real world space of Figure 5.4, the roads are different sizes, and the spatial representation of these roads has classified them into four categories: (i) a main "boulevard" shown as a double red line; (ii) a dual highway shown as a double black line; (iii) main roads shown as single thick black lines; and (iv) smaller roads shown as thin black lines. Good maps will have legends that convey what object classifications have been made for the construction of that particular map (Figure 5.5). Through the processes of classification and generalization, the cartographer will identify all those features of the real world for which classes of objects (entities) have to be described. As well as the roads just mentioned, there will be buildings, forests, waterways, etc. Each entity type may have subcategories. Thus, buildings might be hospitals, offices, factories, houses, etc., and each entity or entity subcategory must also have attributes. Attributes are terms that describe the entity. For instance, houses could be brick,

FIGURE 5.5
Legend to show water-related features on a topographic map



Source: Ordnance Survey (2012).

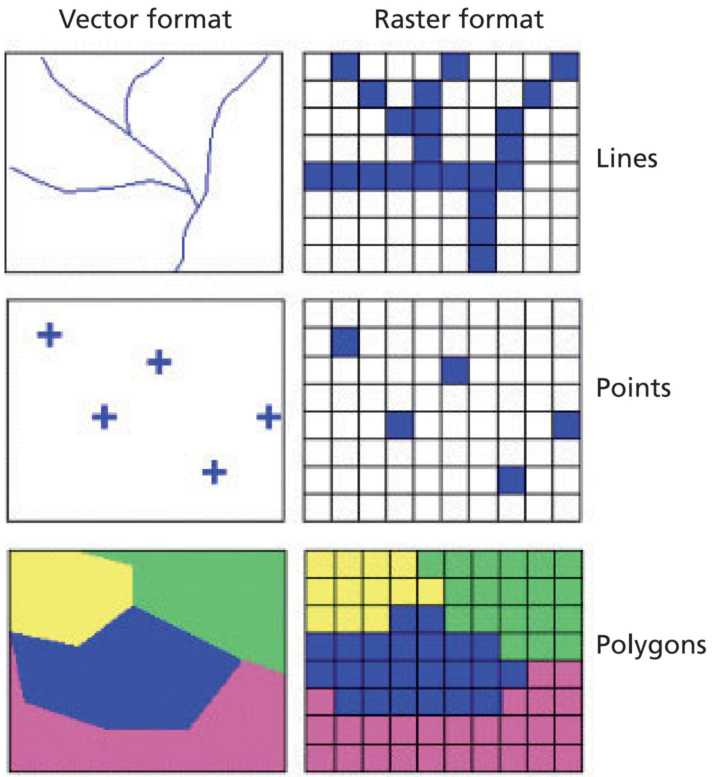
[133] Information that is considered as important to map will vary according to the purpose of the mapping being undertaken, i.e. this is the basis on which "thematic" mapping occurs.

[134] The process of generalization is very important in cartography; further details can be found in Longley *et al.* (2005b) and Harvey (2008).

or wood, and they could be detached, three storey or terraced. Clearly, map construction has to be able to "accommodate" the depiction of a vast array of entities and their attributes. Tables of data are constructed to convey this information to the computer (see Section 5.8.1 and Table 5.2). Moreover, the data being conveyed must contain both graphical information (that associated with where and how to draw the mapped information) and the entity and attribute data associated with the description of the features being mapped.

Figure 5.5 shows the legend that describes all the water-related features appearing on a United Kingdom Ordnance Survey topographic map at a 1:50 000 scale. A close inspection of either the map (spatial) representation in Figure 5.5 or the map legend in Figure 5.6 shows that all the graphical (drawn) features shown on maps can be conveniently categorized as being either point, line or polygon features, as illustrated in Figure 5.6. This means that in terms of the map drawing, or the data modelling processes shown in Box 5.1, all features in the real world can be readily depicted on a digital map as some kind of point, line or polygon (areal) feature.[135] The legend in Figure 5.5 illustrates point features such as beacons, lighthouses, footbridges, locks and weirs; line (or linear) features such as the high water marks, canals, towpaths and streams; and polygon (areal, spatially extensive or 2D) features such as mudflats, lakes, shingles, and sand and water areas in the estuary. It is important to know that, with a change in scale, point features can become polygons or lines and vice versa. For instance, on a small-scale map (showing a large area – typically >1:250 000), the aqueduct shown in Figure 5.5 might only be a point feature, whereas on a large-scale map (<1:50 000) this might be shown as a linear feature. Equally, the lake could change from a polygon on a large-scale map to a point on a small-scale map. These points, lines or polygons may represent any of an almost infinite number of entities, and their correct location is achieved through some form of georeferencing having been assigned to all entities that are saved in a GIS database.

FIGURE 5.6
Line, point and polygon representations in vector and raster formats



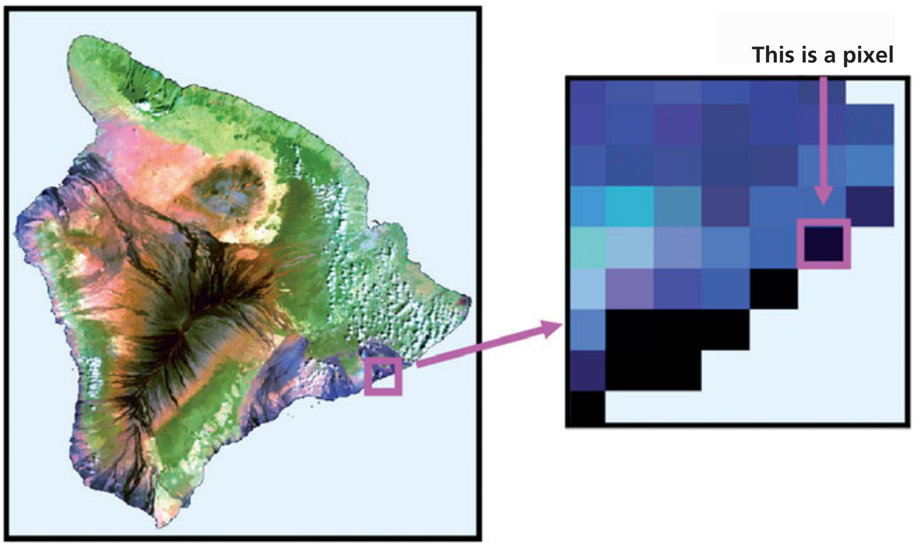
Source: National Informatics Centre (2012).

[135] Some GIS texts identify a fourth form or dimension, i.e. that of "surface". This indicates the fact that land or seascapes have a vertical dimension that needs consideration in some GIS work. Some GIS software packages recognize time as another dimension and allow temporal processes to be mapped and analysed.

5.8 THE STRUCTURE OF SPATIAL DATA

Real world features, as discussed above, can be abstracted into three main feature types: points, lines and polygons (sometimes also called positions, networks and fields). These different feature types can be conveniently stored in two different data structures (also called models or formats) that allow them to be used by GIS software packages, and these are called vector and raster. In principle, both of these structures can be used for the mapping and analysis of points, lines and polygons. However, in practice, there is a strong association between the vector structure and points or lines, and between the raster structure and continuous surfaces.[136] Continuous data are data that either vary across a surface without discrete steps such as temperature or elevation, or data that uniformly and continuously cover an area such as land use or geology (Figure 5.7). Figure 5.6 shows how each structure can be used for this depiction, and a detailed account of the vector and raster structures follows. It should also be noted that the two other basic types of modelling examined in this section – network analyses and 3D analysis – can both be pursued in a vector or raster environment, although vectors are more commonly associated with networks, but 3D surface (or terrain) analyses can use either data structure. Traditionally, different GIS software packages were developed to either handle vector-based or raster-based functionality, but today all major GIS software is capable of handling both data structures and, indeed, they can readily switch between these and data can be converted from one structure to the other. Each data structure has certain advantages and disadvantages and these are examined below. A final introductory point is that much of what follows here describes functions that are embedded within any GIS and thus knowledge of these spatial structures might not be an essential prerequisite for GIS work. However, it is important that background information is provided so that at least the GIS operative is aware of the fundamentals upon which the GIS are operating.

FIGURE 5.7
Raster data set showing land cover on the island of Hawaii, United States of America



Source: Feinholz and Walker (2007).

5.8.1 Vector data structures

The vector data model is ideally suited for representing those real world points, lines or polygons[137] described in Section 5.7, and it does this by storing the feature's real world

[136] Continuous surfaces frequently appear as polygons on thematic or topographic maps.

[137] These are also described as discrete objects because the points, lines or polygons represent specific objects on the earth's surface.

locations as x and y coordinates using some form of georeference, such as latitude and longitude, grid references or state plane coordinates (see Section 3.3.4 and Box 3.5). In this format, a point is simply a coordinate pair giving the location of, for instance, a well or a pond. In the vector data format, a road (or any other linear feature) might consist of a string of nodes stored as x,y coordinate pairs and the software would "connect the dots" when drawing the feature. Likewise, a polygon has its nodes stored as x,y coordinates with the first and last coordinate pair being the same. By using precise georeferences, e.g. perhaps to several decimal places, then it is possible to gain very accurate locations for features, though to some extent the thickness of the drawn mapped line may impede true accuracy.

To store and use vector data for cartographic or GIS work, a number of specialized file formats have been developed. Although there are many formats, the three main types of formats are spaghetti data, topological and ESRI Shapefile, and within these three there are many variations on each format, some of which are specific to the main GIS software houses.

Spaghetti data. This is the simplest vector data format, and though useful for simple drawing or cartographic representation, it is unsuited for GIS work. Spaghetti data can best be described as digitized points, lines or polygons that lack intelligence. Thus, for basic cartographic drawing using the vector structure, the software needs to record a number of attributes about what is being drawn. Apart from the coordinates of every necessary point, line or polygon, the software needs to know what attribute is being drawn. This is achieved by the use of numerical coding[138] series that are compiled by the GIS software as mapped features are drawn, i.e. following the instructions given by the person digitizing the map. For instance, Table 5.2 shows typical numerical coding allocated to vector graphical data in order to identify entity (object) groups and object attributes. Other coding information will need to describe factors such as the line width and types to be drawn, the colour to be used and the size and shape for drawing points, and this information will simply be added to the attributes table (started as per Table 5.2). This information can be useful for basic map drawing purposes, but what is lacking is additional topological information showing how the objects digitized are related to each other. Without this information spatial query and analyses are impossible.

TABLE 5.2
Typical numerical coding allocated to vector graphical data

Numerical code series	Object group
1 000	Survey control stations
2 000	Terrain formation
3 000	Hydrography
4 000	Boundaries
5 000	Built-up areas
6 000	Buildings and facilities
7 000	Communications
8 000	Technical facilities
Numerical code	**Object type**
4 001	National border
4 002	County boundary
4 003	Township boundary
4 011	Property boundary
4 022	National park border

Source: Adapted from Bernhardsen (1999).

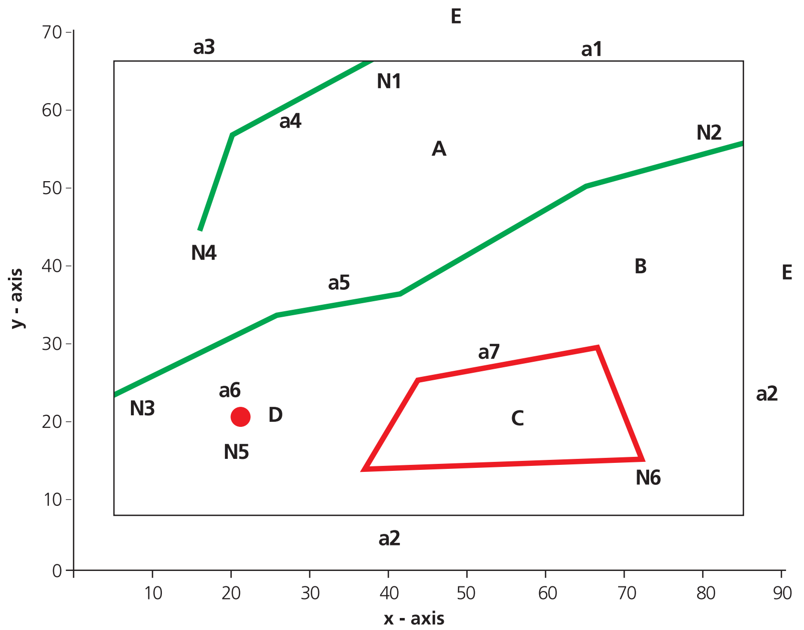
[138] Numerical coding is also called "feature coding". These codes are numeric attributes used in digital map data to describe each feature in terms either of the object surveyed or its representation on the map (or both).

Topological data formats. In order to gain the intelligence for GIS work, the traditional means of formatting vector data has been through the use of the so-called topological data format. Here, a description is made of the basis of this formatting, but there are more variations than the ones described. This data format is based on the concept of topology. Topology is the field of geometry concerned with the mathematics of spatial relationships and, as such, it defines the relationship between features (points, lines and polygons). These relationships are the foundation of spatial analyses and, while their importance cannot be understated, most GIS packages handle topological relationships behind the scenes leaving the user free to perform any analysis. Every GIS is likely to have its own internal means of handling topology, and this section describes only the general principles on which topology is based.[139]

Figure 5.8 shows the topological coding tables relating to the simple "map" at the top of the diagram. In the language of topology, lines are known as "arcs" and points are known as "nodes". The topological information may be stored in three types of "topological tables", in addition to a coordinate table (Figure 5.8). Arcs have a defined start and end node, plus intermediate nodes, and each node has a defined coordinate georeference. The first topology table (polygon topology table) defines the polygons by the arcs that create its boundary. The second table (arc topology) describes which end point nodes occur on each arc and which polygon is to the left or right of each arc. The third topology table stores information about the arcs that end at each of the nodes (node topology table). The fourth arc coordinate data table is not strictly one of the topological tables, but it is an essential associated table allowing the software to know the exact coordinates for drawing all lines or points. Because shared boundaries between polygons are stored as one arc, not the overlapping arcs used in older vector data formats, the storage space needed is reduced. Once the topological relationships have been established for a data set, the GIS package is able to determine all spatial relationships between points, lines and polygons efficiently and to perform an array of functional measurements and analyses. For instance, a set of topological tables containing the attribute and topology data for the river network in Australia would allow the basic river network to be mapped and calculations relating to network lengths could readily be made. If the river network database was then linked to the Australian state boundary information, then the total length of rivers in each state could be calculated. Bernhardsen (1999), Lo and Yeung (2002) and Longley *et al.* (2005b) give more detail on vector data structuring, formats and topology, as do most basic GIS texts, and ESRI offers an interesting background to topology (http://help.arcgis.com/en/arcgisdesktop/10.0/help/index.html#//006200000002000000.htm).

[139] It should be noted that as software evolves, so does the definition of topology. Some modern GIS systems implement topology in new and powerful ways. Topology in the latest versions of ESRI's ArcGIS, for example, no longer store shared boundaries in single arcs. Rather they store the entire vector object for each feature, and they enforce integrity, editing and validation among features within a single data set as well as among associated data sets.

FIGURE 5.8
Simple vector map with associated topological tables



POLYGON TOPOLOGY	
Polygon	Arcs
A	a1, a5, a3
B	a2, a5, 0, a6, 0, a7
C	a7
D	a6
E	Area is outside map

NODE TOPOLOGY	
Node	Arcs
N1	a1, a4, a3
N2	a1, a2, a5
N3	a2, a3, a5
N4	a4
N5	a6
N6	a7

ARC TOPOLOGY				
Arc	Start Node	End Node	Left Polygon	Right Polygon
a1	N1	N2	E	A
a2	N2	N3	E	B
a3	N3	N1	E	A
a4	N4	N1	A	A
a5	N3	N2	A	B
a6	N5	N5	B	B
a7	N6	N6	B	C

ARC COORDINATE DATA			
Arc	Start x, y	Intermediate x, y	End x, y
a1	38, 66	85, 66	85, 53
a2	85, 53	85, 7; 5, 7	5, 23
a3	5, 23	5, 66	38, 66
a4	17, 43	21, 57	38, 66
a5	5, 23	28, 33; 42, 36; 67, 49	85, 53
a6	21, 21		21, 21
a7	72, 14	37, 13; 44, 25; 67, 28	72, 14

The ESRI "Shapefile" format. Since the late 1990s, ESRI has been developing and refining the so-called "shapefile" format for handling vector data, and this has now become a standard data format that can be used by almost all major GIS software.[140] Shapefiles store non-topological geometry and attribute information for all spatial features in a data set and, as such, have no relational intelligence. The geometry for a feature is stored as a "shape" comprising a set of vector coordinates and links to any attribute. Because shapefiles do not have the processing overheads of a topological data structure, as well as lower storage requirements, they have advantages over other data

[140] The term "shapefile" is somewhat misleading because, rather than being a single file, it consists of between three and eleven separate files that allow for the representation of 14 different types of geometric shapes.

formats, such as faster drawing speed and edit ability, and the ability to establishrelational intelligence on the fly. Furthermore, the on-the-fly methods determine important relationships that traditional topology fails to capture. Thus, there is often an interest in proximity, direction and distance between disconnected features, and the topology data do not handle this. The same logic that determines direction and distance can also determine all the topological relationships that used to be stored directly in the data. Shapefiles handle single features that overlap or that are non-contiguous. Because shapefiles are compatible with many software programs, they are likely to be a mainstay for GIS software in years to come. For more information on ESRI shapefiles, see ESRI (1998) (available at www.esri.com/library/whitepapers/pdfs/shapefile.pdf) and Theobold (2001) (available at www.esri.com/news/arcuser/0401/topo.html).

5.8.2 Raster data structures

The second method for structuring data used to create digital mapping is through the use of the raster data format. Figure 5.6 shows that the points, lines or polygons representing all spatial entities can also be depicted using a grid of equal size cells (also known as pixels). Grid cells are almost always square, e.g. perhaps representing 1 metre by 1 metre of real world space but, though rarely used, "cells" could theoretically consist of any shape capable of regular tessellation such as rectangles, equilateral triangles or hexagons.[141] Individual cells in a raster structure may be identified by sequential alpha and/or numeric figures for the columns (x axis) and for the rows (y axis). Figure 5.12 illustrates an example of this, with the map showing the same area as was covered in Figure 5.8, and with a similar numerical coding being shown for each axis.[142]

FIGURE 5.9
Examples of raster output for aerial data collected at 30 metre and 1 metre resolutions

Satellite image
(30 metre spatial resolution)

Aerial photograph
(1 metre spatial resolution)

Source: NOAA Coastal Services Center (2012).

[141] Tessellation is the division of space into polygons in such a way that none of the polygons overlap and there are no gaps between them.

[142] Note that on vector georeferencing (see Figure 5.8), the coordinate numbering refers to fixed points along each axis, though with raster alphanumeric coding, the letters or numbers refer to each column or row.

Raster information is built up in "layers" (or separate files), with each file covering a distinct mapping theme (bathymetric depth, land use, water temperature, etc.) Each raster cell is typically allocated a code (or value) based on the predominant feature or class that occupies the majority of the grid cell,[143] or the presence or absence of a feature. For example, elevation rasters contain elevation values, landscape type maps contain landscape category values, and aerial photographs contain reflectance values. The coding given to each cell might be in terms of a numerical value, a weighting, a coding allocated to a colour or a reflectance value. Therefore, rasters do not actually contain the colours illustrated in Figure 5.9; they contain values that the GIS converts to colours when they are displayed.

Some rasters have a single band, or layer (a measure of a single characteristic), of data, while others have multiple bands. Basically, a band is represented by a single matrix of cell values, and a raster with multiple bands contains multiple spatially coincident matrices of cell values representing the same spatial area. An example of a single-band raster data set is a digital elevation model (DEM). Each cell in a DEM contains only one value representing surface elevation. Most satellite images have multiple bands, typically containing reflectance values within a range or band of the electromagnetic spectrum.

There are three main ways to display (render) single-band raster data sets:

- Using two colours. In a binary image, each cell has a value of 0 or 1 and is often displayed using black and white. This type of display is often used for displaying scanned maps with simple line work such as land parcel maps.
- Greyscale. In a greyscale image, each cell has a value from 0 to another number, such as 255 or 65 535. These are often used for black-and-white aerial photographs.
- Colour map. One way to represent colours on an image is with a colour map. A set of values is coded to match a defined set of red, green and blue (RGB) values.

The three main ways to display single-band raster data sets are shown in Figure 5.10 (A).

When there are multiple bands, every cell location has more than one value associated with it, as presented in Figure 5.10 (B). With multiple bands, each band usually represents a segment of the electromagnetic spectrum collected by a satellite sensor. Bands can represent any portion of the electromagnetic spectrum, including ranges not visible to the eye, such as the infrared or ultraviolet sections.

The dimension of the pixels, known as the spatial resolution (not to be confused with cartographic resolution), is of particular importance to the use of the raster structure. Figure 5.11 illustrates the importance of spatial (cell) resolution. Here, a simple 71 m^2 vector-based polygon is compared with its raster equivalent at three different resolutions. The smallest resolution (in this case 1 m cells) corresponds to a fairly good representation of the original, whereas the larger 4 m cells create only a crude replica of the original polygon shape. The figure also lists advantages and disadvantages of using different resolutions, e.g. in this case nearly 16 times as much data must be stored for the smaller cell size resolution.[144] As computer storage capacity has greatly increased relative to storage costs, raster data sets having very small cell (pixel) sizes are increasingly common and they may typically be much larger than vector data sets. In practice, this may mean that many mapped lines are created from rasters whose pixels are so small that the map user may not be able to discriminate the line from a vector-drawn line. Figure 5.9 illustrates an actual example showing raster output at two widely different resolutions; in the left hand image, there is a huge loss of feature clarity causing features to become pixilated in appearance at the increased cell size. Thus, when users collect or create data for a specific project, they must decide the scale at which to work and the cell size that will provide adequate information for successful project completion. Most GIS packages

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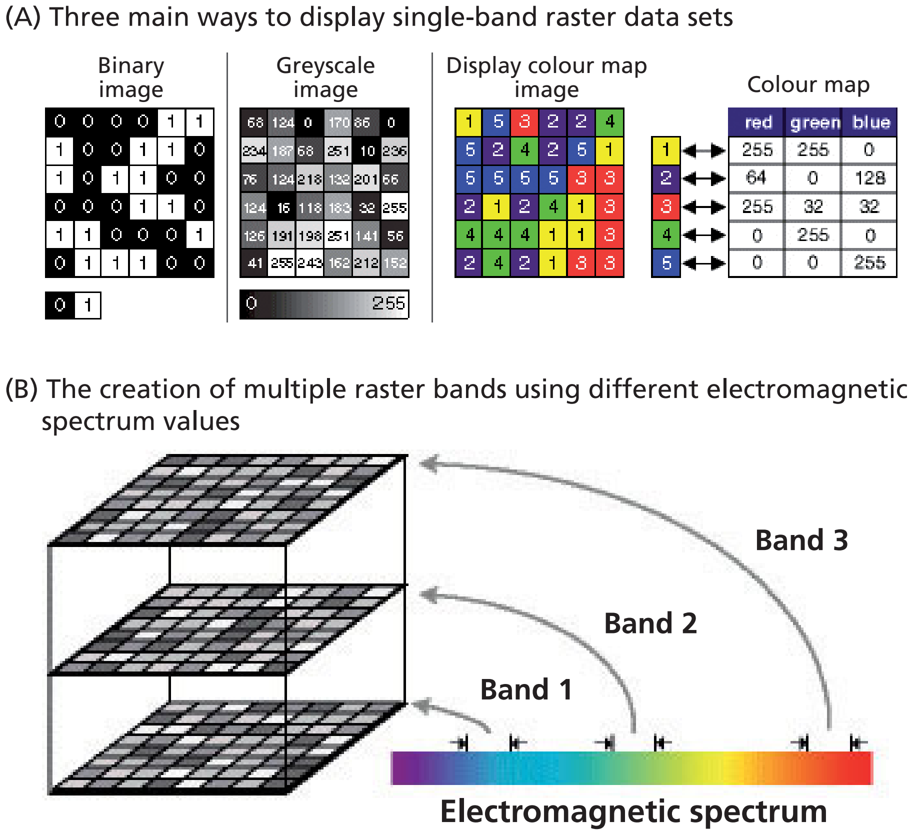
[143] Sometimes an allocated cell value may be that pertaining at the central point of the cell or at a cell corner.

[144] It is worth recording that one complete Landsat Thematic Mapper image (see Chapter 6) may contain about 35 million pixels – all of whose values must be stored.

FIGURE 5.10
Types of raster bands



Source: ESRI (2011c).

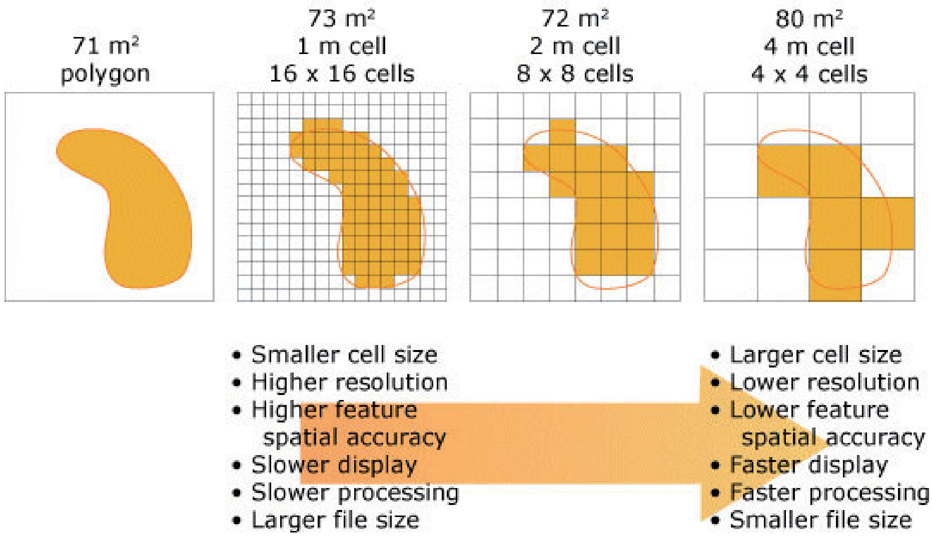
provide the ability to resample raster data[145] so that the data can be changed to a suitable cell size, but it should be noted that any new raster data being created can be of no greater accuracy than that of the original data, e.g. it would make no sense to use the 30 m^2 pixels in Figure 5.9 as the basis for creating the 1 m^2 cell information.

While rasters with small cell sizes tend to take longer to display, a GIS can often accelerate the process with the use of "pyramids". Pyramids are simply lower-resolution versions of the data used only for display purposes. If a large raster image might take minutes to draw on the screen, a pyramid version will draw it in seconds and the appearance will be indistinguishable to the viewer. Pyramids do not speed up raster analysis, but they can make viewing rasters much easier. Detailed information on the use of pyramids can be found at ArcGIS Resource Center (http://help.arcgis.com/en/arcgisdesktop/10.0/help/index.html#//009t00000019000000) or Lowe (2004).

Rasters can require large amounts of storage space, and higher resolutions require exponentially more storage space than lower resolutions. Because of this, a variety of data compression techniques have been developed to reduce the raster file size. There are two broad categories of data compression methods: "lossless" methods preserve all the original data, and are preferred when the data are intended for precise analysis. Popular examples are: LZ77 (Lempel-Ziv 77); LZW (Lempel-Ziv-Welch); RLE (run-length encoding); and quadtree compression. "Lossy" methods alter the data and are generally

[145] Resampling raster data essentially means that various facets relating to the captured data can be changed, e.g. brightness of the image, in order to better discriminate between objects on the ground. For more details, see ArcGIS Resource Center (http://help.arcgis.com/en/arcgisdesktop/10.0/help/index.html#//009t00000082000000.htm).

FIGURE 5.11
Demonstration of different pixel resolutions



Source: ESRI (2007).

used for mapping or aesthetic purposes. The most popular example of this type is JPEG (Joint Photographic Experts Group). A recent advancement is JPEG2000, which uses complex wavelet transform mathematical techniques to produce highly compressed images, and which can be either lossless or lossy depending on the user preference[146].

This section explains how two of the simpler compression methods – RLE and quadtree compression – work. First, Figure 5.12 shows how RLE has been applied to the raster data set displayed.[147] Because many adjacent cells share the same value, for each row it is only necessary to specify a cell value and column number where that value begins and ends. There are several variations of RLE. Further details on raster data compression techniques can be found at Geographic Information Technology Training Alliance (www.gitta.info/DataCompress/en/html/rastercomp_chain.html), or Heywood, Cornelius and Carver (2006).

Second, the quadtree technique is based on the successive subdivision of the area under study into smaller and smaller quadrants, i.e. according to whether or not areas of a similar value are wholly in the quadrant or are not. The lowest level of subdivision is a single pixel. Figure 5.13 shows a raster structure[148] created to map areas having three different "values" (A), with areas being successively subdivided into the smallest quadrats containing a single value. In (B), a quadtree has been constructed, which shows that there are links and nodes in the tree starting from the root node (represented by the blank circle at the top of the tree, i.e. the whole mapped area).

From each node, there are four so-called "edges" representing the four quadrants of northwest (NW), northeast (NE), southwest (SW) and southeast (SE). Subquadrants only emanate from nodes that are shown as being subdivided in the raster map, i.e. it can be seen from (B) that three of the main quadrats (NW, SW and SE) are further subdivided, but that the NE quadrat (numbered 8) is not further subdivided, so it ends at the second level down. For the SE quadrat, no further subdivision occurs after the third level, so the tree ends here (at cell 16). On the other hand, quadrats

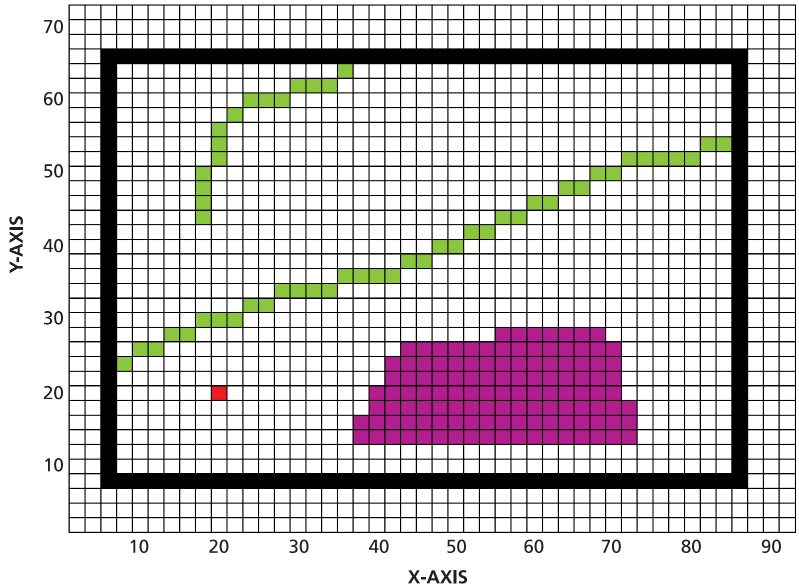
[146] For more detailed information on "lossless" and "lossy" data compression, see ArcGIS Resource Center (http://help.arcgis.com/en/arcgisdesktop/10.0/help/index.html#//009t00000021000000).

[147] For clarity, only alternate pixels have been drawn and numbered in Figure 5.12.

[148] Only the main raster cells are depicted in this figure.

FIGURE 5.12

A simple raster map plus the run-length encoding structure used for data storage



RASTER-RUN LENGTH CODE STRUCTURE

Row	Run-length encoding
72	0, 92, 0
70	0, 92, 0
68	0, 92, 0
66	0, 4, 0; 6, 86, 1; 88, 92, 0
64	0, 4, 0; 6, 1; 8, 34, 0; 36, 2; 38, 84, 0; 86, 1; 88, 92, 0
62	0, 4, 0; 6, 1; 8, 28, 0; 30, 34, 2; 36, 84, 0; 86, 1; 88, 92, 0
60	0, 4, 0; 6, 1; 8, 22, 0; 24, 28, 2; 30, 84, 0; 86, 1; 88, 92, 0
58	0, 4, 0; 6, 1; 8, 20, 0; 22, 2; 24, 84, 0; 86, 1; 88, 92, 0
56	0, 4, 0; 6, 1; 8, 18, 0; 20, 2; 22, 84, 0; 86, 1; 88, 92, 0
54	0, 4, 0; 6, 1; 8, 18, 0; 20, 2; 22, 80, 0; 82, 84, 2; 86, 1; 88, 92, 0
52	0, 4, 0; 6, 1; 8, 18, 0; 20, 2; 22, 70, 0; 72, 80, 2; 82, 84, 0; 86, 1; 88, 92, 0
50	0, 4, 0; 6, 1; 8, 16, 0; 18, 1; 20, 66, 0; 68, 70, 2; 72, 84, 0; 86, 1; 88, 92, 0
48	0, 4, 0; 6, 1; 8, 16, 0; 18, 1; 20, 62, 0; 64, 66, 2; 68, 84, 0; 86, 1; 88, 92, 0
46	0, 4, 0; 6, 1; 8, 16, 0; 18, 1; 20, 58, 0; 60, 62, 2; 64, 84, 0; 86, 1; 88, 92, 0
44	0, 4, 0; 6, 1; 8, 16, 0; 18, 1; 20, 54, 0; 56, 58, 2; 60, 84, 0; 86, 1; 88, 92, 0
42	0, 4, 0; 6, 1; 8, 50, 0; 52, 54, 2; 56, 84, 0; 86, 1; 88, 92, 0
40	0, 4, 0; 6, 1; 8, 46, 0; 48, 50, 2; 52, 84, 0; 86, 1; 88, 92, 0
38	0, 4, 0; 6, 1; 8, 42, 0; 44, 46, 2; 48, 84, 0; 86, 1; 88, 92, 0
36	0, 4, 0; 6, 1; 8, 34, 0; 36, 42, 2; 44, 84, 0; 86, 1; 88, 92, 0
34	0, 4, 0; 6, 1; 8, 26, 0; 28, 34, 2; 36, 84, 0; 86, 1; 88, 92, 0
32	0, 4, 0; 6, 1; 8, 22, 0; 24, 26, 2; 28, 84, 0; 86, 1; 88, 92, 0
30	0, 4, 0, 6, 1; 8, 16, 0; 18, 22, 2; 24, 84, 0; 86, 1; 88, 92, 0
28	0, 4, 0; 6, 1; 8, 12, 0; 14, 16, 2; 18, 54, 0; 56, 68, 3; 70, 84, 0; 86, 1; 88,92, 0
26	0, 4, 0; 6, 1; 8, 0; 10, 12, 2; 14, 42, 0; 44, 70, 3; 72, 84, 0; 86, 1; 88, 92, 0
24	0, 4, 0; 6, 1; 8, 2; 10, 40, 0; 42, 70, 3; 72, 84, 0; 86, 1; 88, 92, 0
22	0, 4, 0; 6, 1; 8, 40, 0; 42, 70, 3; 72, 84, 0; 86, 1; 88, 92, 0
20	0, 4, 0; 6, 1; 8, 18, 0; 20, 4; 22, 38, 0; 40, 70, 3; 72, 84, 0; 86, 1; 88, 92, 0
18	0, 4, 0; 6, 1; 8, 38, 0; 40, 72, 3; 74, 84, 0; 86, 1; 88, 92, 0
16	0, 4, 0; 6, 1; 8, 36, 0; 38, 72, 3; 74, 84, 0; 86, 1; 88, 92, 0
14	0, 4, 0; 6, 1; 8, 36, 0; 38, 72, 3; 74, 84, 0; 86, 1; 88, 92, 0
12	0, 4, 0; 6, 1; 8, 84, 0; 86, 1; 88, 92, 0
10	0, 4, 0; 6, 1; 8, 84, 0; 86, 1; 88, 92, 0
8	0, 4, 0; 6, 86, 1; 88, 92, 0
6	0, 92, 0
4	0, 92, 0
2	0, 92, 0

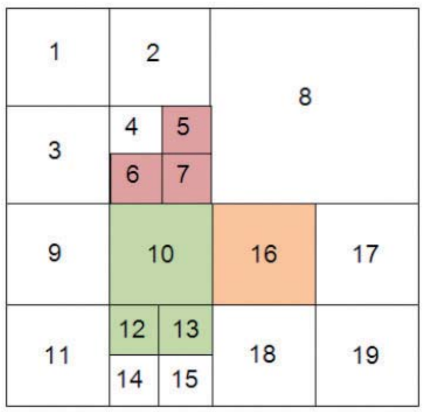
Source: Adapted from Meaden and Do Chi (1996).

NW and SW can be further subdivided to another level. Where edges can be further subdivided, an open (white) circle (node) is drawn; where cells cannot be further divided but there is none of the mapped (white area) showing, a blank square is shown; and where cells cannot be further subdivided and there is mapped area showing, a colour-shaded square is shown. The software encodes this map by only recording georeferencing data for the coloured squares. Savings of at least 50 percent in data volumes are possible using quadtrees. Longley *et al.* (2005b) note that quadtrees offer various advantages for GIS-based work over other methods of data compression.

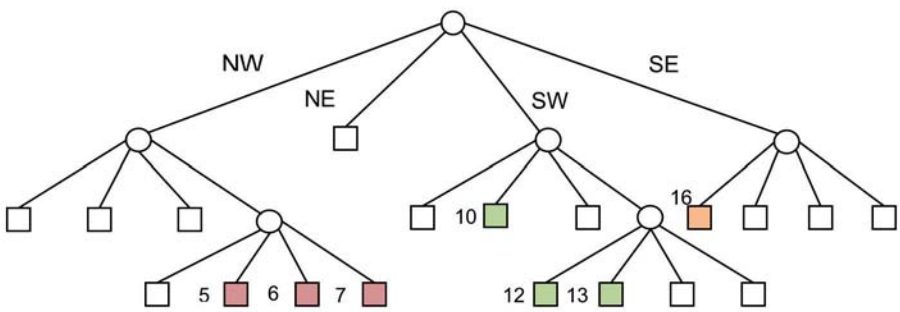
In the past, GIS packages might have been designed to work with one or the other type of data, raster or vector. Now most GIS packages can integrate both raster and vector using additional "add-on" software or extensions. Even though the raster and vector structures are both valid ways of representing real world features, preferences for either can come down to the user's perceived preference of one format over another for use in specific applications. The advantages and disadvantages of each data format have been extensively discussed and Box 5.6 briefly lists these qualities.

FIGURE 5.13
The quadtree raster data compression method

(A) Raster map



(B) The quadtree structure



BOX 5.6
Comparison of raster and vector data structures

Raster data format

Advantages

- simple data structure;
- numerous data sets have been generated through remote sensing and scanning technologies;
- spatial analysis procedures are simple (overlays, area analysis, merging, etc.) and are often faster;
- the inherent nature of raster maps is ideally suited for mathematical modelling and quantitative analysis.

Disadvantages

- large data storage requirements;
- topological relationships can be difficult to represent;
- without very small cell size, detail can be lost;
- map products can be relatively crude if cell size (resolution) is large;
- linear analysis is more difficult and less accurate.

Vector data format

Advantages

- compact data structure takes up less storage space;
- features can be accurately located;
- topological relationships can be established;
- very small features can be shown and all features can be accurately drawn;
- data about individual features can be easily retrieved and updated;
- linear analysis is easily performed;
- map products can be more aesthetically pleasing resembling hand-drawn analogue maps.

Disadvantages

- the data structure is more complex;
- overlay procedures can be more time consuming;
- data capture can be slow and expensive;
- some spatial analysis procedures can be difficult (e.g. area analysis);
- it is not compatible with remotely sensed data.

5.8.3 Terrain (surface) data models

The mapping of terrain is a common task for cartographers, and various techniques have been devised to facilitate this process. Most of these techniques can be easily transferred to a submarine environment where there is a varied interest in reproducing bathymetry[149] and bathymetric modelling. The breadth of interest in, and uses for, bathymetric modelling using GIS is provided in Breman (2010). It should be mentioned that the mapping of terrain or bathymetry is considered as 2.5D (two-and-a-half dimensional) mapping. This means that the vertical dimension of the ground surface, seafloor or lake-bed area being mapped, measured or modelled is only considered in terms of the altitude and/or depth of the "surface" level above or below a datum line,[150] i.e. no consideration is made of objects that are either in the air or in the waterbody. The datum used may be a locally agreed mean tidal level, or it is increasingly measured

[149] Bathymetry is the measurement of the depth of oceans, seas or other large bodies of water.

[150] Most countries that have a marine coast line will establish a "datum line". This is typically an accurately measured and demarcated small section of the coast lying midway between and high and low water tidal marks. Once this line has been designated, it serves as a baseline above (or below), which all altitudinal (or bathymetric) heights (or depths) are measured.

using an internationally agreed datum such as that based on WGS 84.[151] True 3D modelling is also possible using GIS, but this modelling is not discussed here because it has rarely been used for fisheries or aquaculture purposes,[152] i.e. it is mainly used for geological purposes or for volumetric calculations.[153] Data for bathymetric mapping and modelling are commonly gathered from field surveys (mostly using GPS), archived maps containing depth soundings, various photogrammetric techniques[154] or, more recently, from light detection and ranging (LIDAR) and acoustic single or multibeam echosounding surveys (Kearns and Breman, 2010). Terrain data modelling is usually called "digital terrain modelling" (DTM), and within this modelling there are two common data formats: (i) a vector format that is used to create triangulated irregular networks (TINs); and (ii) a raster format to create digital elevation models (DEMs).[155] Most modern GIS packages are capable of viewing and analysing terrain models. DTM can be used for a variety of GIS-based analyses, as follows:

- drawing of block diagrams;
- estimations of water volumes or materials in civil construction projects;
- interpolation and contour mapping;
- line of sight (or intervisibility) mapping;
- calculations and mapping related to aspect, hill shading or slope (gradient);
- catchment estimation;
- defining river networks;
- hydrologic modelling of water flow potential.

Some of these analyses procedures are explained in Chapter 7, where GIS functionality based on TINs and DEMs are examined.

Additional detail on terrain modelling can be obtained from Wilson and Gallant (2000) or Lo and Yeung (2002), who also outline a range of stand-alone terrain analysis and contouring packages, and there is now a searchable DEM database being developed for tsunami inundations and described in the National Geophysical Data Center (www.ngdc.noaa.gov/mgg/inundation). Other sources of DEMs include: ASTER Global Digital Elevation Model, which provides free DEM data to various categories of user (see ASTER Global Digital Elevation Model: www.ersdac.or.jp/GDEM/E/3.html); GEBCO global bathymetry data for oceanic areas (see GEBCO: www.gebco.net/data_and_products/gridded_bathymetry_data); or SRTM (Shuttle Radar Topography Mission elevation data (see USGS: http://eros.usgs.gov/#/Find_Data/Products_and_Data_Available/Elevation_Products).

Triangulated irregular networks

In its simplest form, raster-based DTMs or DEMs record spot height values on a regular grid pattern, and typically the values would be recorded at each grid intersection (Figure 5.14). However, the use of regular grids often causes a loss of detail because actual data on highest or lowest points are often omitted and thus only a generalized terrain surface can be created. A better quality terrain model is created through the use of vector-based triangulated irregular networks (TINs). The TIN approach to

---

151 World Geodetic System 1984 (WGS 84) is a model of the earth's surface based on an oblate spheroid with an equatorial radius of 6 378 137 m and a polar radius of 6 356 752 m, with an origin approximately at the centre of the earth's mass and a zero-longitude set at the International Earth Rotation and Reference Systems Service (IERS) reference meridian. This datum is designed for positioning anywhere on earth.

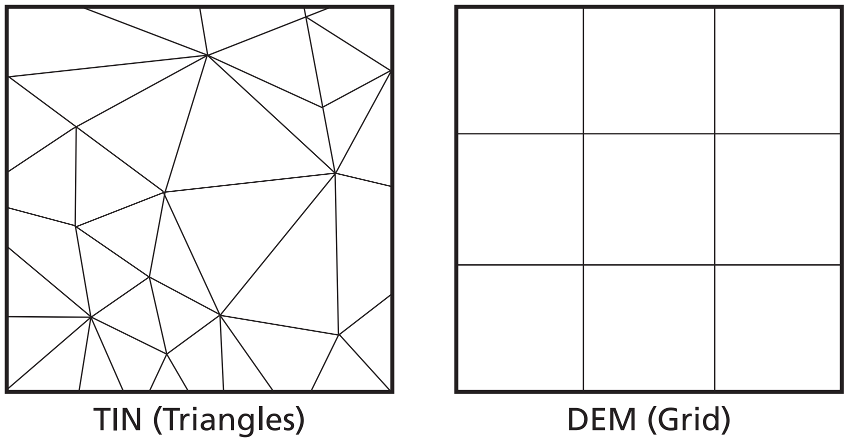
152 One of the few studies on 3D is a study by Moreno Navas (2010) to explore the use of a 3D-hydrodynamic model coupled to a particle tracking model to study the circulation patterns, dispersion processes and residence time in the Irish loch for marine cage culture.

153 Note that 2.5D modelling can only have one "z" (vertical) value per x,y location, whereas 3D modelling can utilize multiple z values per x,y location.

154 Photogrammetric techniques are the processes of making maps or scale drawings from photographs, especially aerial photographs and satellite remotely sensed images.

155 Sometimes there is confusion with the terms DEMs and DTMs. A DEM is a DTM, but a DTM is not necessarily a DEM.

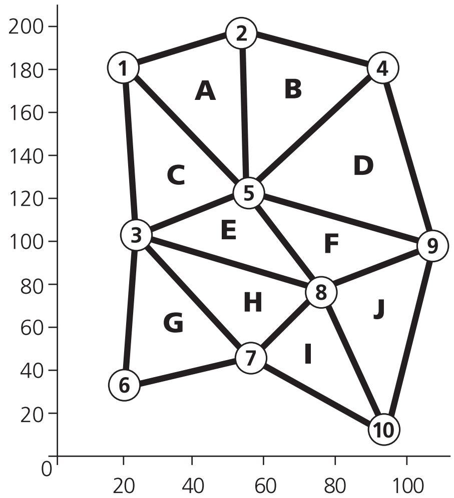
FIGURE 5.14
Vector-based approaches to digital terrain modelling



digital terrain modelling relies on the recording of height or depth values at sampled (surveyed) georeferenced points across an area to be mapped. Here, more purposefully placed height or depth data are recorded in a non-regular way, e.g. in very flat areas only a few values need to be recorded, but areas with rugged topography require frequent height or depth values. The TIN method joins the height observations at the nodes by straight lines to create a mosaic of irregular triangles (Figure 5.14).

Each triangle in a TIN defines a relatively flat surface covering a small part of the total topographic surface. The vertices (or nodes) of the triangles store x, y and z information, i.e. location and elevation values. Given this nodal information, the surfaces of each triangle can provide information on length of slope, area, slope gradient and orientation (aspect), and this information can be stored as attribute data for each triangle. Each GIS package may have its own algorithm for determining the basis for how the triangles are apportioned, i.e. what nodes are chosen for each link (edge).

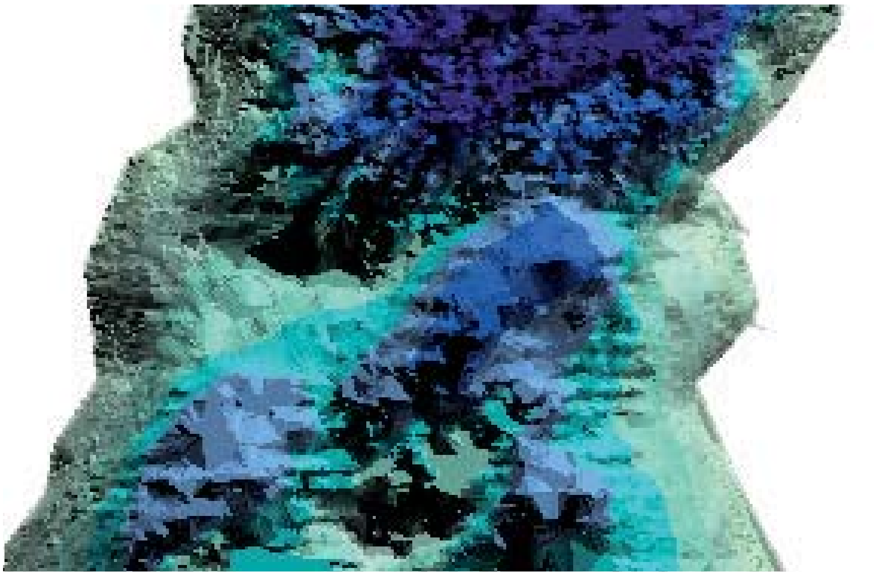
FIGURE 5.15
The topology of a TIN



Node	x - y coordinate	z elevation
1	21, 180	89
2	58, 198	91
3	23, 103	69
4	96, 180	83
5	58, 122	69
6	20, 37	54
7	58, 46	52
8	77, 78	58
9	110, 99	60
10	93, 13	46

Triangle	Node list	Neighbours
A	1, 2, 5	-, B, C
B	2, 4, 5	-, D, A
C	1, 5, 3	-, A, E
D	4, 9, 5	-, F, B
E	3, 5, 8	C, F, H
F	5, 9, 8	D, J, E
G	3, 7, 6	-, H, -
H	3, 8, 7	E, I, G
I	8, 10, 7	H, J, -
J	8, 9, 10	-, I, F

FIGURE 5.16
Triangulated irregular network showing bathymetric data for Lake Michigan, United States of America



Source: University of Michigan (2012).

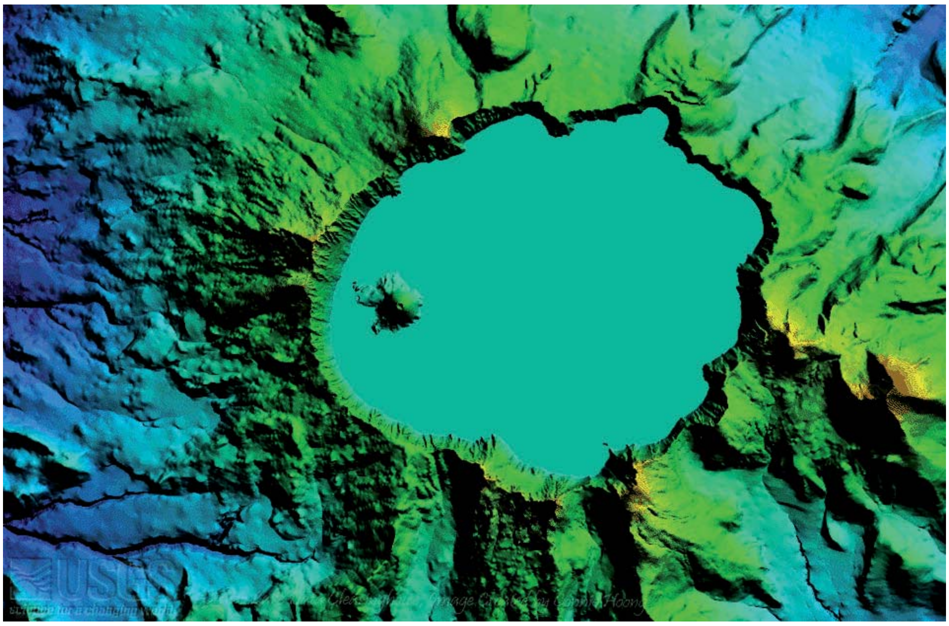
TINs use the topological model vector-based data storage methods as described in Section 5.8.1 and shown in Figure 5.15. The TIN data structure provides information that allows a GIS to create contour maps (using interpolation techniques), including maps showing gradient, aspect or hill shading. Figure 5.16 shows that sophisticated submarine bathymetry can be created based on depth soundings; in this case also showing "depth" shading (deepest areas in dark blue) and bottom gradients across a central portion of Lake Michigan, United States of America.[156]

Digital elevation models

Digital terrain modelling using the raster data format produces digital elevation models (DEMs). It is clear that the raster data structure described in Section 5.8.2 can be utilized to record a single height or depth (z value) for each cell (pixel). The z value can be the height or depth pertaining to the centre of the cell or to a given cell corner. As with other raster-based work, it is clear that the cell resolution will greatly affect the accuracy of the GIS output. Because height or depth data may not be available for every cell, it is usual to use the interpolation functions that are provided in most GIS packages to calculate missing pixel values (see Section 7.5.3). Raster-based DEMs provide a simple structure but one that allows efficient modelling with low computational overheads (fewer calculations) plus easier storage. Figure 5.17 illustrates how a DEM produced map of Crater Lake in Oregon, the United States of America, has been enhanced by altitude and relief shading. The data sets behind DEMs are often available from national mapping agencies at different resolutions, though marine or lacustrine (lake) bathymetric data are unlikely to be widely available. Most GIS packages support raster DEMs and provide for the conversion of x, y and z values to the raster grid cell structure. There are relative advantages offered by each of the two terrain models described and these are summarized in Box 5.7, though it should be mentioned that the relative resolutions adopted can greatly influence the quality of the GIS terrain modelling and, contrary to the apparent evidence in Box 5.7, Longley *et al.* (2011) argue that DEMs are the most useful and accurate form of terrain modelling.

[156] The apparent "flat" areas shaded in grey are in fact islands protruding above the lake's surface.

FIGURE 5.17
Digital elevation model of Crater Lake, Oregon, United States of America enhanced by altitude and relief shading



Source: Rob's maps (2009).

5.8.4 Network data models

A network is an interconnected set of points, lines and polygons that represent possible routes (or "pathways") from one location to another. Although a network is commonly perceived as a human routeway in terms of various forms of transport (airplanes, shipping, vehicles, pedestrians, etc.), it can also represent other built features such as pipelines and cabling routes, plus a range of designated boundaries, e.g. county or zip code boundaries. Besides human features, networks are also represented by natural features such as waterways, vegetation corridors and migration routes. Given this huge array of networks, their modelling is an important task for any GIS. Network data models are usually enacted using the vector data structure because this is more readily associated with the points, lines and polygons that make up networks, although some types of network analysis (least-cost path models in particular), lend themselves better to raster formats. Here, the focus is mainly on vector models.

For GIS functionality, all network data models envisage that networks are comprised of links (arcs or edges) and nodes (points) (Figure 5.18). Links represent the linear element of a network and nodes represent junctions, starting or ending places, stopping places, switching stations, confluences, centres, etc., depending on the type of network being modelled.[157] There are two broad classes of network models[158]:

(i) Looped (or circuit) networks. These are so-called "undirected" models, meaning that movement through the network can proceed in either direction, e.g. most transport routes.

(ii) Geometric (also called radial, tree, directed, oriented or unidirectional) networks. Here, movement can only be in one direction, e.g. one-way streets, electrical cables, storm drainage or rivers.

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157 There are an almost infinite number of potential nodes, and these will largely depend on the purpose and/or scale of the mapping or modelling process.

158 To add some confusion to a complex topic, many references (especially in the field of graph theory) refer to the undirected "looped" models as "directed networks", and to "geometric models" as "oriented networks". These sources also refer to "looped" networks as a special case where a node is only connected to itself without going through any other nodes.

BOX 5.7

Relative advantages of TIN and DEM surface models

Advantages of TINs

- Linear features are more accurately represented.
- Aspect and gradient can be more accurately produced.
- Fewer points are needed to represent topography; therefore, less storage space is required.
- Elevation nodes can be concentrated in areas where topography is more variable or where more detail is required.
- Survey data and known elevations can easily be incorporated into the TIN.
- Some functions cannot be performed using DEMs but are easily accomplished with TINs, for example:
  - creating storage-capacity curves for reservoirs;
  - floodplain delineation.
- TINs can be draped with imagery such as remotely sensed data.
- Field surveying and map digitizing is better suited to producing data for use in TINs.
- TINs can readily be converted to DEMs.
- *Z* values can more accurately be interpolated.
- Cross-sections of a terrain can more accurately be portrayed.
- Choosing an appropriate resolution is incorporated into the methodology.

Advantages of DEMs

- Most analyses are more easily performed.
- Provides a very simple model.
- DEMs are computationally efficient.
- Provides uniform data coverage over an area.
- Can provide very detailed elevational data (with small cell size).
- The raster data format is more readily compatible with other data sets.

Each of these network models rely upon different algorithms for their functionality. As with some other vector-based models, network data are held as topological tables with every link and node having a unique identifier. For network analysis to function correctly, it is vital for the digital network to be an exact topological representation of the real world network, i.e. meaning that each line segment is "aware" of the lines it is attached to at a specified node. This is far more important than the fact of the network being cartographically correct, i.e. with features being located on the map in the correct locations.[159] Figure 5.18 shows a hypothetical undirected model for a transport routeway, and Figure 5.19 shows a real undirected network model – that of the proposed high-speed rail network for the Kingdom of Spain. The nodes in Figure 5.18 are connected by links whose values show "impedance", e.g. in this case impedance might be showing travel times. So, impedance is a value demonstrating a "cost" (or weighting) of getting from or to adjacent nodes, and the cost can be in terms of fares, fuel, or time taken, etc. Factors that influence impedance include the time of day, whether there are road repairs, how many traffic lights, maximum speed limits, to name a few. This type of undirected model can be used for tasks such as calculating the shortest route between two nodes, working out the quickest route, establishing a route that is the shortest one going through specified nodes,[160] and showing all parts of the mapped area that are within x kilometres or y travelling time of a specified node. It is easy to see how network analysis could be used to optimize the railways for new high-speed trains in the Kingdom of Spain when the whole system is needed. Section 7.5 gives examples of different analyses that may be performed using the network data modelling structure.

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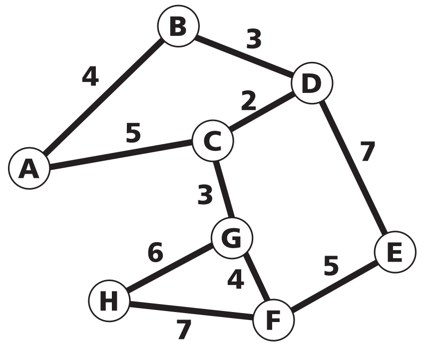
[159] Many of the world's underground railway maps provide examples of where the topological connections and the lines are all correct but their geo-location on the map may not be correct.

[160] This is known as the "travelling salesman" problem.

FIGURE 5.18
Network data structure showing nodes and impedance plus topological table



Node ID	Connected nodes (+ impedance weighting)
A	B(4), C(5)
B	D(3), A(4)
C	D(2), G(3), A(5)
D	E(7), C(2), B(3)
E	D(7), F(5)
F	H(7), G(4), E(5)
G	C(3), F(4), H(6)
H	G(6), F(7)

FIGURE 5.19
The proposed network of high-speed railway lines in Spain (2007)

Source: Sánchez de León (2007).

Economic feasibility is an indispensable criterion for aquaculture development. In a strategic assessment study on the potential for freshwater fish farming in Latin America, Kapetsky and Nath (1997) conducted an analysis for market potential to calculate the least-cost path from any cell location to the closest town in real distances along the roads. Because oil prices have been rising worldwide, at a rate far in excess of general inflation rates, the transport-related costs become ever more important as a location decision factor, and it is likely that most aquaculture facilities will need to include network analyses as a fundamental input to their location decision.

6. Remote sensing and GIS integration

A.M. Dean (Hatfield Consultants Partnership, North Vancouver, Canada) and J. Populus (IFREMER, Plouzané, France)

6.1 INTRODUCTION

As described in Chapter 1, the majority of the problems currently faced by world fisheries lie in the spatial domain, and fisheries and aquaculture management challenges extend over large geographic areas, including inland areas, coastal zones and open oceans. As a result, remote sensing (from fixed coastal locations, aircraft and satellites) has been used to provide a large range of observation data to support fisheries and aquaculture management, which complement and extend data acquired from in situ observations. Satellite remote sensing in particular provides a unique capability for regular, repeated observations of the entire globe or specific regions at different spatial scales. There is unprecedented availability of global and regional oceanographic and terrestrial remote sensing data and derived information products, which can meet many of the needs of fisheries and aquaculture managers. Much of the useful data and information are directly derived from satellite remote sensing[161], but in many cases remote sensing data are integrated with in situ and other spatial data.

This chapter introduces the basics of remote sensing and its main applications to support fisheries and aquaculture management. There often appears to be an overwhelming number of remote sensing data options and sources; therefore, an aim is to provide practical guidance for planning and implementing the use of remote sensing, including data selection and acquisition, image processing and the integration of images with GIS. While remote sensing is often viewed only as a source of input data for GIS, remote sensing data can also be integrated into Web-based or desktop applications that are not GIS in the traditional sense, such as Google Earth or decision-support systems. This chapter also illustrates four case studies, which provide an overview of how remote sensing has been applied to support coastal aquaculture mapping and sensitive habitat mapping, monitoring development of potentially harmful ocean conditions, and the identification of potential fishing grounds.

6.2 THE BACKGROUND TO REMOTE SENSING

Remote sensing is defined as "the science and art of obtaining information about an object, area or phenomenon through the analysis of data acquired by a device that is not in contact with the object, area or phenomenon under investigation" (Lillesand, Kiefer and Chipman, 2007; p. 1). Usually, the devices are sensors mounted on satellites or aircraft, or are installed at fixed coastal locations, that measure the electromagnetic radiation (EMR) that is emitted or reflected by features of the earth's surface, and which then convert the EMR into a signal that can be recorded and displayed as either numerical data or as an image. There are numerous introductory texts on remote sensing and image processing, which provide comprehensive information on concepts and foundations and specific applications (see Section 6.7 below) and an extensive glossary of remote sensing is available at www.ldeo.columbia.edu/res/fac/rsvlab/glossary.html#S. The following subsections provide a basic overview of some important remote sensing concepts, including electromagnetic energy, remote sensing platforms plus their orbits and sensing systems, and a range of general characteristics about remote sensing.

[161] Though remotely sensed data from aircraft-based sensors may be important in certain situations.

6.2.1 Electromagnetic energy

The science of remote sensing is based on the physics of wave theory, which describes how electromagnetic energy takes the forms of waves (Rees, 2001). Sensors measure variations in the EMR emitted by or reflected from an object, area or phenomenon. EMR is classified into several types according to the wavelength or frequency of the wave, e.g. X-rays, visible light, infrared or microwaves. The full range of wavelengths of electromagnetic energy is often referred to as the electromagnetic spectrum and classes of wavelengths are often called spectral bands (see Table 6.1). Sensors will usually detect energy in more than one spectral band in a part of the electromagnetic spectrum and are therefore called multispectral sensors.

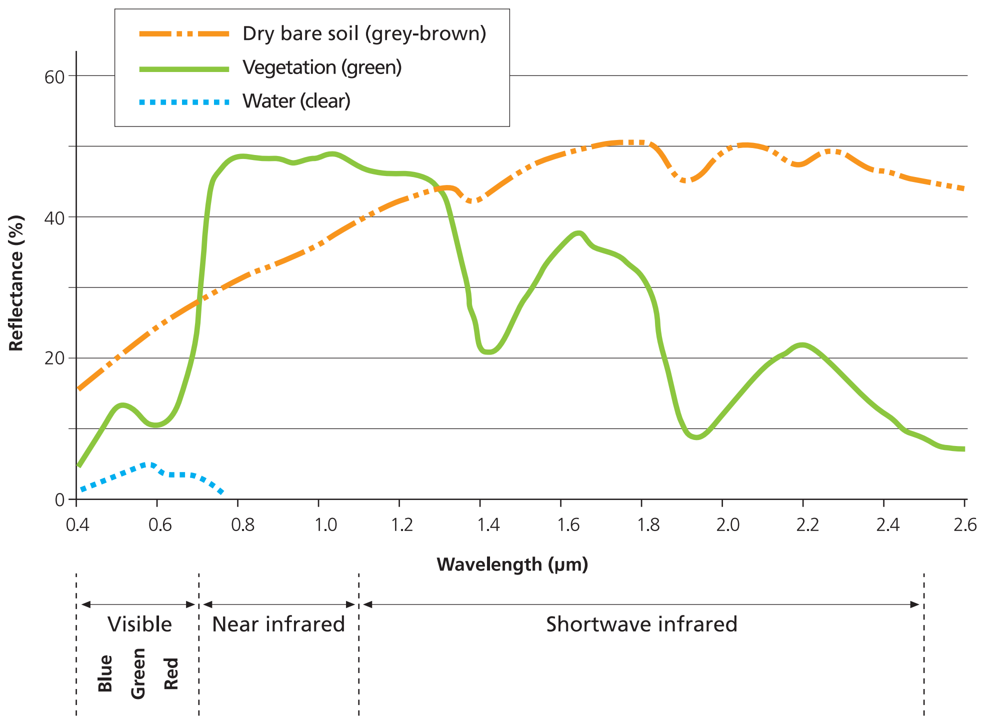
TABLE 6.1
Wavelengths and spectral bands of the electromagnetic spectrum of interest for fisheries and aquaculture applications

Spectral band or wavelength	Characteristics	Examples
Visible 0.4–0.7 µm	High atmospheric scattering effect. Most energy is reflected solar radiation and therefore only detected during the day. Penetrates water to a certain depth.	Natural colour photography and video.
Near infrared 0.7–3.0 µm	High reflectance by vegetation. Most energy is reflected solar radiation and therefore only detected during the day.	Black and white and colour photography, video camera, optical scanner.
Medium infrared 3.0–8.0 µm		Infrared photography, multispectral optical scanner.
Thermal 8.0–1 000 µm	Energy emitted by the earth and ocean surfaces and atmosphere.	Thermal imager or scanner.
Microwave 1 mm–100 cm	Energy emitted at low levels by the earth and ocean surfaces. Penetrates clouds and is possible to detect during the night. Possible to generate the microwave energy as part of an active remote sensing system, or detect emitted microwaves where the original source of energy was the sun.	Imaging radar, radar altimetry, high-frequency radar, Passive microwave radiometer.

In a remote sensing system, EMR that has been reflected or emitted from an object or area of the earth's surface is measured by a sensor. The source of the energy can be the sun (optical remote sensing) or a radar system that provides its own source of energy. Energy measured in the thermal band comes mainly from the sun's incident energy that has been absorbed by the object or area and re-emitted as thermal radiation.

Objects, areas and phenomena often reflect and emit energy in different parts of the electromagnetic spectrum in a predictable repeatable way; this is often called a "spectral signature" for optical remote sensing (visible and infrared wavelengths). The spectral signatures can be analysed to look for relationships and to determine useful information such as the vegetation type or water quality. Figure 6.1 gives the spectral signature of various natural terrestrial features. In imaging radar remote sensing, the term spectral signature is not commonly used because satellite radar systems usually only measure one wavelength or frequency.

FIGURE 6.1
Spectral signature of water, vegetation and soil surface features



Spectral signatures may vary with time (e.g. as plants grow and ocean productivity changes) and as the amount and angle of incident energy from the sun changes (e.g. with season or latitude); therefore, when analysing remotely sensed data it is important to consider the date and time of acquisition and the topography (for terrestrial applications).

6.2.2 Types of remote sensing systems

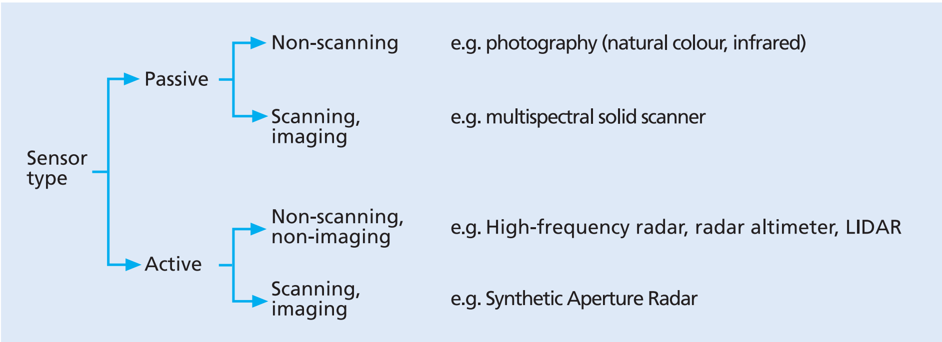
Remote sensing systems can be categorized based on many criteria, and a useful hierarchy is shown in Figure 6.2. First, there is the distinction between“active” and “passive” types of sensor – passive sensors only measure reflected EMR whereas active sensors emit their own sources of EMR and measure the response. Subsequently, there are “scanning” and “non-scanning” sensing systems. Scanning implies motion across the surface over a time interval, and non-scanning implies that the sensor is fixed on an area or target of interest as it is sensed. Finally, “imaging” and “non-imaging systems”are categorized, where the imaging systems build up a two-dimensional image of the surface and non-imaging sensors take measurements in one linear dimension.

The most relevant types of remote sensing systems for fisheries and aquaculture are:

- Multispectral optical – passive scanning systems that collect images (imaging) as the sensor passes or sweeps over the surface to build up an image.
- Camera photography – passive non-scanning system.
- Imaging radar – active scanning systems that illuminate objects or areas with their own source of microwave energy that is directed to the side and downwards to the earth’s surface. It arrives at the surface at an angle and the backscattered energy is measured by the sensor to create an image. A synthetic aperture radar (SAR) is a special type of imaging radar and is a complex system that measures both the amplitude and phase of the return signals to create a high-resolution image (Travaglia *et al.*, 2004).

- Light detection and ranging (LIDAR) – active non-scanning system that is non-imaging. However, through data processing the data may be represented as an image, i.e. because the millions of point measurements can be processed to form a digital elevation model in raster-image format.
- Radar altimetry and high-frequency (HF) radar – active non-scanning and non-imaging systems that are used to measure sea surface height and currents.

FIGURE 6.2
Types of sensor

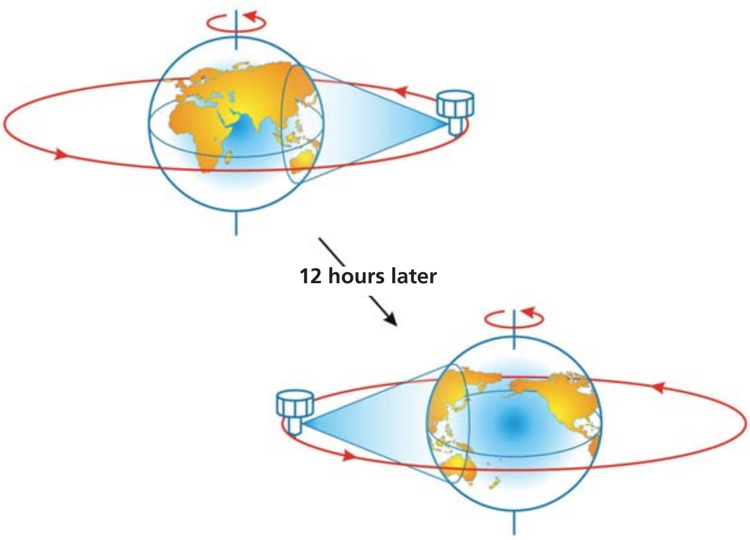


Source: Adapted from Harvey (2008).

6.2.3 Platforms and satellite orbits

A platform refers to the structure on which the sensor or multiple sensors are mounted. A platform is typically an aircraft or satellite, but platforms can also be established in fixed locations as is the case for coastal HF radar used for sea surface current monitoring. Satellites orbit the earth to provide repetitive coverage. The satellite altitude and orbit play an important part in the resolution or scale of the data that can be acquired and the revisit frequency; the main types of orbit are described in Box 6.1 and Figures 6.3 and 6.4. Satellite platforms provide repetitive coverage and an opportunity to build up long-time series of imagery, but they are not as flexible as airborne platforms in terms of scheduling acquisitions. Airborne platforms are usually fixed-wing aircraft flying at 400 to 3 000 m altitude, and modern optical digital cameras or radar systems can acquire imagery from these platforms at scales from 1:5 000 to 1:20 000 depending on the requirements of the user. Airborne systems can carry sophisticated sensors, for example, the hyperspectral Compact Airborne Spectrographic Imager (CASI) that provides a large number of adjustable spectral bands.

FIGURE 6.3
Geostationary satellite orbits



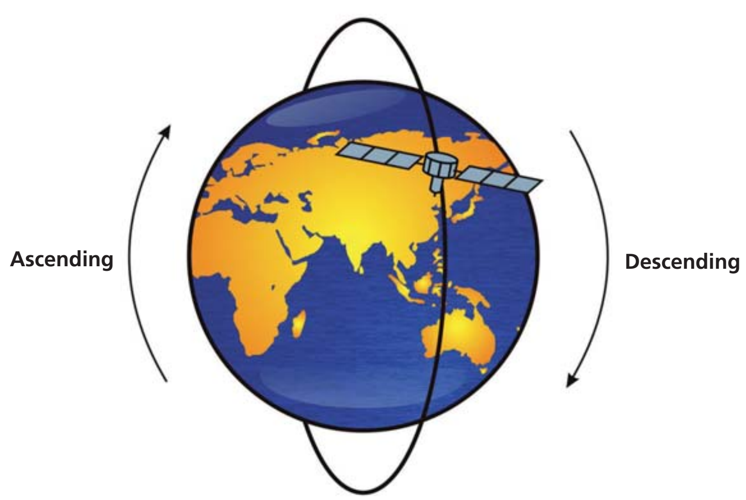
BOX 6.1
Satellite orbits

Satellite revolutions around the earth can be characterized under the two main headings: (i) geostationary and (ii) orbiting.

(i) Geostationary satellites operate from a geosynchronous orbit at approximately 35 900 km above the equator – at this altitude the speed of the satellite can exactly match the speed of the earth's rotation so they remain stationary above a specific point (Figure 6.3). This means that they can achieve a high observation frequency, but their spatial resolution has remained in the kilometre range so far. High latitudes regions are not well observed because of the oblique angle between the earth's surface and the satellite sensor. The main applications are communications and meteorology.

(ii) Orbiting satellites operate at altitudes between about 270 and 1 600 km and are usually polar orbiting and sun-synchronous, meaning that they have orbits that cross the north and south polar areas and that cross the equator at the same sun time each day. As a satellite revolves around the earth, the sensor "sees" a certain portion of the earth's surface. The width of the surface area imaged is referred to as the swath (see Canada Centre for Remote Sensing: www.ccrs.nrcan.gc.ca/resource/tutor/fundam/chapter2/02_e.php). There are a huge number of different orbiting satellites, some of which are designed for global mapping and have a very broad extent or swath (e.g. 500 to 2 000 km) and relatively coarse spatial resolution (300 m to 4 km). Other orbiting satellites carry sensors designed for more detailed mapping, which have smaller extents or swaths (e.g. 10 to 50 km), but can provide high spatial resolution data (e.g. 50 cm to 10 m). The satellite orbits as the earth rotates, which enables the sensors to build up global coverage; eventually, the satellite sensor observes the same point above the earth, which defines its revisit schedule. Change analysis using multitemporal data is one of the most useful aspects of remote sensing. Radar satellites have the ability to operate at night and can, therefore, acquire imagery as they orbit from north to south (descending) and from south to north (ascending) as shown in Figure 6.4.

FIGURE 6.4
Polar satellite orbits

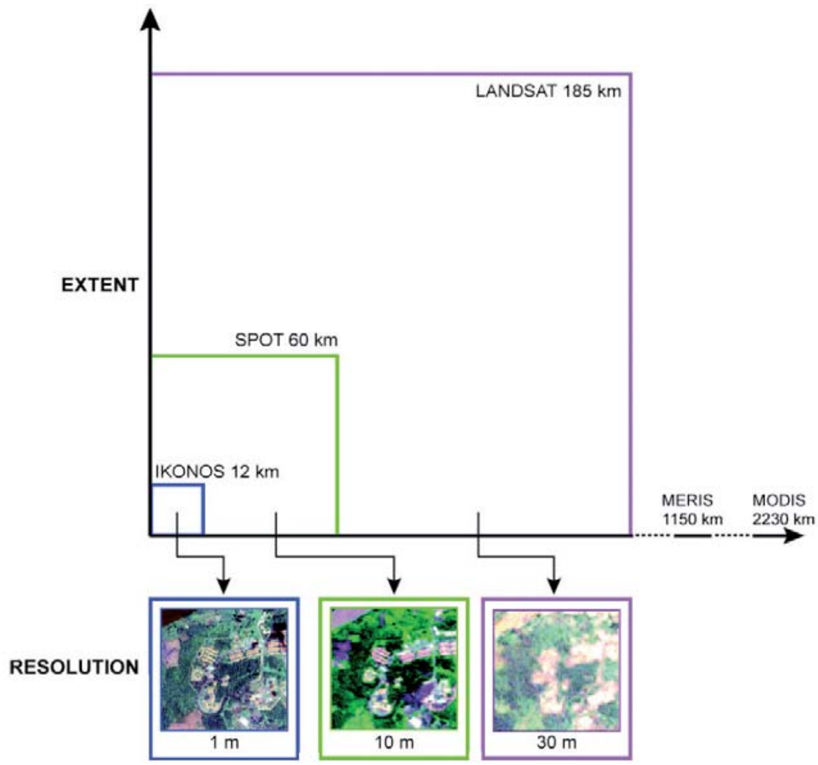


6.2.4 Characteristics of remote sensing systems

Sections 6.2.1 and 6.2.2 provide a very succinct background to the ways in which remote sensing operate as a complex data gathering system, and Figure 6.2 shows that there is a range of different sensors being utilized with numerous parameters being measured at different temporal and spatial resolutions. In order to "navigate" the available systems and their products, the user needs to consider the varied characteristics of the whole system:

- **Information content.** Defines what is being measured by the satellite sensor and/or what parameters are being derived using models and complementary in situ data. The number and precision of the "spectral bands", or wavelengths, over which the sensor operates is an important property – further information on this is provided in Section 6.2.1. The accuracy and precision of the measurements and the amount of processing already completed by the data provider are also important considerations.
- **Spatial extent.** Information derived from remote sensing can be global or cover only regional or local areas. Figure 6.5 shows the aerial extent of the scenes (or images) gathered by three of the main satellite systems. Depending on the remote sensing systems, there will be different properties, such as spatial resolution and revisit frequency for different spatial extents. Data and information acquired for global studies are typically less detailed (relatively coarse) compared with those acquired for specific areas.
- **Spatial resolution.** Remote sensing data are usually processed into an image format and it is sufficient to understand that spatial resolution is the size of the individual picture element (pixel) recorded by the sensor. Depending on the application, "low resolution" might be 30 m and "high resolution" might be 1 m, e.g. aquaculture pond mapping; or low resolution may be 20 km and

FIGURE 6.5
Overview of the spatial extent and resolution of selected types of remote sensing imagery



high resolution might be 4 km, e.g. sea surface temperature (SST).The spatial resolution has an important impact on the mapping scale of the product and whether the geographic patterns of interest can be described in enough detail for an application. Users often desire high-resolution satellite data, but for very large areas a compromise is often needed, i.e. as data may be too expensive to acquire and the volumes impractical to process.

- Revisit frequency. This defines the frequency that observations can be made of the same area, which for satellite remote sensing depends on the satellite orbit, extent and spatial resolution of the imagery. Cloud cover also affects the revisit potential of optical systems. While many sensors claim frequent revisit, their capacity to cover large areas may be limited. Some satellite sensors can "look" to the side of their orbit to provide more frequent coverage, but in most cases vertical observations are better for accurate, detailed mapping. Constellations of three or more of the same or compatible satellites can improve the revisit frequency.
- Time series. The time period for which consistent observations are available. Future continuity of data supply from a particular sensor, or a group of sensors with similar spatial and spectral resolutions, may be important to ensure that frequent, ongoing information will be available to support the user's information needs.
- Timeliness. The speed that a product is made available to a user. Real time and near real-time products are designed to be delivered as quickly as possible, often called "nowcast" by oceanographers. Historical time-series products can be developed over long periods and are delivered after careful compilation and calibration, which may be called "hindcast" by oceanographers and modellers. The capability for a product to be delivered in a very timely manner may also depend on the amount of processing that is required.
- Levels of processing. Many data suppliers refer to "data levels", which describe the amount of processing that the data supplier has conducted before the product is made available to the user. Data levels can be summarized as follows[162]:
  - Level 1A – unprocessed instrument data at full resolution.
  - Level 1B – instrument calibrations have been applied to Level 1A data to provide more consistent values
  - Level 2 – derived variables at the same resolution as the source Level 1 data, e.g. SST data, where the spatial resolution of the data may vary across the image;
  - Level 3 – derived variables in a regular grid formation, e.g. a regular grid of SST data. Level 3 data are sometimes called "binned" because they have a regular grid, or "mapped" if they have been map projected.

6.3 REMOTE SENSING OUTPUT OF USE TO FISHERIES OR AQUACULTURE GIS

Different types of remote sensing data are suitable for specific fisheries and aquaculture applications, and user requirements can vary considerably. For most fisheries and aquaculture applications, the main types of remote sensing data are categorized into optical imagery and radar, so these provide convenient headings to examine the information received from the sensors.

Box 6.2 summarizes the features and strengths of each type of remote sensing system; more information on the electromagnetic spectrum is provided in Section 6.2.1.

[162] Adapted from the National Aeronautics and Space Administration (NASA): http://oceancolor.gsfc.nasa.gov /PRODUCTS/product_level_desc.html.

BOX 6.2
Main types of optical and radar remote sensing systems

Optical: These images are intuitive to interpret, but cloud cover can limit their availability. Specifications and costs of data vary considerably.

- **Visible and infrared** – Sensors can provide land cover and land use information for inland fisheries applications, ocean condition data such as chlorophyll-a and suspended sediment concentration, bathymetry and sea surface temperature (SST), and data to support coastal zone fisheries and aquaculture management.
- **Light detection and ranging (LIDAR)** – An airborne system that can provide precise elevation data, usually for small areas. When combined with detailed visible and infrared optical imagery, this can be used for land cover and topography mapping, for example, in intertidal zones.

Radar: These systems are not affected by cloud cover, but radar data are less intuitive to interpret than optical imagery.

- **Imaging radar** – Images can contain unique information compared with optical images, such as the flooded status of vegetation or surface roughness of a waterbody, but it typically can determine fewer land cover classes than optical data.
- **Radar altimeter** – Can be processed to provide information on sea surface height, surface currents, waves and winds.

High-frequency radar: Installed in fixed locations along the coastline and provides data on surface currents and waves within a specific (localized) geographic area.

6.3.1 Optical remote sensing systems and products

Sea surface temperature

A summary of satellites and sensors relevant for sea surface temperature (SST) observations is provided in Table 6.2. Since the late 1970s, SST measurements have been operationally available from the Advanced Very High Resolution Radiometer (AVHRR) sensors on the National Oceanic and Atmospheric Administration (NOAA) and TIROS meteorological satellites. Other sensors include the National Aeronautics and Space Administration (NASA) Moderate Resolution Imaging Spectroradiometer (MODIS) sensors on board the Earth Observing System (EOS) Aqua and Terra satellites, and NOAA's Geostationary Orbiting Earth Satellites (GOES) that are geostationary over the Western Hemisphere (see Box 6.1). Section 6.5.2 on selecting and acquiring data provides some information on obtaining SST products from these satellites.

TABLE 6.2
Summary of SST-related optical remote sensing systems

Sensor	Satellite(s)	Operational period	Orbit/swath width	More information
AVHRR	NOAA 4 to 19 and TIROS METOP-A	1978 to present 2007 to present	Polar orbit 2 399 km swath Global coverage every day	www.oso.noaa.gov/poesstatus
MODIS	EOS TERRA EOS AQUA	1999 to present 2002 to present	Polar orbit 2 330 km swath Global coverage every one to two days	http://modis.gsfc.nasa.gov
Imager, Sounder	GOES 1 to 12	1975 to present	Geostationary orbit Western Hemisphere	http://goespoes.gsfc.nasa.gov/goes/project
ATSR AATSR	ERS-1 and 2 Envisat	1991 to present 2002 to present	500 km swath Global coverage every three days	http://envisat.esa.int/instruments/aatsr http://envisat.esa.int/handbooks/aatsr

Ocean colour

Ocean colour refers to obtaining information about the ocean using optical sensors, including parameters such as concentration of chlorophyll-*a*, which is a measure of primary productivity, and total suspended matter (TSM), which is related to turbidity. A summary of satellites and sensors related to ocean observations is provided in Table 6.3. No single ocean colour sensor is capable of observing every part of the globe every day, so a combination of sensors is often used. Following the successful launch in 1978 of the Coastal Zone Color Scanner (CZCS), there have been several overlapping ocean colour satellite missions. Currently, SeaWiFS, MODIS, Medium Resolution Imaging Spectrometer (MERIS) and others provide data to support operational oceanography products. There are also national missions, such as Oceansat-1 (India). The International Ocean Colour Coordinating Group (IOCCG) provides a good summary of the current and future availability of ocean colour sensors (IOCCG: www.ioccg.org/sensors_ioccg.html). Future sensors of particular interest are those on board the European Space Agency (ESA) Sentinel-3 (launch 2014) and NOAA's NPP and NPOESS (2011 and 2014). Section 6.5.2 provides some information on obtaining ocean colour products.

TABLE 6.3

Summary of ocean colour related optical remote sensing systems

Sensor	Satellite(s)	Operational period	Orbit/coverage
SeaWiFS	OrbView-2	1997 to present	Polar orbit, 1 500 km swath
MODIS	EOS Terra, EOS Aqua	1999 to present, 2002 to present	Polar orbit, 2 330 km swath, global coverage every one to two days
MERIS	Envisat	2002 to present	Polar orbit, 1 200 km swath
Ocean Colour Monitor (OCM) 1 and 2	Oceansat-1 and 2	1999 to present, 2009 to present	1 400 km swath, global coverage every one to two days

Source: International Ocean Colour Coordinating Group (www.ioccg.org/sensors_ioccg.html).

Inland and coastal zone mapping using optical sensors

There are many optical remote sensing systems suitable for mapping land cover, inland waterbodies and the coastal areas that are of interest for fisheries and aquaculture. Some of the sensors for SST and ocean colour mapping can also provide information for terrestrial mapping, although the spatial resolution of the sensors is usually considered to be too coarse. The main optical systems are shown in Table 6.4 and ESA's future Sentinel-2 satellite is described in Box 6.3.

TABLE 6.4

Summary of optical remote sensing systems relevant for inland and coastal zone mapping

Sensor	Satellite(s)	Operational period	Swath width, spatial resolution	More information
MSS	Landsat 1 to 3	1972 to 1983	185 km, 70 m	http://landsat.gsfc.nasa.gov
TM	Landsat 4 to 6	1982 to 2011	185 km, 30–120 m	
ETM+	Landsat 7	1999 to present	185 km, 15–60 m	
HRG	SPOT 4, SPOT 5	1998 to present, 2002 to present	55 km, 20 m, 55 km, 2.5–20 m	www.spot.com
MSI	RapidEye	2009 to present	77 km, 6.5 m	www.rapideye.de
LISS-III AWiFS	IRS-P6	2003 to present	140 km, 23.5 m, 740 km, 56 m	www.isro.org
CCD	CBERS-2 and 2B	2003 to present	113 km, 20 m	www.cbers.inpe.br
	Quickbird, WorldView-2	2001 to present, 2009 to present	16.5 km, 0.66–2.4 m, 16.4 km, 0.46–1.8 m	www.digitalglobe.com
	Ikonos, GeoEye-1	1999 to present, 2008 to present	11 km, 1– 4 m, 15.2 km, 0.41–1.6 m	www.geoeye.com

BOX 6.3
European Space Agency's Sentinel-2

An important future sensor for land cover applications is the European Space Agency's Sentinel-2, which will provide systematic global acquisitions of high-resolution multispectral imagery with a high revisit frequency and provide enhanced continuity of multispectral imagery provided by the SPOT series of satellites. The Sentinel-2 mission is envisaged to fly as a pair of satellites with the first planned launch in 2014. Each Sentinel-2 satellite carries a Multispectral Imager (MSI) with a swath of 290 km. It provides 13 spectral bands spanning from the visible and near infrared to the shortwave infrared, featuring 4 spectral bands at 10 m, 6 bands at 20 m and 3 bands at 60 m spatial resolution.

The United States of America's Landsat TM/ETM+ sensors have been the most widely used for land cover monitoring and there is now an extensive archive. However, the remaining operational satellite in the Landsat series is in a degraded status and subject to failure in the near future. NASA and the United States Geological Survey (USGS) are developing a follow-on initiative with the Landsat Data Continuity Mission (LDCM), which is expected to be launched in 2013. The French SPOT 4 and 5 are well-known commercial optical data sources with better spatial resolution compared with Landsat. SPOT 6, launched in September 2012, and Spot 7 (to be launched in 2014) will extend the SPOT programme at least until 2022. Additionally, the European Union supported high-resolution satellite Pleiades-1 was launched in late 2011 and Peliades-2 is due to be launched in 2013. Other commercial options referred to in Table 6.4 include RapidEye and the Disaster Monitoring Constellation (DMC). Each DMC satellite is owned by a partner nation and focuses mostly on daily image acquisition for their countries and provides imagery with a resolution similar to Landsat. RapidEye is a constellation of five satellites that can gather daily 5-m resolution multispectral images and is a cost-effective option. Several sub-metre spatial resolution optical satellites also exist, the best known being Quickbird (launched in 2001), WorldView-2 (launched in 2009), plus GeoEye-1 and Ikonos (launched in 2008 and 1999, respectively), with GeoEye-2 scheduled for launch in 2013. GeoEye-2 will be capable of discerning objects on the earth's surface as small as 0.25-m in size, which will provide the world's highest resolution and most accurate colour imagery. Section 6.5.2 provides information on obtaining optical image products.

6.3.2 Radar remote sensing systems and products

Radar imagery

Imaging radar do not penetrate water surfaces and interpretation is based on an understanding that radar "sees" or detects the surface differently to optical sensors, and characteristics such as surface roughness and (for soil or snowpacks) water content are important. An example application of imaging radar by Travaglia, *et al.* (2004) is provided in Section 6.8.1.

Several existing imaging radar satellites are described in Table 6.5. The different wavelengths of the sensors influence the way the radar interacts with objects or areas and thus the potential applications for fisheries and aquaculture. New imaging radar systems additionally provide information on the backscatter in different polarizations,[163] which can help a remote sensing specialist gain a better

[163] Polarization defines the orientation of the wave transmitted or received by a radar system, for example, "horizontal" (H) or "vertical" (V). For a more detailed definition, see Canada Centre for Remote Sensing: www.ccrs.nrcan.gc.ca/glossary/index_e.php?id=2818.

understanding of the properties of an object or area. Another advantage of the new imaging radar systems is the higher spatial resolution that can be achieved and multiple options for resolution and image swath size. However, the data may be considered expensive for many developing countries for fisheries and aquaculture applications. Important future developments include ESA's plan to launch two Sentinel-1 satellites with the first in 2013 and the second a few years later. Sentinel-1 will have a full and open Sentinel data policy (European Space Agency: www.esa.int/esaLP/SEMXK570A2G_LPgmes_0.html) and the Canadian Space Agency (CSA) is also planning a lower cost and more accessible RADARSAT Constellation (Canadian Space Agency: www.asc-csa.gc.ca/eng/satellites/radarsat). There are also plans for TerraSAR-X and ALOS-2 continuity. Section 6.5.2 provides some information on obtaining imaging radar products.

TABLE 6.5
Summary of radar remote sensing systems

Satellite sensor	Operational period	Swath width, spatial resolution	Band	Polarization	More information
ERS-1, ERS-2	1991 to 2000, 1995 to 2011	100 km, 30 m	C	VV	http://earth.esa.int/ers
Envisat ASAR	2003 to present	100–400 km, 30–150 m	C	Multi-polarization	
RADARSAT-1	1995–present	50–500 km, 9 m–100 m	C	HH	www.asc-csa.gc.ca
RADARSAT-2	2006 to present	8–500 km, 3–100 m	C	Multi-polarization	http://gs.mdacorporation.com/
TerraSAR-X	2007	10–100 km, 1.8–15 m	X	Multi-polarization	www.terrasar.de
ALOS PALSAR*	2006 to 2011	40–350 km, 10–100 m	L	Multi-polarization	www.eorc.jaxa.jp/ALOS/en

*Although this satellite ceased operations in mid-2011, its archived data is still valuable.

Ocean salinity

Passive radar detects the low levels of emitted microwave radiation from the earth's surface. The data have very coarse spatial resolution, meaning that they are not generally used for fisheries and aquaculture applications.

Launched in 2011, the joint Argentina and the United States of America Aquarius satellite provides monthly maps of global changes in ocean surface salinity with a resolution of 150 km, showing how salinity changes from month to month, season to season, and year to year at a global scale.
(www.nasa.gov/mission_pages/aquarius/news/aquarius20110922.html).

In 2010, the ESA Soil Moisture and Ocean Salinity (SMOS) satellite was launched and became operational. This satellite carries the MIRAS instrument (European Space Agency: www.esa.int/esaLP/ESAL3B2VMOC_LPsmos_0.html) to measure microwave radiation emitted within the L-band (1.4 GHz) using an interferometric radiometer. Of interest for global fisheries and aquaculture applications are the ocean salinity measurements that are provided by SMOS from late 2010; the goal is to observe open ocean salinity down to 0.1 practical salinity units (PSU) averaged over 10–30 days and with a coarse pixel size of approximately 200 × 200 km (for more information, see European Space Agency: www.esa.int/esaLP/ESAS7C2VMOC_LPsmos_0.html).

Sea surface conditions using radar altimetry

There has been an almost continuous series of radar altimetry missions starting with GEOSAT (1985) and measurements are currently continuing from JASON-1 (2001), Ocean Surface Topography Mission (OSTM) on JASON-2 (2008), and from Envisat RA-2 (2002). Altimeter systems are capable of measuring sea surface height (SSH), from which ocean circulation patterns and sea level are determined on a global scale. The ocean surface topography seen on Google Earth is derived using radar altimetry. Altimeter data are also used to compute significant wave heights (SWH) and wind velocity both of which are important for marine aquaculture. Section 6.5.2 provides some information on obtaining altimetry products.

Sea surface conditions from high frequency radar

High-frequency (HF) radar sea surface data requires investment in radar stations along the coastline of interest. HF radar now cover increasingly large areas of the United States of America, e.g. through the NOAA HF Radar National Server and Architecture Project (NOAA: http://hfradar.ndbc.noaa.gov), which provides a demonstration of the HF Radar display capability using Google Maps. HF Radar operates at long wavelengths (6–30 m) and requires two or more radars to be looking at the same area of water using two or more different viewing angles (CODAR: www.codar.com/intro_hf_radar.shtml). The complex radar processing allows precise information on the surface currents and wave heights, which can be provided in high spatial resolution (e.g. 1 km) and in real time (e.g. hourly).

6.4 REMOTE SENSING APPLICATIONS IN FISHERIES AND AQUACULTURE

The remote sensing systems described in Sections 6.2 and 6.3 have not been designed specifically to support fisheries and aquaculture management, and users take advantage of system capabilities mainly developed for broad applications in land surface mapping, weather forecasting and oceanography. The main applications of remote sensing for fisheries and aquaculture are in support of aquaculture development, aquaculture practice and management (including impact assessment), and for various aspects of marine fisheries monitoring and management. A small number of studies have looked at remote sensing applications to inland fisheries.

6.4.1 Aquaculture development

It is of interest to know where most of the work relating remote sensing to aquaculture is being undertaken. A recent analysis of the FAO Aquatic Sciences and Fisheries Abstracts (ASFA) database using the search criteria of "aquaculture + remote sensing" found 516 publications for the period 1996–2010. Table 6.6 shows the top 30 records by country (or marine area) in which the study took place, with these accounting for 333 of the publications. Another 167 of the records are not assigned to specific countries or regional seas because they focused on methodologies, etc. Although the United States of America dominates the publications, it is interesting that many of the rapidly developing countries are playing a major role in aquaculture applications of remote sensing, e.g. the People's Republic of China, the Republic of India, the Socialist Republic of Viet Nam, the Democratic Socialist Republic of Sri Lanka, the United Mexican States, the Kingdom of Thailand and the Republic of Indonesia. In contrast, it is perhaps unexpected that so little work should be European based, i.e. with only four mentions in the top 30 and, indeed, with only one European country being mentioned. One-third of the areas listed are Asian countries and another third are named marine areas where the origin of the work is not defined.

TABLE 6.6
Number of publications recorded in the FAO ASFA database for 1996–2010 that link “aquaculture” to “remote sensing”

No.	Country/region	No. of applications
1	United States of America	89
2	China	43
3	India	29
4	Gulf of Mexico + Caribbean Sea	23
5	Canada	16
6	Viet Nam	12
7	North Atlantic	9
8	Sri Lanka	8
9	Australia	8
10	Japan	8
11	France	8
12	Mexico	7
13	Thailand	7
14	Indonesia	6
15	North Pacific	6
16	Indian Ocean	5
17	Antarctic	5
18	Arctic	5
19	South Atlantic	4
20	Brazil	4
21	Africa	4
22	North Sea	3
23	Baltic Sea	3
24	Mediterranean Sea	3
25	The Philippines	3
26	New Zealand	3
27	Colombia	3
28	South Africa	3
29	Bangladesh	3
30	Peru	3

Source: FAO (2012b).

The main issues addressed by remote sensing in aquaculture development are: (i) strategic planning for development; and (ii) suitability of site and zoning; each issue presents different data requirements. As summarized in Table 6.7, strategic planning for development deals with data at a relatively low resolution using a few key data sets to generate indicative results of aquaculture potential. Suitability of site and zoning require progressively more detailed data at higher resolutions, and analyses should provide relatively higher accuracy of results.

TABLE 6.7
Summary of the extent and resolution of GIS and remote sensing data and information needs for different tasks for aquaculture development

Varying scales of aquaculture development tasks		
Characteristics relative to remote sensing requirements	Strategic planning for development	Suitability of site and zoning
Extent of analysis	Comprehensive at a large area of interest	Sub-areas within the large area of interest
Spatial resolution	Low	Moderate
Accuracy and precision	Indicative; general	Moderate
Sponsoring entities for the remote sensing tasks	Researchers, central government	Central and local governments
Scope of varied aquaculture input parameters required	Few; very basic, but broad in scope	Many; diverse and broad in scope

Offshore mariculture may offer significant potential for increasing world food production in an environmentally sustainable way. Kapetsky and Aguilar-Manjarrez (2010) illustrate that data from satellite remote sensing are indispensable to conducting estimates of the area suitable for offshore mariculture. Data wholly or partly from satellite remote sensing (i.e. sea surface temperature, chlorophyll-*a*, depth, and current speed) can be used to conduct the estimates of offshore mariculture potential. Furthermore, the build up of long time series of data and advances in data processing mean that series of daily, weekly, monthly, annual and seasonal "climatology" data are now readily available at increasingly higher resolutions that in turn will, in the near future, improve estimates of mariculture potential at all levels. In addition, emerging remote sensing products such as more reliable identification and tracking of harmful algal blooms will provide improved spatial and temporal risk assessment for operational management of mariculture.

Planning for aquaculture development requires understanding of the environment and assessing the suitability of a given region or site for a project to be sustainable. Several water quality and physical properties of the waterbodies of interest to aquaculture can be assessed by remote sensing, with some limitations related to the complexity of coastal environments. Remote sensing can meet part of the information needs; other important suitability data such as dissolved oxygen[164] cannot be determined from remote sensing and data such as salinity, ocean colour and currents may not be provided at sufficient temporal and spatial resolution from satellite remote sensing in coastal environments. To mitigate the issue of spatial resolution, airborne surveys have been conducted. In Indonesia, a CASI airborne survey was carried out by Populus *et al.* (1995) to map water type and, together with land use mapping, to make a preliminary assessment of the suitability of an area for shrimp aquaculture development. Rajitha, Mukherjee and Chandran (2007) refer to the capabilities of satellite remote sensing technology and GIS for the sustainable management of shrimp culture, especially to support prediction of water quality parameters. In Canada, the Ministry of Agriculture and Lands (Carswell, Cheesman and Anderson, 2006) surveyed an area of Vancouver Island's tidal zone with low altitude aerial photography for environmental assessment of shellfish aquaculture.

[164] In extreme cases levels of dissolved oxygen in marine waters may be inferred from remote sensing, e.g. if levels of chlorophyll-*a* are very high then this could be indicative of an algal bloom that can result in low dissolved oxygen levels.

In tropical areas, shrimp farming suitability and planning need to address sustainability issues concerning mangroves and coral reefs, which are important habitats for coastal fisheries. Mapping their extent using remote sensing is described in Green *et al.* (2000) and Mellina *et al.* (2009). Remote sensing derived data on coral reefs are available from the Millennium Coral Reef Mapping Project (USF Millennium Global Coral Reef Mapping Project: http://oceancolor.gsfc.nasa.gov/cgi/landsat.pl).

Satellite remote sensing also shows good potential for mapping the seafloor in shallow areas, but penetration of visible and infrared wavelengths through the water column is often limited and most high resolution sensors do not contain a blue visible band that provides for the best penetration.[165] High spatial resolution satellite imagery has demonstrated good potential for mapping coral reefs. SPOT 5 optical satellite imagery has been used in the Mediterranean by Pasqualini *et al.* (2005) to provide a method for mapping Posidonia oceanica, which is the dominant seagrass (more information is provided in Section 6.8.3).

6.4.2 Aquaculture practice and management

The main applications of remote sensing for aquaculture practice and management are: (i) inventory and monitoring of aquaculture and the environment; and (ii) environmental impacts of aquaculture.

Monitoring of aquaculture requires similar information on water quality and physical properties of waterbodies as those required for aquaculture planning described in Section 6.4.1 above. However, it is the temporal aspect of monitoring that is very important and applications must meet users' requirements related to the frequency of observation and the speed with which data and information are delivered to the users. Monitoring applications include regulators wanting to monitor development in the coastal zone, which can make use of both high and low resolution optical and imaging radar data. With reference to Table 6.7, monitoring of aquaculture operations has similar data needs as the siting of aquaculture structures. The extent of analysis would be focused on a single site or group of sites preferably with high spatial resolution; acceptable precision of parameters of interest (e.g. chlorophyll-*a*) can be more moderate because the data are required frequently and in real time.

The government as well as the private sector may be interested in monitoring. Remote sensing provides government agencies with capabilities to regularly monitor the extent of aquaculture development, and to check if it is proceeding according to marine spatial plans and/or regulations, or if it is adversely affecting the environment. De Graaf *et al.* (2004) used two types of satellite image – (IRS 1D) black and white images and multispectral (SPOT) colour images – to detect and map fish ponds in the People's Republic of Bangladesh. Imaging radar has supported land cover and aquaculture mapping and change detection, for example, Travaglia *et al.* (2004) demonstrated the potential of satellite imaging radar for mapping coastal fisheries and aquaculture structures in the Lingayen Gulf, the Philippines (see Section 6.8.1). Boivin *et al.* (2004) also described the potential for high resolution radar to monitor shrimp ponds and to detect if they are active, i.e. based on the aeration devices increasing water surface roughness. The United Nations Environment Programme (UNEP) Atlas of Our Changing Environment (UNEP: http://na.unep.net/atlas/webatlas.php?id=50) provides an example of using optical satellite imagery for monitoring the increase in large shrimp pond developments between 1987 and 1999 in the Gulf of Fonseca bordered by the Republic of El Salvador, the Republic of Honduras and the Republic of Nicaragua. Béland *et al.* (2006) demonstrated the use of a change detection methodology between 1986 and 1992, and 1992 and 2001 to assess mangrove forest alterations caused by aquaculture development in the district of Giao Thuy, the

[165] In 2010, Digital Globe launched WorldView-2, which has eight spectral bands including the blue band.

Socialist Republic of Viet Nam, which helped to assess the effectiveness of government measures taken to mitigate deforestation.

The near real-time delivery of remote sensing data and its integration with in situ data and models for monitoring the environment can provide timely information and even forecasts that are useful for aquaculture management. Recent progress in ocean colour imagery processing and the availability of catalogues of images processed for primary production and suspended matter open up new monitoring perspectives. Brown *et al.* (2005) describe the use of satellite imagery to identify the environmental conditions favourable for the occurrence of Emiliania huxleyi blooms in Chesapeake Bay, United States of America, which threaten local aquaculture. The blooms can also be distinguished from most other conditions in visible satellite imagery (e.g. SeaWiFS) by their milky white to turquoise appearance. In the Republic of Chile, a number of initiatives have been undertaken with the government and private aquaculture companies to develop near real-time ocean colour and SST remote sensing and hydrodynamic models as part of harmful algal bloom monitoring; e.g. Mariscope Chilean (Rodríguez-Benito, Alvial and Haag, 2003) and the ESA Chile Aquaculture Project (European Space Agency: www.esa.int/esaCP/SEMUS5AATME_index_0.html), which was implemented by Hatfield Consultants and ACRI-ST (see Section 6.5.2). Some of the challenges posed for remote sensing by complex coastal waters and environments are now less problematic further offshore; therefore, applications of remote sensing should allow for an increase in development and management of mariculture further off the coast and offshore.

The use of remote sensing coupled with GIS could be of immense value to developing or enhancing environmental impact assessment (EIA) related studies for assessing the potential impacts of aquaculture on coastal environments. In the Kingdom of Thailand, Patil, Annachhatre and Tripathi (2002) showed how a so-called geospatial EIA of potential shrimp farming sites offered advantages over a conventional EIA, where the geospatial EIA procedure involved sampling and analysis and the fitting of mathematical models for spectral reflectance data obtained from Landsat satellite imagery. More complex modelling applications are also possible, where a combination of different remote sensing data, in situ and biological data, are used to understand carrying or production capacity. For example, scientists from the French Research Institute for the Exploitation of the Sea (IFREMER) have conducted studies of the mussel and oyster production potential in the Bay of Mont St. Michel, the French Republic, in order to predict the production carrying capacity for existing sites as well as potential new sites (Thomas *et al.*, 2006). Kapetsky and Aguilar-Manjarrez (2007) summarize studies that have investigated carrying capacity for a range of aquaculture species.

6.4.3 Fisheries monitoring and management

As was shown for aquaculture in Section 6.4.1, it is useful to see where applications of remote sensing are being applied to fisheries monitoring or management. Table 6.8 shows the top 17 countries, as derived from the FAO ASFA database for the period 1996–2010 and using the search commands "marine fisheries + remote sensing".[166] This search revealed 266 entries in total, of which 107 applied to no specific country or marine area. The United States of America is easily the foremost country for this work, but here the rest of the countries or areas show a fairly equal mix between developed and developing nations.

[166] Applications of remote sensing to inland fisheries by country or marine area have not been shown because total records for the 1996–2010 period was only 14, with eight of these not applying to any area or named inland water area.

Remote sensing has been relatively little used for inland fisheries, i.e. compared with its use in aquaculture and marine fisheries. However, some notable work has been accomplished. Malthus and George (1997) used Daedalus Airborne Thematic Mapper remotely sensed imagery to monitor the distribution of submerged aquatic macrophyte species in the Cefni Reservoir on the Isle of Anglesey, the United Kingdom of Great Britain and Northern Ireland. Remote sensing has been used to assess river channel geomorphic units (Wright, Marcus and Aspinall, 2000) and stream temperature (Torgersen *et al.*, 2001) to evaluate the suitability of fish habitat in streams and rivers. Although remote sensing technologies are becoming more commonplace in inland fisheries management, they are still relatively expensive to operate and require time intensive ground truthing to conduct the image classification and verify the classification results.

TABLE 6.8
Number of publications recorded in the FAO ASFA database for 1996–2010 that link "marine fisheries" to "remote sensing"

No.	Country/region	No. of applications
1	United States of America	59
2	North Pacific	12
3	India	11
4	Caribbean Sea + Gulf of Mexico	8
5	South Atlantic	7
6	China	7
7	Canada	7
8	Indian Ocean	6
9	North Atlantic	5
10	Australia	5
11	Africa	4
12	Mexico	4
13	New Zealand	2
14	Brazil	2
15	Norway	2
16	Portugal	2
17	Central America	2

Source: FAO (2012b).

Since the 1980s, satellite remote sensing has been used to support marine fisheries through locating potential fishing zones (PFZ) using temperature and productivity data to identify areas where fish tend to aggregate for feeding. In open ocean areas, chlorophyll-*a* and SST data show correlations in their values and gradients; cool waters detected using SST data typically indicate the upwelling of deep waters containing higher concentrations of nutrients. These nutrients support increased productivity in the euphotic zone that can be detected through increased chlorophyll-*a* in ocean colour images. A good review of fisheries information services and remote sensing is found in the IOCCG publication (Forget, Stuart and Platt, 2009). A commercial

PFZ system is provided by Catsat (www.catsat.com), which integrates radar altimetry and surface currents, SST, cloudless temperature (from passive radar), ocean colour, modelled subsurface temperature, marine meteorology, and global currents to provide information to fishing vessels. The Traceable and Operational Resource and Environment Data Acquisition System (TOREDAS) fisheries information system, providing estimates of optimal fishing areas (Forget, Stuart and Platt, 2009; Kiyofuji *et al.*, 2007) for Japanese waters, is described in the case study in Section 6.9.4. Vessel monitoring systems using satellite remote sensing are mature applications for national security, but many regions have also applied the systems to locate and monitor vessels for fisheries management. Radar is the mainstay of the systems, which usually include fully automated image processing and communication protocols with the authorities (Kourti *et al.*, 2005). Vessel detection rates depend on image type and vessel size, and vessel positions can be compared with reported positions. The systems, which can also be linked to fishery logbooks for the georeferencing of catches, provide surveillance for follow-up actions by authorities.

Platt and Sathyendranath (2008) review the potential ecosystem indicators that can be applied for detection of ecosystem change in response to environmental perturbations such as climate change or overfishing. They suggest that several indicators can be supported by remote sensing (ocean colour and SST), including the seasonal cycle and spatial variances of phytoplankton biomass and delineation of ecological provinces and phytoplankton size structure.

6.5 THE IMPLEMENTATION OF REMOTE SENSING

The implementation of remote sensing activities for fisheries and aquaculture is most likely part of a wider multidisciplinary programme, for example, involving fisheries scientists, GIS specialists and planning specialists. Implementation of remote sensing work and its integration with other components of a programme must be based on a well-defined need for data or information. Before selecting and acquiring remote sensing data and image processing, it is important to define clearly what information or outcome is expected to ensure that the final products deliver the information required.

6.5.1 Scoping study

A scoping study helps define the viability of the proposed activity and addresses important questions, such as those in Box 6.4. The scoping study requires an understanding of the basic characteristics of remote sensing as described in Section 6.2. The scoping study should determine if time and resources are available, if the activities are compatible with other proposed activities or existing operations, dependencies, establish cost-effectiveness, and address any administrative and legal requirements. From a technical perspective, the scoping study may result in some compromises because of the availability of imagery, software tools and resources. Data available from Internet portals and applications such as Google Earth may be helpful to support a scoping study.[167]

6.5.2 Selecting and acquiring remotely sensed data

After completing a scoping study, remote sensing data can be selected and acquired with confidence that such data should contribute to the overall project or programme objectives. Google Earth, Google Maps and/or Microsoft Bing Maps contain data that

[167] One of the potential limitations of Google Earth is that high-resolution optical imagery is not available over the ocean away from the coast, although this distance from the coasts is not consistent worldwide. This is likely due to a lack of available data, as Google largely relies on imagery provided by commercial aerial photography or satellite imagery that were originally commissioned or purchased by governments or by other commercial clients. Now that Google is investing more in imagery, including investing in the GeoEye-2 satellite, the situation may improve and Google Earth certainly is an excellent source for many coastal and terrestrial areas.

BOX 6.4
Important questions to address in a scoping study

- What are the overall goals and objectives of the programme? For example, identify areas of national economic exclusive zones (EEZs) suitable for marine aquaculture. If the needs are not documented, a needs assessment is required.
- What is the area of interest? For example, a national EEZ, a small inlet or a freshwater lake. The size of area of interest and the complexity of the coastline or landscape will influence the type of remote sensing data that are appropriate.
- What spatial scale and/or spatial resolution are desired? For example, mapping scale of 1:10 000 or spatial resolution of 1 metre.
- What is the frequency of data required, how quickly does it need to be delivered, and for what time period? For example, daily chlorophyll-a data delivered in near real-time for algal bloom monitoring for a high-risk six-month period.
- Can existing data address the information needs?
- Can information provided by remote sensing meet project needs? For example, ocean productivity (chlorophyll-a).
- 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? For example, a radar remote sensing specialist and image processing software.

can be browsed, but a scientific study will probably need to access original data. There are many global and regional sources of satellite remote sensing data. It is important to investigate the freely available data first. National government departments or agencies may have unique archives for several sensors, including Landsat TM, and this material may be freely obtained. The following subsections provide information on sources of remote sensing data and information products. Of particular interest for marine aquaculture and marine fisheries are long-term ocean "climatologies" (multiyear mean, variance and anomalies) and near real-time data, which if integrated with models could be used to provide forecasts.

Data are also available according to different "data levels" (see Section 6.2.1), which describe the amount of processing that the data supplier has conducted before the product is made available to the user. The simplest approach for non-specialists is to start with the higher-level data because they are most likely to be products that can be directly integrated within a GIS and used for analysis. It is also important to review the metadata (information about the data) to ensure that the parameters provided by the product, format and level are understood. Metadata is often summarized in a data specification document or a text file.

Sea surface temperature

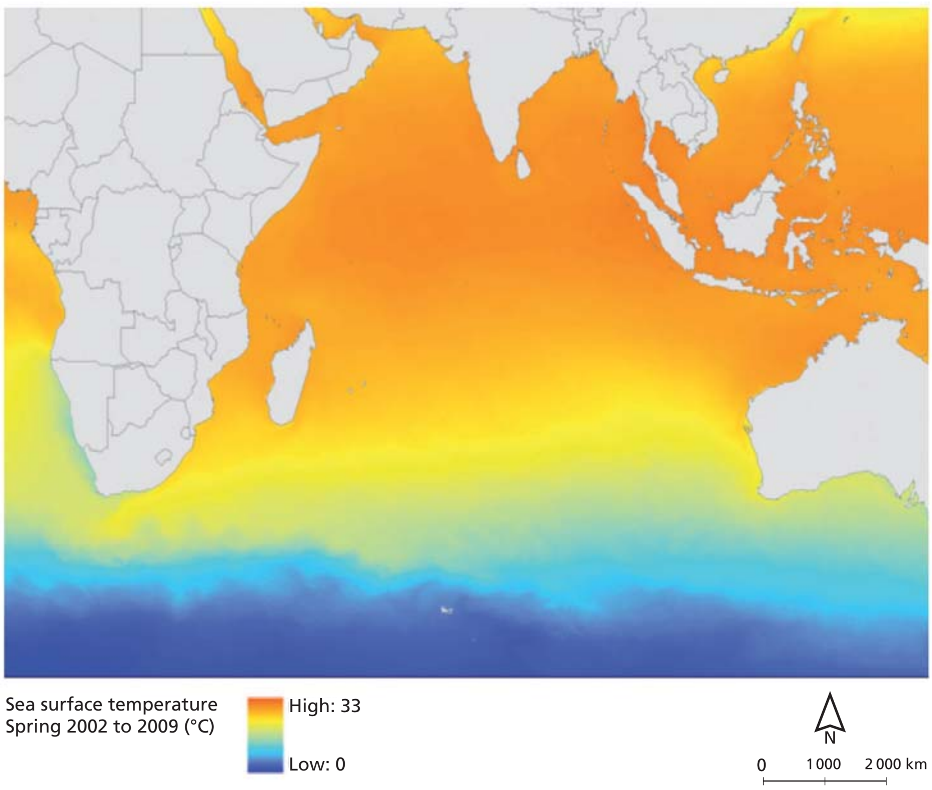
Table 6.9 provides an overview of popular sources of SST data. The Group for High Resolution Sea Surface Temperature (GHRSST: www.ghrsst.org) provides operational access to nearly all satellite SST data sets in a common format and within several hours of acquisition by the satellite instrument. GHRSST products (typically 10–50 km spatial resolution) are generated by combining complementary satellite and in situ observations within "optimal interpolation" systems. Several high spatial resolution (< 5 km resolution) regional SST analysis products are available; e.g. from ESA for the Mediterranean (based on the Medspiration project).

TABLE 6.9
Sources of SST data and information products

Source	Details	Access
NOAA	4 km AVHRR Pathfinder Project: 4 km global product provides long-term SST "climatologies", including mean, variance and anomalies.	www.nodc.noaa.gov/SatelliteData/pathfinder4km (Free)
GHRSST	Level 4 gridded SST products (typically 10–50 km spatial resolution)	www.ghrsst.org (Free)
Rutgers University	AVHRR: Real-time and archive SST daily composite for the eastern United States of America, including the Gulf of Mexico.	http://marine.rutgers.edu/mrs/sat_data (Free)
MyOcean	Provides access to a range of regional and global SST data, including GHRSST.	www.myocean.eu.org (Free)

Complementary to GHRSST, SST data products are also provided by national agencies that operate SST-related missions. The 4 km AVHRR Pathfinder Project, as the name suggests, has produced a 4 km global coverage product using the AVHRR sensor series for the entire 1985–2001 time series; a sample is shown in Figure 6.6. A good source of oceanographic information, especially for Europe, is the MyOcean Service. More information on accessing data through Google Earth and integration into ArcGIS is provided in Section 6.7.

FIGURE 6.6
Demonstration of the global 4 km AVHRR pathfinder project sea surface temperature product for the Indian Ocean



Source: ESRI (2010); NASA (2012).

Ocean colour

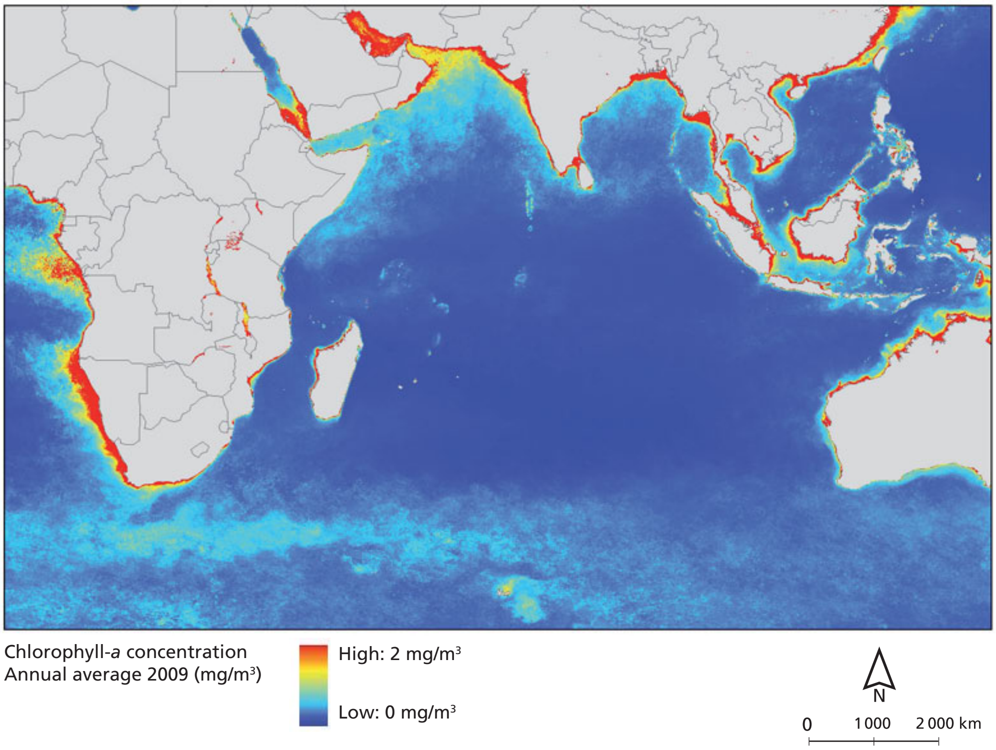
Table 6.10 provides an overview of popular sources of ocean colour data. The ESA DUE GlobColour project has merged observations made with different satellite systems to enable global daily coverage. GlobColour provides time series from 1997 to the present of consistently calibrated and validated global ocean colour information with a 4.6 km spatial resolution coverage (see Figure 6.7). The ESA DUE GlobColour project is continued in the context of MyOcean (EU FP7). A pilot Web-based harmful algal bloom warning system for the Chilean aquaculture sector is described as a case study in Section 6.9.2, which used MERIS and MODIS remote sensing data. In addition, the NASA Ocean Color[168] Web provides access to CZCS, SeaWiFS, MODIS level 1 to 3 data, including daily, weekly, monthly and seasonal climatologies. Other regional ocean colour services exist, including NOAA Coastwatch and the Canadian Department of Fisheries and Oceans.

TABLE 6.10
Sources of ocean colour data and information products

Source	Details	Access
GlobColour/ HERMES	Merging of MERIS, SeaWiFS and MODIS level-2 data: daily, weekly and monthly Level 3 products (15-day delay or daily near real-time). Extraction of ocean colour data for user-defined areas is possible and a free GlobColour subscription service allows users to systematically obtain near real-time products at 1 km spatial resolution for a specific area.	http://hermes.acri.fr/ (free, with commercial services offered)
NASA Ocean Color Web	CZCS, SeaWIFS, MODIS level 1 to 3 data: Daily, weekly, monthly and seasonal climatologies.	http://oceancolor.gsfc.nasa.gov (free)
ESA	MERIS level 1, 2, 3.	http://envisat.esa.int/level3/meris (free)
NOAA Coastwatch	Provides access to multiple satellite ocean remote sensing data and products for selected marine zones of the United States of America.	http://coastwatch.noaa.gov (free)
MyOcean	As part of MyOcean, the ACRI-ST Global Ocean Colour Processing Unit provides access to a range of regional and global ocean colour data, including GlobColour.	www.myocean.eu.org or http://hermes.acri.fr (free)

[168] Ocean colour refers to information about the optical properties of the ocean, including parameters such as concentration of chlorophyll-*a* and suspended sediment.

FIGURE 6.7
Example of GlobColour ocean colour data product for chlorophyll-*a* concentration



Source: ESRI (2010); ACRI-ST (2012).

Optical and radar data for inland and coastal zone mapping

Table 6.11 provides an overview of popular sources of optical and radar imagery products. National government departments or agencies, and other regional departments, may also have data archives that are worth investigating. For optical data, there are a huge range of government and commercial suppliers; and only a sample of the well-known suppliers is provided here. For commercial products, there will be a reseller or distributer in most countries, or at least a regional office (e.g. Spot Asia in Singapore). It is better to start exploring the lower resolution data such as Landsat TM/ETM+ and ASTER first before purchasing more expensive higher resolution imagery. A good option to begin exploring imaging radar data is ALOS PALSAR, because there is a systematic observation strategy to acquire imagery on a regular basis (JAXA EORC www.eorc.jaxa.jp/ALOS/en/obs/overview.htm) and the data are not expensive. Under the ALOS Kyoto and Carbon Initiative, there is a free 50 m and 500 m resolution PALSAR mosaic available, including a Google Earth KML file. For a research and development project, it is also possible to apply to propose a “Category 1” (CAT-1) project to ESA that can provide radar data (Envisat ASAR and ERS) at the cost of reproduction with some products free via a Web server (see EOPI: http://eopi.esa.int/esa/esa?cmd=aodetail&aoname=cat1).

TABLE 6.11
Sources of optical and imaging radar data products

Source	Details	Access
Optical		
SpotImage	SPOT, Ikonos, GeoEye: SpotImage, a regional network supply with a range of commercial imagery, including SPOT, Ikonos, GeoEye-1. Reseller list for new acquisitions	www.spotimage.com (commercial)
Landsat.org	Landsat: Entire current global collection of Landsat ETM+. Searchable online catalogue and downloadable data.	www.Landsat.org (mostly free)
Tropical Rain Forest Information Center	Landsat: Searchable online catalogue and downloadable data.	www.trfic.msu.edu/ (mostly free)
Global Land Cover Facility	Landsat, ASTER, others: Searchable online catalogue and downloadable data.	http://glcf.umiacs.umd.edu (mostly free)
GloViS	Landsat, ASTER: USGS Global Visualization Viewer (GloVis) online catalogue and ordering.	http://glovis.usgs.gov/ (Mostly free)
TerraLook	ASTER: Provides access to satellite images for users that lack prior experience with remote sensing or GIS.	http://asterweb.jpl.nasa.gov/TerraLook.asp (free)
GeoEye GeoFuse	GeoEye-1, Ikonos: A browseable archive integrated with Google Maps and Google Earth. Reseller list for new acquisitions.	http://geofuse.geoeye.com/ (commercial)
Digital Globe	Quickbird and WorldView: ImageFinder browseable archive. Reseller list for new acquisitions.	www.digitalglobe.com (commercial)
RapidEye	RapidEye: Geodata Kiosk online data store, submit new acquisitions.	http://kiosk.rapideye.de/datadoorsweb/Order.aspx (commercial)
Radar		
JAXA	ALOS PALSAR: 50 m and 500 m Mosaic, including data, image and Google Earth KML files.	www.eorc.jaxa.jp/ALOS/en/kc_mosaic/kc_mosaic.htm (free mosaic)
CROSS	ALOS PALSAR: Searchable online catalogue.	https://cross.restec.or.jp/ (commercial, cost effective)
eoPortal	ASAR and ERS and others: Searchable online catalogue, particularly useful for searching ESA archives.	http://catalogues.eoportal.org (free and cost-effective)
Infoterra	TerraSAR-X: Downloadable archive file for GIS software, plan new acquisitions.	www.infoterra.de (commercial)
MDA Geospatial Services	RADARSAT-1 and 2 and others: Contact for new acquisitions and archive.	http://gs.mdacorporation.com/ (commercial)

Radar altimetry

Table 6.12 provides an overview of the main sources of radar altimetry-based products. AVISO distributes satellite altimetry data from Topex/Poseidon, Jason-1, ERS-1 and ERS-2, and Envisat in near real-time on a daily basis. AVISO products include a 25 km spatial resolution "geostrophic current" product, significant wave height (SWH), and surface winds. ESA has recently established the GlobWave project, with support from the French space agency (CNES), to provide satellite-derived wave products to users around the globe. The project will provide free access to satellite wave data and products in a common format, both historical and in near real-time.

TABLE 6.12
Sources of radar altimetry products

	Details	Access
AVISO	Geostrophic currents, significant wave height, and surface winds	www.aviso.oceanobs.com/en/data/products/ (free, with commercial services offered)
GlobWave	Satellite wave data products (under development)	www.globwave.org/ (free)
MyOcean	Provides access to a range of regional and global ocean data, including AVISO products.	www.myocean.eu.org/ (access to free data)
eoPortal	ASAR and ERS and others: Searchable online catalogue, particularly useful for searching ESA archives.	http://catalogues.eoportal.org/ (access to free data)

6.5.3 Costs of data

The cost of remote sensing data varies considerably, i.e. considering that some data are provided freely by international or national space and oceanographic agencies and others are commercial products where a company is trying to run a profitable business based on data sales. Google Earth contains a very valuable range of high spatial resolution data that can be browsed freely.

In almost all cases, the end users must make some compromises on the data they would like to use and what is practically and economically possible. For example, it may be desirable to have up to date, 1 m spatial resolution optical data for the entire coastal zone for a country or province, but this may be prohibitive in terms of cost and the data volumes may be hard to manage. Costs of imagery are not the same in different regions. For example, countries with satellite receiving stations often have lower government pricing for imagery (e.g. RADARSAT in the People's Republic of China). Space agencies may reduce pricing for their imagery in developing countries, e.g. ESA in Africa or JAXA for parts of Southeast Asia.

As described at the start of this section, it is best to first investigate what your own national government departments or agencies have available. The range of potential applications and size of areas of interest is obviously an important factor. It is important to remember that there are costs associated with fieldwork, image processing and analysis, accuracy assessment and cartography that must also be considered. Development of Web-based or desktop information management systems for remote sensing applications will often greatly exceed the data costs, depending on labour costs in the region. A scoping study is an essential step to determine if a proposed activity or application is economically feasible and sustainable.

As an indicative guide, the typical cost of data for some common fisheries and aquaculture applications is provided in Table 6.13. The total cost for data in the table is the cost before image processing; however, data products can be purchased at these prices (with the exception of ALOS PALSAR) with certain image processing already completed (e.g. geometric correction described in Section 6.6.3). The number of images is also estimated, although this depends on the shape of the area of interest, and many products are now available at prices based on the area of data required rather than images or "scenes". It is very important to appreciate that prices change and the market for satellite data is becoming more competitive.

TABLE 6.13

Indicative costs of satellite image data for two typical fisheries and aquaculture applications

	Mapping aquaculture structures		Coastal vegetation mapping	
Area of interest size	1 000 km^2		5 000 km^2	
Sensor type	Imaging radar		Multispectral optical	
Data type/mode	ALOS PALSAR, fine beam	TerraSAR-X, StripMap	RapidEye	SPOT 5
Spatial resolution (m)	10	3	5	5
Estimated number of images	1	1	2	2
Example mapping scale	1:30:000	1:15 000	1:20 000	1:20 000
Cost (US$/km^2)	0.5–1	5–8	1.5–2.5	2.5–3
Total cost for data (US$)	500–1 000	5 000–8 000	7 500–12 500	12 500–15 000

6.6 PREPARING REMOTELY SENSED IMAGERY FOR GIS USE

Once remotely sensed imagery has been acquired, it is almost certain to require some processing. Most processing tasks can be undertaken via the use of specialist image processing software such as ERDAS or ENVI, though there are a number of proprietary GIS software that includes image processing and other editing functions, e.g. IDRISI, ArcGIS and Manifold. The following site provides access to free image processing software (FreeGIS.org: www.cof.orst.edu/cof/teach/for421/Software.html), though the site does not include OSSIM (www.ossim.org) and ILWIS (www.ilwis.org). See Section 6.7.4 for further details on remote sensing software.

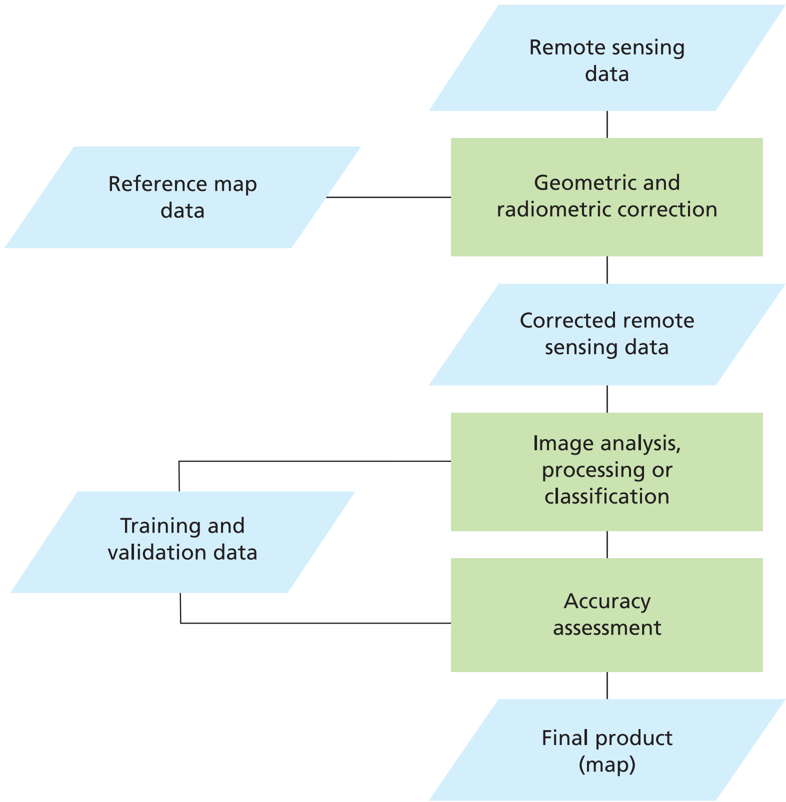
Image processing includes all activities that are performed with the imagery or data in order for it to be useable for the desired application, i.e. before possible integration into a GIS. Depending on the applications, there may be very little or no processing required, e.g. a chlorophyll-*a* product from NASA Ocean Color Web could be directly integrated into a GIS. Alternatively, significant image processing may be required using specialized software, e.g. using radar data for mapping aquaculture ponds. Figure 6.8 and the following subsections briefly describe some main steps in image processing. The Canada Centre for Remote Sensing (www.ccrs.nrcan.gc.ca/resource) provides good outreach materials in English and French related to image processing.

6.6.1 Reference map data

To locate ground features on imagery, or to compare a series of images, a geometric correction procedure is used to register each pixel to real world coordinates (Jensen, 1996). Many types of remote sensing data can be acquired with a defined coordinate system and datum, and the data can be directly integrated in a GIS with other map data. The metadata and the reported accuracy of geometric corrections should be reviewed to determine if they meet user requirements, and care is required if re-projecting data (see Section 3.3.4). It is also possible to order and receive data without any geometric corrections, and to perform corrections using specialized image processing software. Often this is considered to provide more accurate results, as the user should have access to "ground control points" or reference map data that can be used to precisely and accurately identify locations on the map. For terrestrial applications, a digital elevation model (see Section 5.8.3) is also required to ensure that the geometric distortions caused by terrain can be corrected.

To compare imagery from different places or dates, the impact of illumination and atmospheric effects should be removed from the imagery – this is "radiometric correction". Similar to geometric distortions, many available products have been

FIGURE 6.8
Typical activities in remote sensing image processing



processed to remove atmospheric and illumination distortions, e.g. ocean colour or SST data. Other optical or radar data may not have been corrected. Radiometric correction is often one of the more challenging stages in image processing for many users and requires more sophisticated software tools and knowledge. Therefore, it is important that remote sensing imagery acquired should be already in a trustworthy and useable form.

The output from geometric and radiometric correction is "corrected remote sensing data" that can be further assessed and analysed.

6.6.2 Training and validation data

Often called "ground truth" or "sea truth",[169] supporting data are an important input to most remote sensing projects. For example, ground truth can include land cover observations (vegetation types) and sea truth data can include in situ measurements (direct water temperature measurements). The ground or sea truth data often has two purposes: (i) to help develop the product; and (ii) to help assess the accuracy of the product.

When ground or sea truth data are used for product development they are often called "training data". When used for accuracy assessment, the data are referred to as "validation data." As described in Section 6.6.4 on accuracy assessment, it important that the same ground or sea truth data are independent and not used for training and accuracy assessment because then the accuracy statistics may be biased.

[169] Readers might see the processes involved in relating the imaged data to the real on-the-ground data as "ground truthing" or "sea truthing".

6.6.3 Image analysis, processing or classification

Thematic mapping or image classification and analysis, or "retrieval" of biophysical parameters such as chlorophyll-*a* or SSH, can be included under image analysis. Usually the biophysical modelling is conducted by skilled specialists and only the validated products are integrated into GIS (e.g. GlobColour or AVISO products). On the other hand, optical imagery and imaging radar are more often analysed by GIS specialists with remote sensing knowledge.

There are many methods and approaches for thematic classification of satellite data, which range from visual interpretation and classification to almost fully automated classification (see Table 6.14). Automation has the potential to save costs by minimizing the time required for manual editing; however, inappropriate automation could result in increased costs owing to time-consuming manual revisions of automated products. The best option can be semi-automated approaches, where the manual delineation and interpretation process is supported by inputs from automated classification approaches.

The output of image analysis, processing or classification is a thematic product that can be evaluated in an accuracy assessment.

TABLE 6.14
Advantages and disadvantages of thematic classification approaches

Visual interpretation	Semi and fully automated
Advantages • Can on-screen digitize using GIS software, no specialist software required • Accurate and pleasing thematic map, if work is completed by a skilled image analyst and there are good interpretation guidelines • Better feature or object extraction, especially linear features • Delineation and attribution can be achieved in a single step	**Advantages** • Faster • Cheaper (depending on labour costs) • More repeatable, e.g. for future updates • New software can identify objects or features • Can be more efficient for large mapping projects, or operational services
Disadvantages • Classification may not be easily repeatable by different people • Time consuming • Costly (depending on labour costs) • Needs skilled interpreters	**Disadvantages** • Requires specialist knowledge and understanding of different options • May require specialist and expensive software, although there are now several open source options • Processing and results will require manual work to create a thematic map

6.6.4 Accuracy assessment

An accuracy assessment or validation report provides important information to the users of the products that have been derived from remote sensing, but it is too rarely performed. The accuracy assessment uses the part of the validation data not used for the product development (i.e. independent data) and these values are cross-checked with the classified remote sensing product. Quality georeferencing is important so that the location of the validation samples is accurate. Authors must also describe how their assessment was performed and refer to well-established standards; a useful review was provided by Congalton (1991).

Product accuracy is very important when change detection analysis is performed (post-classification comparisons) because errors in each product can be compounded. Users should exercise caution in analysing the differences recorded by their maps as map inaccuracies almost invariably compromise their change estimation (Fuller, Smith and Devereux, 2003).

Following an accuracy assessment, the output of image analysis, processing or classification is a thematic product where users of the product can understand the limitations and suitability of the product for their application.

6.7 CHANGE DETECTION

A time series of images, created by repeated image acquisition over the same location, can be used to assess change. There are many approaches and methods of change detection analysis depending on the application. Usually a "baseline" image or reference image is defined and other images are directly compared. Some popular approaches include:

- Manual change detection is the simplest approach and is commonly used for land cover change mapping. An experienced image analyst visually compares two or more images and identifies changes in land cover. The areas and types of change are digitized using GIS software. Because this approach relies on visual interpretation, it is important to ensure that the rules for interpretation are defined so that the analysis is standard and repeatable.
- Comparing classified images. The images from each date are classified (following the same method) and the change between them is analysed. The analysis is normally performed using a GIS, which also allows for the integration of other data such as management units and administrative boundaries.
- Direct change detection. A baseline image and a new image are compared directly. Differences in the image values are used to identify areas of environmental change. Local knowledge and validation data are required to interpret what the change is, for example, mangrove loss.

Regardless of the method used to detect change, images should be geometrically corrected and coregistered so that they can be compared in a standard and direct way. More advanced image processing may also be required in order to remove the bias of factors such as different solar illumination and atmospheric conditions on the dates that the satellite images were collected.

6.8 TECHNICAL SUPPORT AND TRAINING FOR REMOTE SENSING

The following subsections introduce some resources (Web sites, organizations, references) giving further information and technical support for remote sensing applications for fisheries and aquaculture.

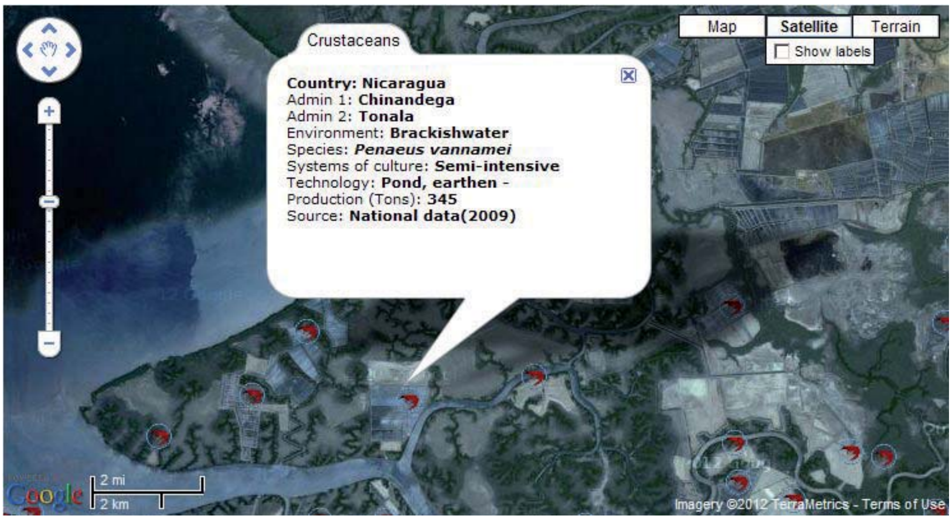
6.8.1 Web resources and organizations

As well as providing mixed resources to aid in the use of remote sensing, some of the sites listed below provide a much wider range of materials such as data, tools, publications, etc that are useful to fisheries, aquaculture and marine applications of GIS.

- **GISFish (www.fao.org/fishery/gisfish/index.jsp)** – Managed by FAO, GISFish is a "one stop" site from which to obtain the global experience on GIS, remote sensing and mapping as applied to fisheries and aquaculture. GISFish sets out the issues in fisheries and aquaculture and demonstrates the benefits of using GIS, remote sensing and mapping to resolve them. The global experience provided by GISFish is captured in issues, publications, activities, training, data and tools, contacts, discussions, news and events. Using the "Data and Tools" menu of GISFish, access is gained to a wide range of inland fisheries and aquaculture associated data including links to remote sensing data and tools.
- **Census of Marine Life (http://comlmaps.org/how-to/layers-and-resources)** – Produced an excellent Layers and Resources section for their Web site where there are simple instructions for data download and data conversion for many of the data sets described in this chapter.

- **International Ocean Colour Coordinating Group (www.ioccg.org)** – is a useful resource to understand ocean colour data. The IOCCG has published several useful reports, including remote sensing in fisheries and aquaculture (Forget, Stuart and Platt, 2009), and conducts and sponsors advanced training courses on applications of ocean-colour data in various developing countries.
- **Marine Geospatial Ecology Tools (MGET; http://code.env.duke.edu/projects/mget)** – for ArcGIS provides a geoprocessing toolbox of more than 180 tools for coastal and marine researchers and GIS analysts who work with spatial ecological and oceanographic data;
- **National Aquaculture Sectors Overview (NASO) Maps Collection (www.fao.org/fishery/naso/search/en)** – The NASO map collection consists of Google maps showing the location of aquaculture sites and their characteristics at an administrative level (state, province, district, etc.) and in some cases even at an individual farm level. The data are being collected by country experts, and the detail available depends on the degree of aquaculture development in each country, the resources available for data collection and the level of clearance provided to publish data (see Figure 6.9).
- **Remote sensing for decision-makers – aquaculture study and lagoon management: pilot study in Morocco (www.fao.org/SD/eidirect/EIre0068.htm)** – An aquaculture case study from a series on the use of remote sensing and GIS in management of renewable natural resources in agriculture, forestry and fisheries. The series is intended for managers and division directors of national and international organizations and administrations, as well as for project managers, planners and policy-makers at development institutions.
- **SAFARI project (www.geosafari.org) – the IOCCG co-sponsors the project, which was developed under the umbrella of the Group on Earth Observations (GEO) (www.earthobservations.org)** – The SAFARI project aims to accelerate the pace of assimilation of remote sensing data into fisheries research and ecosystem-based fisheries management on a world scale.

FIGURE 6.9
Illustration of part of the NASO map collection for Nicaragua



Source: FAO (2012c).

6.8.2 Book resources

The following provides a selection of popular remote sensing reference books:

- Campbell (2008) – Introduction to Remote Sensing (Third Edition) – a popular text that introduces students to widely used forms of remote sensing imagery and their applications in plant sciences, hydrology, earth sciences and land use analysis.
- Cracknell (2007) – Introduction to Remote Sensing (Second Edition) – a comprehensive introduction covering the physical principles of common remote sensing systems, processing, interpretation, and applications of data. This edition features updated and expanded material, including greater coverage of applications from across earth, environmental, atmospheric and oceanographic sciences.
- Lillesand, Kiefer and Chipman (2007) – Remote Sensing and Image Interpretation (Sixth Edition) – a comprehensive introduction to the latest developments in the field of remote sensing and image interpretation. Examines the basics of analog image analysis while placing greater emphasis on digitally based systems and analysis techniques. The presentation is discipline neutral, so students in any field of study can gain a clear understanding of these systems and their virtually unlimited applications.
- Martin (2004) – An Introduction to Ocean Remote Sensing – Examining the use of satellite data in the retrieval of oceanic physical and biological properties, this book presents examples of the kinds of data that can be acquired and their oceanographic application. The textbook, designed for graduate and senior undergraduate courses in satellite oceanography, will prepare students and interested scientists to use satellite data in oceanographic research.
- Mesev (2007) – Integration of GIS and Remote Sensing – explores the potential that lies along the interface between GIS and remote sensing for activating interoperable databases and instigating information interchange. It concentrates on the rigorous and meticulous aspects of analytical data matching and thematic compatibility – the true roots of all branches of GIS and/or remote sensing applications.
- Rees (2001) – Physical Principles of Remote Sensing – aimed at students and researchers in remote sensing, geography, cartography, surveying, meteorology, earth sciences and environmental sciences generally, as well as physicists, mathematicians and engineers. This text covers the subject matter mainly from the physics viewpoint.
- Tan (2011) – Remote Sensing of the Changing Oceans – is a comprehensive account of the basic concepts, theories, methods and applications used in ocean satellite remote sensing, and it also includes new developments in satellite remote sensing technology and international cooperation in this emerging field.
- The whole of the ICES Journal of Marine Science (Vol. 68. No. 4, 2011) is given over to symposium reports on remote sensing in fisheries.

6.8.3 Technical training materials

- **Canada Centre for Remote Sensing (CCRS) (www.ccrs.nrcan.gc.ca/resource)** – Remote sensing outreach materials in English and French. Includes an excellent glossary of remote sensing terms.
- **NASA Remote Sensing Tutorial (http://rst.gsfc.nasa.gov)** – An online training manual for learning about remote sensing. The tutorial was updated in March 2010.
- **ESA EduSpace (www.esa.int/SPECIALS/Eduspace_EN/index.html)** – The Eduspace Web site aims to provide secondary school students and teachers with learning and teaching tools. It is meant to be an entry point for space image data, and, in particular, to a widespread visibility of earth observation applications for education and training. The Web site provides a good and accessible introduction to remote sensing that should appeal to non-specialists.

- **NOAA Coral Reef Watch Remote Sensing Tutorial (http://coralreefwatch.noaa.gov/satellite/education/reef_remote_sensing.html)** – Provides a curriculum aimed at grade four to six students in remote sensing and coral reefs, but the content is applicable for older age groups and any non-remote sensing specialist who wants a good introduction to the application.
- **Columbia University Remote Sensing Image Analysis Laboratory, Remote Sensing Glossary (www.ldeo.columbia.edu/res/fac/rsvlab/glossary.html#S)**.
- **UNESCO-BILKO (www.noc.soton.ac.uk/bilko)** – Bilko is a complete system for learning and teaching remote sensing image analysis skills. Current lessons teach the application of remote sensing to oceanography and coastal management, but Bilko routines may be applied to the analysis of any remote sensing image in an appropriate format and include a wide range of standard image processing functions.

6.8.4 Software and tools

It is important to explore different free and/or open source GIS and remote sensing software, to discover if software can support the analysis required. An index of some open source projects is found at http://opensourcegis.org; some good free remote sensing options are listed below:

- **BEAM (www.brockmann-consult.de/cms/web/beam)** – Toolbox and development platform for viewing, analysing and processing of medium resolution remote sensing data from MODIS, MERIS, AVHRR, AVNIR, PRISM and CHRIS/Proba. Various data and algorithms are supported by dedicated extension plug-ins.
- **Fusion (http://forsys.cfr.washington.edu/fusion/fusionlatest.html)** – A powerful LIDAR viewing and analysis software developed by the Remote Sensing Applications Center of the United States Department of Agriculture (USDA) Forest Service.
- **Google Earth (http://earth.google.com)** – Version 6.0 of Google Earth contains a range of oceanographic and other data in the Ocean Layer. For example, the United States Navy's Daily, Dynamic SST. Many other organizations provide access to Google Earth KML files to explore land, coastal and ocean data.[170]
- **ILWIS (www.ilwis.org)** – GIS software with a comprehensive set of image processing tools and capabilities for image georeferencing, transformation and mosaicing
- **Nest ESA SAR Toolbox (NEST; http://earth.esa.int/nest)** – NEST is an ESA toolbox with an integrated viewer for reading, post-processing and analysing ESA and third party SAR data. NEST allows users to further develop the software package by means of a Java Application Programming Interface (API). NEST is developed by Array Systems Computing Inc. under contract to ESA.
- **Opticks (http://opticks.org)** – An expandable remote sensing and imagery analysis software platform
- **Radar Tools (RAT; http://radartools.berlios.de)** – Tool for processing radar data. Advanced algorithms in SAR polarimetry (PolSAR), interferometry (InSAR) and polarimetric interferometry (PolinSAR) are included.

[170] Google generally focuses on providing imagery over land and coastal areas, although more attention has been recently directed at exploring the oceans of the world with the development of Google Ocean (http://earth.google.com/ocean) (S. Bradt, personal communication, 2012). It is advisable to keep the Google Earth installation up to date because since version 5 there is an easy way to check the date of the satellite imagery – simply by holding the cursor over the centre of the image and the acquisition date appears at the bottom of the image. The toolbar of the latest version also contains an excellent "historical image time slider", which enables the user to easily review multitemporal imagery if it exists. Because Google Earth is regularly updated and enhanced, it is recommended to check the Web site and keep the software up to date.

A few examples of some of the main proprietary remote sensing software are listed below:

- **ERDAS IMAGINE (www.erdas.com/products)** – Claims to be the brand leader in image analysis software.
- **ENVI (www.ittvis.com/language/en-us/productsservices/envi.aspx)** – This is also a leading proprietary supplier of image analysis software.
- **ArcGIS (www.esri.com)** – ArcGIS is the leading commercial GIS software package, offering an integrated collection of GIS software products. There are numerous extensions to the software, some of which are free such as MGET (described above).
- **IDRISI (www.clarklabs.org)** – As a commercial GIS and remote sensing software, it is relatively cheap, user friendly and very powerful.
- **Manifold (www.manifold.net)** – Manifold is a cost-effective GIS software package that can be used to integrate a variety of oceanographic data in available formats.

6.8.5 Data formats

A key challenge for many non-remote sensing or GIS specialists is the range of data formats and projections in which remote sensing and oceanographic data are provided. Even the most common data formats can be confusing to those who are not programmers or remote sensing and GIS specialists. Some effort and time is required to learn how to use available data and tools, but there is substantial user guidance available. Table 6.15 provides a summary of the common data formats for remote sensing and oceanographic data and reference to some of the tools for viewing and converting the data. It is also important to review the "metadata" (information about the data product) to ensure that the parameters provided by the product, format and level are understood. Metadata is often summarized in a data specification document or a text file.

TABLE 6.15
Summary of common remote sensing formats for operational oceanography data

Name	Description	Tools and conversion
netCDF	Network Common Data Form (netCDF) is a common, machine-independent format for representing scientific data.	ArcGIS and MGET Toolbox can be used to download and import netCDF files to ESRI GRID format. Technical information on netCDF: www.unidata.ucar.edu/software/netcdf
HDF	Hierarchical Data Format (HDF) is a common, machine-independent, self-describing format for representing scientific data. Many open source and commercial tools understand HDF.	ArcGIS and MGET Toolbox can be used to download and import netCDF files to ESRI GRID format. ArcGIS has built-in capabilities to import HDF Technical information on HDF: www.hdfgroup.org
GeoTiff	GeoTIFF is a public domain metadata standard that allows georeferencing information to be embedded within a TIFF file, such as projections, coordinate systems, ellipsoids and datums. It provides a TIFF-based interchange format for georeferenced raster imagery.	Most GIS and remote sensing software packages support GeoTIFF. Technical information on GeoTIFF: http://trac.osgeo.org/geotiff

6.9 CASE STUDIES

Four case studies are described below covering applications in aquaculture practice and management and fisheries monitoring and management. These case studies build on the general principles of remote sensing as described in Section 6.2 and strengthen the general examples of applications described in Section 6.4.

6.9.1 Mapping coastal aquaculture and fisheries structures by satellite imaging radar. Case study of the Lingayen Gulf, the Philippines.

Original publication reference: Travaglia, C., Profeti, G., Aguilar-Manjarrez, J. & Lopez, N.A. 2004. Mapping coastal aquaculture and fisheries structures by satellite imaging radar: case study of the Lingayen Gulf, the Philippines. FAO Fisheries Technical Paper No. 459. Rome, FAO. 45 pp. (available at www.fao.org/docrep/007/y5319e/y5319e00.htm).
Spatial tools: Remote sensing.
Main issues addressed: Inventory and monitoring of aquaculture and the environment.
Duration of study: Six months; the study began in 2003 and ended in 2004.
Personnel involved: (i) Remote sensing specialist with a working knowledge of remote sensing applications in fisheries and aquaculture (FAO Remote Sensing Officer); assisted with the design of the study and analyses and managed the project; full time. (ii) Fisheries and aquaculture specialist with a working knowledge of GIS and remote sensing applications (FAO Aquaculture Officer); assisted with the design of the study; part time for the duration. (iii) Digital image processing specialist (consultant and professor); modelling, image processing and analyses; full time. (iv) Philippine aquaculturist who wrote the description of the structures: fish pens, cages and traps and played a key role in ground verification; part time for the duration. (v) Field verification personnel from the Bureau of Fisheries and Aquatic Resources of the Philippines (four staff), full time for short duration. (vi) Advisers at large (four advisers), who provided data and advice from time to time.
Target audience: The study is aimed at the general fisheries and aquaculture public, governmental administrators and planners, and remote sensing and GIS specialists.

Introduction and objectives: Travaglia *et al.* (2004) implemented the study to map coastal fisheries and aquaculture structures by satellite imaging radar in the Lingayen Gulf, the Republic of the Philippines. The objective of this FAO led study was to test, under operational conditions, a methodology for the inventory and monitoring of shrimp farms using radar satellite imagery. Radar data are known to offer unique capabilities for mapping shrimp farms not only for their inherent all-weather capabilities (important in tropical and subtropical areas where cloud cover is frequent), but mainly because of the way radar interacts with pond dykes (Travaglia, Kapetsky and Profeti, 1999). Because pond dykes are distinguishable from surrounding water surfaces and from the much lower dykes surrounding rice paddies and other flooded areas, they can readily be identified.

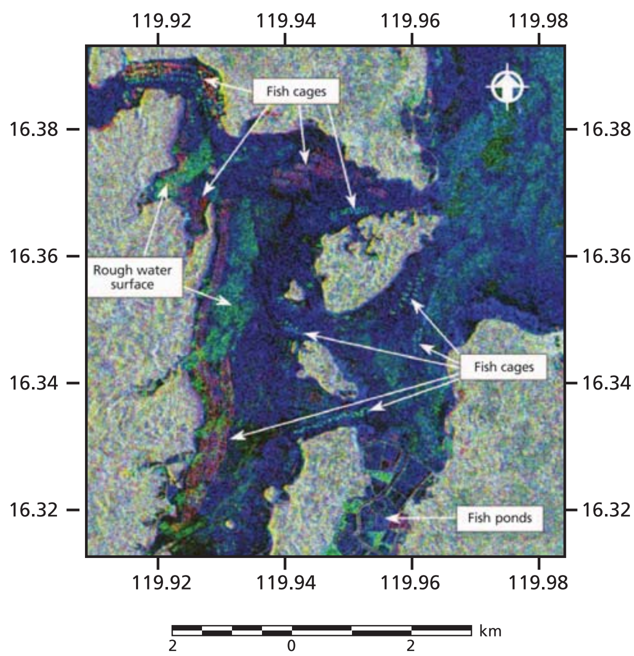
Methods and equipment: The study focused on various types of structures: onshore fish ponds, fish pens in the tidal zone and offshore fish cages and fish traps in the Lingayen Gulf, the Republic of the Philippines, and aimed to compare the suitability of different types of remote sensing imagery. Fish traps are stationary fishing gear with many variations in structural form and materials depending on the target species; in this case, the traps are corrals made from bamboo stakes and other materials that are detectable by radar.

The study area was covered by two ERS-2 SAR images acquired in descending and ascending orbits in December 2002 with a spatial resolution of 25 m (see Box 6.2 for description of satellite orbits). Orbit direction is relevant because it influences the characteristics of the SAR images, and aquaculture features are enhanced in a complementary way. A RADARSAT-1 Fine Mode SAR image was acquired in February 2001 with a ground resolution of 9 m, which covers a smaller area than the ERS images but covered the majority of the area where the aquaculture and fisheries structures are located. The images were geometrically corrected. A fish pond dyke reflects back a large amount of the incident radar energy, but this varies with the angle between the object and the direction of the incident beam. Hence, if a dyke is parallel to the radar beam it may not be detected, which is why ascending and descending orbits were acquired. The other aquaculture and fisheries structures influence the radar signal in a similar way. The vertical sides of fish cages, pens and traps emerging from the water surface, create a corner reflector effect that allows them to be identified.

Classification (feature extraction) was conducted using visual interpretation (as described in Section 6.6.3). This means that a skilled image analyst manually identified and digitized the boundaries of the aquaculture structures. The validation data for an accuracy assessment was collected during field surveys by a team from the Bureau of Fisheries and Aquatic Resources of the Philippines.

Results: The presence of the elevated surrounding dykes ensured straightforward visual interpretation. The area having fish ponds in 2002 was compared with the area mapped in 1977 topographic maps; the comparison indicated that the area had increased by 60 percent, but some of the fish ponds mapped in 1977 had been converted to other uses. Fish cages were detectable in all images, but windy conditions causing rough sea surfaces at the time of image acquisition negatively affected their detectability. Fish cages may be of several shapes (square, rectangular, circular) and made of various materials; those mainly made of metal have a brighter appearance on SAR images, a common detection characteristic in radar technology.

FIGURE 6.10
Interpreted RADARSAT-1 SAR image and the resulting map of the aquaculture and fisheries structures



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

Fish traps that emerge from the sea surface were separated into two categories: offshore traps and traps inside major rivers. The area occupied by fish traps was calculated to estimate their aerial extent. In many cases, only the central structure of the traps is visible in the images. However, because of their small size, the uncertainty in identification of traps was higher than that of the other structures. An example of the RADARSAT-1 imagery and the classification product of the aquaculture and fisheries structures is provided in Figure 6.10.

Table 6.16 shows the total area covered by the features of interest in the entire study area. This includes various types of aquaculture and fisheries structures, plus the salt pans. The study area completely covers the Pangasinan province, plus approximately two-thirds of La Union and a small portion of Zambales provinces on the island of Luzon. All mapped aquaculture and fisheries structures occur in the Pangasinan province only, with the exception of some fish ponds (90 units covering 18.762 km^2) and of some fish ponds classified as uncertain (13 units covering 2 .613 km^2) existing in the other two provinces. Table 6.17 summarizes the statistics on fish traps. These include all the segments composing the arrow-like traps, if detectable.

TABLE 6.16
Total area covered by the classes of interest (Pangasinan province)

Class description	Number of units	Total area (km^2)
Salt pans 2002	1	4 .156
Fish ponds 2002	587	157 .723
Fish ponds 2002, uncertain[1]	33	2 .036
Fish pens 2001	22	1 .600
Fish cages 2001	105	2 .439
Fish cages, uncertain[2]	7	0.054
Fish cages 2002	267	1 .390
Fish cages 2002, uncertain[2]	16	0.019
Areas with fish traps in the open sea 2001[3]	12	18 .943
Areas with fish traps inside rivers 2001[3]	6	1 .703

[1] Identified in one image only, out of two or three.
[2] Uncertain assignment: may be a small island or a rough patch in the sea surface.
[3] Polygons drawn around the areas on which fish traps were detected to have an estimate of their extension.
Source: Travaglia *et al.* (2004).

TABLE 6.17
Length of the fish traps detected in the study area

Class description	Number of elements	Cumulative length (km)	Average length (km)	Minimum length (km)	Maximum length (km)	Standard deviation
Traps in the open sea	378	50.104	0.133	0.018	0.642	0.093
Traps inside rivers	84	7.886	0.094	0.024	0.364	0.061

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

The accuracy of the visual interpretation procedure was close to 100 percent for all structures except for fish cages and fish traps, as they may have been moved in the time interval between the image acquisition and the field verification. The clear appearance of fish cages in the SAR imagery permitted a 90 percent estimated mapping accuracy. Mapping accuracy for fish traps was estimated at 70 percent of fish traps that had potential to be detected by remote sensing.

Discussion and recommendations: RADARSAT fine mode imagery provided the best "detectability"for all aquaculture and fisheries structures considered in this study and, therefore, allowed them to be inventoried and monitored with greater accuracy. ERS imagery enabled successful mapping of fish ponds and fish cages but failed to map fish pens and fish traps. For mapping fish ponds and fish cages, using images from ascending and descending orbits acquired within a limited time interval is recommended.

Since the study, there has been significant development in imaging radar as described in this chapter, especially the new high resolution sensors and multi-polarization sensors. The potential for mussel line and fish cage mapping using RADARSAT-2 was clearly demonstrated by Dean *et al.* (2007), but for most developing countries ALOS PALSAR offers the most cost-effective option for imagery with resolution close to RADARSAT-1.

6.9.2 Ocean monitoring in Chile for harmful algal bloom mitigation

Authors: Alan Stockwell, Thomas Boivin, Cristian Puga, Jason Suwala, Erin Johnston, Philippe Garnesson and Antoine Mangin.
Original publication reference: This work is not derived from a peer reviewed or conference publication. The work was delivered as internal ESA reports and to clients and/or users.
Publication/date: Environmental information system for harmful algal bloom monitoring in Chile, using earth observation, a hydrodynamic model and in situ monitoring data. January 2006.
Spatial tools: Ocean colour satellite imagery, hydrodynamic model, web development
Main issues addressed: Harmful algal blooms and aquaculture.
Duration of study: 1 year (January 2005 to February 2006).
Personnel involved: Thomas Boivin, Alan Stockwell, Cristian Puga, Jason Suwala, Erin Johnston, Antoine Mangin, Philippe Garnesson and Loredana Apolloni.
Target audience: Marine aquaculture industry.

Introduction and objectives: Hatfield Consultants (Hatfield), in collaboration with ACRI-ST and Apolloni Virtual Studios (AVS), collaborated on a project called "Integrating Earth Observation into Aquaculture Facilities Monitoring in Southern Chile", also referred to as the "Chile Aquaculture Project" (CAP). The CAP project was funded by ESA and conducted with Mainstream Chile, part of the Norwegian holding company CERMAQ, a world leader in salmon production.

The objective was to demonstrate integrated application of remote sensing data and modelling to provide advanced warning of potentially harmful algal blooms (HAB) so that their impacts can be minimized by the aquaculture industry. The monitoring of the emergence and movement of HABs can provide sufficient time for mitigation measures to be taken by farmers to help reduce potential losses. Long-term data can help improve the site selection process for new facilities.

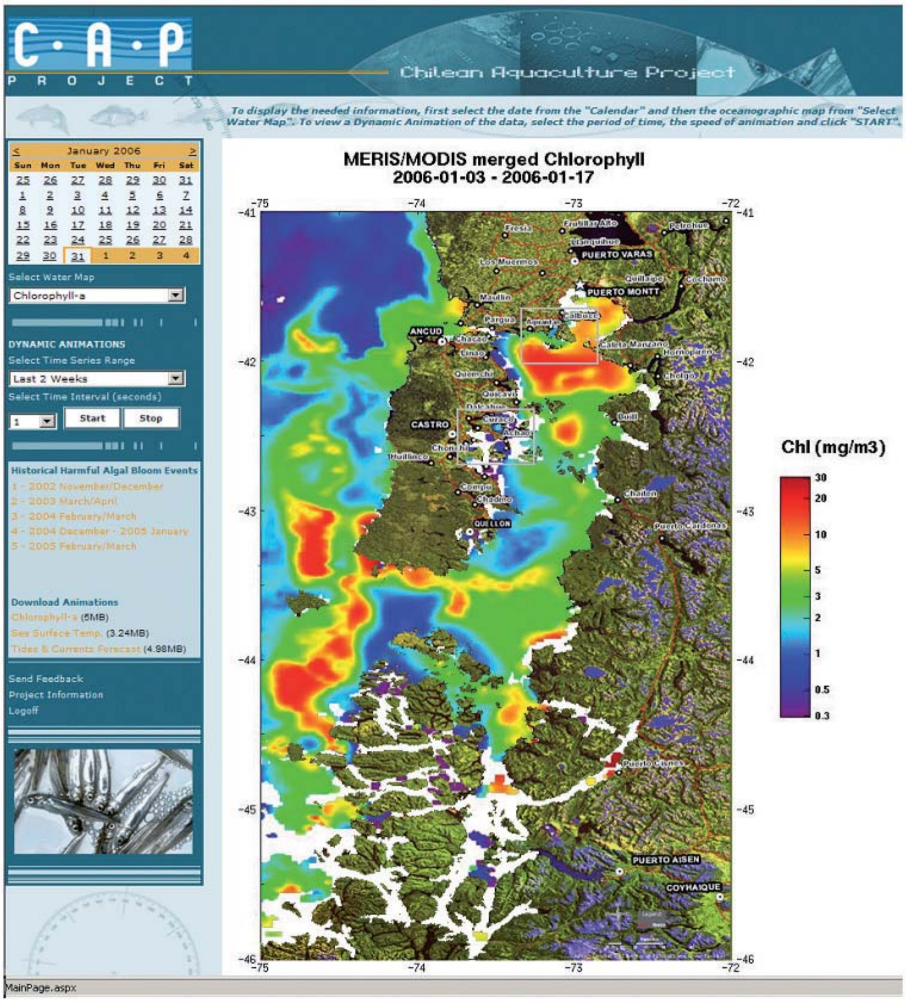
Methods and equipment: To develop a prototype of a HAB warning system, several information sources were used:

- Remote sensing products were provided by ACRI-ST. Chlorophyll-*a* concentration and Secchi depth transparency maps were generated on a daily basis from merged MERIS and MODIS data. Daily SST data were acquired from MODIS with in situ data from buoys.
- *In situ* environmental data were provided by Mainstream Chile.
- Oceanographic, meteorological and land GIS data were collected by Hatfield.

Using these inputs, an oceanographic currents and tidal model was developed, which in combination with transparency and chlorophyll-*a* products, was the basis for development of a HAB risk/warning map. The combination of ocean colour data from different sensors and daily SST meant that product delivery was possible on a daily basis, dependent on cloud cover.

Results: The image processing system and modelling were integrated to produce automatic products of chlorophyll-*a*, SST and Secchi depth. The products were integrated with a GIS to build easy-to-interpret maps, which along with tabular data, were also displayed via a Web portal that was updated each day. The end user could choose the level of detail required by selecting overview maps of the aquaculture production area (e.g. Chiloe Island area) or by selecting specific salmon farm sites to analyse available data. An example of the Web portal page is provided in Figure 6.11, which shows an overview map with a 15-day average of chlorophyll-*a* concentration.

FIGURE 6.11
Chile Aquaculture Project Web portal – main page



Source: Hatfield Consultants (2009).

Validation using in situ and other data enabled accuracies to be estimated as follows:

- Chlorophyll-*a*: within 15 percent;
- SST: within 0.5 °C;
- Secchi depth: ± 2 m (after algorithm recalibration);
- Tide elevation from model: 10 cm at the Puerto Montt control point (astronomical tides);
- Surface current: estimated to be within 1 m/s (but with few means of validation).

Discussion and recommendations: According to the needs of users and the state of the technology, the main focus for HAB warning is on the delivery of chlorophyll-*a* data and on Secchi depths (SST is obviously of importance as well to support modelling). Based on the CAP experience, there was a need for improvements in the accuracy and quantification of the error for the products. Secchi depths should be within an error of 2 metres (± 1 m).

In addition to HAB warnings, another recommendation was exploitation of available ocean colour remote sensing data to derive maps of statistics of chlorophyll-*a* persistence, variability and other statistical parameters at high resolution (e.g. 1 km spatial resolution). This type of climatology information is extremely valuable for site selection for aquaculture production areas. Also, to improve the understanding of the evolution of the environmental parameters, automatic procedures could strongly benefit the system, for example, chlorophyll-*a* front extraction by local gradient computations and quantification of differences between one daily image and the previous images.

Finally, for users there is a real need for derivation of a synthetic "HAB index" that includes all relevant environmental components. This synthetic HAB index could be expressed in the form of a very simple graphic (ideally three colours from green to red, meaning non-risk to high risk).

The CAP project provided important information on HAB occurrences in the key aquaculture regions of Southern Chile, which proved to be extremely valuable to the industry and local government. Long-term monitoring of HAB information is important to help protect the aquaculture industry from possible losses in production, which can be significant in the event of a major HAB event.

6.9.3 Use of SPOT 5 for mapping seagrasses (*Posidonia oceanica*)

Original publication reference: Pasqualini, V., Pergent-Martinia, C., Pergenta, G., Agreila, M., Skoufasb, G., Sourbesc, L. & Tsirikad, A. 2005. Use of SPOT 5 for mapping seagrasses: an application to *Posidonia oceanica*. Remote Sensing of Environment. Vol. 94: 39–45.
Spatial tools: SPOT 5 multispectral imagery, GIS.
Main issues addressed: Environmental impacts of aquaculture; management of aquaculture together with fisheries.
Duration of study: Not reported.
Personnel involved: Not described.
Target audience: Coastal management community.

Introduction and objectives: *Posidonia oceanica* is the dominant seagrass in the Mediterranean Sea (Marba *et al.*, 1996). *P. oceanica* plays an important role in many coastal processes, contributing to sediment deposition and stabilization and to attenuating currents and wave energy (Fornes *et al.*, 2006). Seagrass meadows are also considered to be among the most productive ecosystems, supporting diverse flora and fauna and providing nursery and breeding grounds for many marine organisms (Francour, 1997; Hemminga and Duarte, 2000). *P. oceanica* is a slow-growing climax species that forms large stable meadows, but there is evidence of decline in many areas as a result of warming sea temperatures and pollution (Marba *et al.*, 1996, Holmera *et al.*, 2008, Marba and Duarte, 2010)

Potential sites for coastal aquaculture, if utilized, may affect ecologically sensitive areas such as coral reefs and seagrass beds, and off-the-coast and offshore sites may still need to consider potential impacts on sensitive areas such as *P. oceanica* meadows and apply the precautionary principle. Maps of the distribution of *P. oceanica* are required for effective management and conservation.

A wide range of methods may be used for mapping seagrasses (McKenzie, Finkbeiner and Kirkman, 2003), including optical satellite and aerial remote sensing and acoustic sampling. Generally, the key challenges for mapping *P. oceanica* using optical images are: (i) limited light penetration to the maximum depth of *P. oceanica* distribution (about 40 m); and (ii) spatial resolution of the sensor in relation to the potential patchy distribution of *P. oceanica* with substrates such as rock and sand. Aerial photographs (Pasqualini *et al.*, 1998, 2005), Compact Airborne Spectrographic Imager (CASI) (Mumby and Edwards, 2002) and Ikonos imagery have been employed (Fornes *et al.*, 2006) in recent studies to map seagrasses.

Pasqualini *et al.* (2005) investigated the potential of SPOT 5 optical satellite imagery for mapping *P. oceanica* in Zakynthos Marine National Park (Mediterranean Sea, Greece). The objective of the study was to examine the potential of different spatial resolution SPOT 5 images to map seagrass. The bay is 12 km long by 6 km wide with seagrass known to range from the near surface to approximately 30 m depth. Four types of community and seabed type are found: mobile sediments (silts and sands), communities on hard substrates (including shingle), continuous beds of *P. oceanica* and mosaics of beds (on a mat, rock or sand).

Data: SPOT 5 imagery has four spectral bands: green (0.50–0.59 μm); red (0.61–0.68 μm); near infrared (0.78–0.89 μm); and mid-infrared (1.58–1.75 μm). The first three bands have a spatial resolution of 10 m while the mid-infrared has a resolution of 20 m. Combination of multiple SPOT 5 images acquired at the time also provides multispectral imagery enhanced to 2.5 m spatial resolution. Because there is little penetration of longer infrared wavelengths through the water column, only the green and red visible bands were used at 10 m and 2.5 m resolution in a SPOT 5 imagery acquired on 1 September 2003.

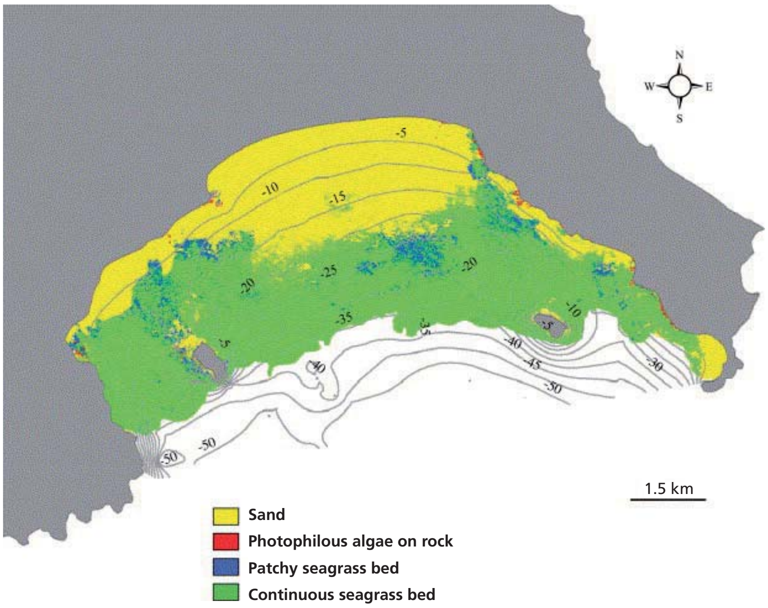
Methods: Processing of the two SPOT images was carried out using Multiscope software (Matra Systems and Information). The terrestrial part was masked in order to optimize the distinction between communities and types of seabed in the marine part. Principal Component Analysis (PCA) was applied to the two bands in each image. A supervised classification was then applied separately to the depth layers 0–10 m and 10–20 m so as to minimize any confusion between classes due to depth. This technique was previously applied on aerial photographs (Pasqualini *et al.*, 1997) and caution is required because it can result in classification bias near the depth limit boundary.

Classification training data were 189 field observations points obtained by scuba diving or observing the seabed from a boat. These data enabled the communities and types of seabed in Laganas Bay, Greece, to be identified. The accuracy of the habitat maps was determined using the overall accuracy. Subsequently, some manual corrections were made, for example, masking beyond the maximum possible depth of *P. oceanica* beds.

Outputs: The classification results revealed the predominance of *P. oceanica* beds in the bay, from the surface down to a depth of about 30 m. The map at 10 m resolution is shown in Figure 6.12 – a large area of sand occupied the northeast of the bay down to a depth of 20 m, while the southeast and northwest were occupied by large rocky slabs, colonized by photophilous algae. These rock-dwelling photophilous algae were absent beyond the 10 m isobath. On the maps with a resolution of 2.5 m, substantial areas of patchy seagrass beds were identified over the whole of the depth range studied.

The overall accuracy of the habitat maps ranged from 73 to 96 percent. The 10 m image provided a better overall accuracy for each depth band. Sand was mapped least accurately. The patchy seagrass beds were mapped with a higher degree of accuracy using the 2.5 m resolution SPOT images because their improved spatial resolution compared to the other images revealed the patchiness of the habitat.

FIGURE 6.12
Main benthic assemblages and bottom types at Laganas Bay, Greece, based on classification of a SPOT image (10 m resolution)



Source: Pasqualini *et al.* (2005).

In summary, SPOT image classification was considered a valuable method for a rapid identification of seabed types. The large image size of SPOT 5 makes it an attractive tool for the management of coastal waters; however, SPOT 5 and several other sensors lack a blue spectral band. Since the study by Pasqualini *et al.* (2005), WorldView-2 was launched in 2009 with a 1.8 m resolution visible spectrum "coastal band" (400–450 nm) that penetrates the water to greater depth. This sensor offers potential for improved and detailed mapping of *P. oceanica* beds. In general, satellite-based methods offer most potential in shallow waters where significant *P. oceanica* losses caused by human impact are expected to occur. The use of remote sensing, coupled with GIS, could be of immense value to supporting improved coastal management decisions and in EIA for assessing the potential impacts of aquaculture on coastal environments on *P. oceanica* meadows.

6.9.4 Fishing ground forecasts in Japan

Original publication reference: Saitoh, S.-I., Mugo, R., Radiarta, I.N., Asaga, S., Takahashi, F., Hirawake, T., Ishikawa, Y., Awaji, T. In T. & S. Shima. 2011. Some operational uses of satellite remote sensing and marine GIS for sustainable fisheries and aquaculture. ICES Journal of Marine Science, 68(4): 687–695.
Publication/date: 2007, 2009 and 2011.
Spatial tools: Remote sensing and satellite communication systems.
Main issues addressed: Fisheries management systems.
Duration of study: Multiple years.
Personnel involved: Researchers and developers from a research centre, two private companies and a regional local development agency.
Target audience: Fishers, fisheries and resource managers, fisheries researchers.

Introduction: The Traceable and Operational Resource and Environment Data Acquisition System (TOREDAS) provides fishing ground forecasts for Japanese common squid (Todarodes pacificus), Pacific saury (Cololabis saira), skipjack tuna (Katsuwonus Pelamis) and albacore tuna (Thunnus alalunga). TOREDAS aims to promote sustainable fisheries operation and management in the offshore zone around Japan.

Satellite-derived temperature and productivity data are used to identify areas where fish and squid tend to aggregate for feeding. TOREDAS delivers prediction of potential fishing zones in near real-time to fishing vessels via Internet and satellite connection. Users can generate products dynamically, such as overlaying maps, and measuring the distance from the nearest port or fishing ground (Kiyofuji *et al.*, 2007).

Methods and equipment: TOREDAS has four components: (i) data acquisition system; (ii) database; (iii) analysis module; and (iv) Internet and on board GIS. Chlorophyll-*a* concentrations are derived from MODIS and SST are processed in near real-time at 1-km resolution and sent to the database server via file transfer protocol (FTP). Data analysis is performed using commercial image processing software to extract and calculate contours, gradients and anomalies in the oceanographic data that indicate potential fishing grounds. ArcGIS software is used for analysis and GEOBASE software development platform is used for mapping on board the vessels.

TOREDAS also integrates data on vessel locations using a high-resolution vessel monitoring system (VMS) (Saitoh *et al.*, 2011). Using the VMS data, TOREDAS is able to measure the distance and speed of vessels and to categorize vessel activity. This type of information can improve operational fishery management and fishing effort control. TOREDAS products have a hierarchical structure defined as from Level 1 to Level 5[171]:

- Level 1 products are raster images of SST and chlorophyll-*a* concentrations.
- Level 2 products are obtained by image analysis to extract gradients, fronts or anomalies in the SST and chlorophyll-*a* concentration.
- Level 3 products are overlays of Level 1 and Level 2 data.
- Level 4 products comprise fishing ground areas estimated from algorithms using Level 3 results as inputs.
- Level 5 products are a one- or two-day forward prediction of fishing ground formation.

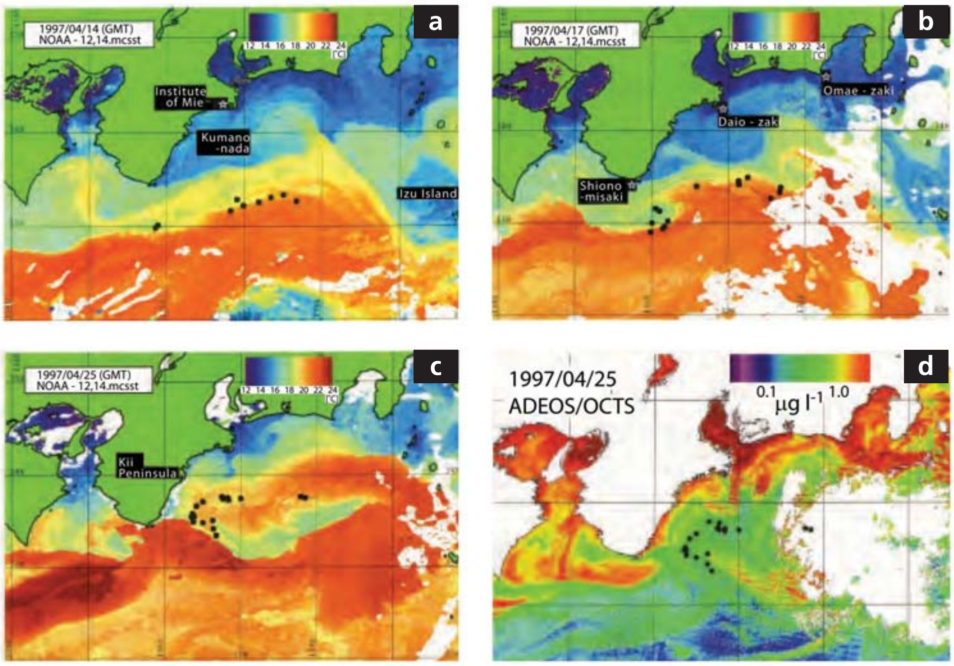
These processing of data into the product levels described above is automatic so that the fishers can receive information in near real-time.

[171] Note this is different from data levels that are often defined by international space agencies.

Results: An example of the research and development of fishing ground predictions for the southeast coast of Honshu Island, Japan, is described by Saitoh *et al.* (2009, 2011). AVHRR data from NOAA were received and processed into SST maps; chlorophyll-*a* concentration maps were obtained from the OCTS and SeaWiFS sensors. For validation, satellite SST and chlorophyll-*a* data were compared with in situ measurements of temperature recorded by the fishing boats and chlorophyll-*a* concentrations. Figure 6.13 shows the SST and chlorophyll-*a* concentration products. In Figure 6.13 (a) to (c), the SST over a period of ten days is shown, and the warm Kuroshio Current (red) and cold coastal waters (blue) are clearly visible. Figure 6.13 (d) shows the chlorophyll-*a* image for the same date as the SST data in Figure 6.13 (c).

Skipjack fishing vessels are shown as black dots in the images and are located along the edges of the ocean colour front between the coastal and offshore waters. Optimal fishing grounds were concentrated in the Kuroshio waters near the ocean colour front, with chlorophyll-*a* concentrations ranging from 0.2 to 0.5 µg.l^{-1}. The potential skipjack tuna fishing grounds and the effectiveness of using SST data for predicting fishing grounds is apparent. Ocean colour data are also important for identification of fishing grounds, especially when strong summer solar radiation heats up the surface layer of the ocean, rendering the SST data less effective.

FIGURE 6.13
Sea surface temperature and chlorophyll-*a* concentrations for the southeast coast of Honshu Island, Japan



Note: Black dots represent the trolling-line skipjack fishing grounds

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

Discussion: The TOREDAS system provides operational fishing ground forecasts and can support improved fishery management. Although the system could contribute to greater catching power, under sustainable fisheries management regulations it should be seen as a management tool to help monitor activities and improve fisheries economics. Thus, the benefits of TOREDAS include improving the understanding of fishing ground formation and fish migration, contributing to reduced fuel consumption and time spent searching for suitable fishing areas, reducing input costs and improving energy efficiency.

The use of VMS and remote sensing information together can provide a detailed account of the activities of fishing vessels. VMS can also aid in fine-tuning fishery forecasting models by including information on how fishing vessel skippers select fishing grounds relative to remotely sensed oceanographic data. Another potential application is as an educational tool for transferring fishing skills and knowledge from experienced to new captains (Saitoh *et al.*, 2011). In 2006, TOREDAS was handed over to a company called SpaceFish LLP.

6.10 CONCLUSIONS

Advances in remote sensing systems, communications technology and computer processing mean that remote sensing data are now much more accessible. Many former impediments preventing applications of remote sensing within GIS for aquaculture and fisheries may no longer apply, including affordability, information content, timeliness and revisit frequency. Many remaining challenges are more related to lack of awareness, poor management and a lack of training and support, plus the necessary expertise to integrate different data sets (imagery) within GIS or other information systems. However, because of the efforts of several international organizations, including FAO, the European Space Agency and IOCCG, there are many well-documented applications of remote sensing for fisheries and aquaculture and opportunities for GIS specialists to access new and important sources of data.

This chapter has recommended reviewing optical satellite sensors by considering the information that the user wants to obtain; for example, ocean colour, SST, or land cover and coastal zone mapping. Some sensors were designed for specific applications, such as global ocean colour monitoring, but most have several potential applications including deriving information for ocean, coastal and land areas. Optical data are affected by cloud cover, which can limit the available time series, revisit frequency and timeliness of data acquisition. However, there are an increasing number of options for optical data acquisition, and relatively high spatial resolution optical data are becoming available at lower costs. Radar offers the advantage that they are not affected by cloud cover and they can provide different and complementary information to optical remote sensing systems. An increasing range of imaging radar sensors are available and provide a range of spatial resolutions, wavelengths and polarizations. The accessibility and cost of data varies, and some countries have more cost-effective access to radar data through national ground receiving stations and agreements with commercial operators. There are often good time series of radar imagery, and the potential for fast acquisition and delivery of new data is a key advantage of radar. In the future, continuity of radar is assured and the cost of data access looks set to decrease significantly.

Fisheries and aquaculture are practiced worldwide in vastly variable environments and at greatly varying scales, but the biological systems and sustainable human exploitation are controlled to a greater or lesser extent by many variables that can be measured by remote sensing. It is likely that remote sensing will play an ever more important role in monitoring, planning and management activities, especially given the large proportion of the earth's surface that is covered by aquatic environments and the costs that would be involved in collecting data requirements by other means. The unique capability of satellite remote sensing to provide regular, repeated observations of the entire globe or specific regions at different spatial scales is also increasingly important in the context of global climate change. The time series of information products that are operationally derived from remote sensing should be part of government assessments of climate change impacts and action plans for industry adaptation.

7. GIS functionality

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7.1 INTRODUCTION

This chapter discusses the functional tools and techniques offered by typical GIS software packages. It is possible that most data processing discussed in earlier chapters could be performed without GIS software but, in most cases, the functionality that will be discussed here are specific to GIS software.[172] As mentioned in Chapter 2, for any user organization there are several choices when it comes to selecting a GIS software package. Each package has its own strengths and weaknesses and each varies in the range of operations that they perform. More expensive GIS packages may have over a thousand "tools" or other operations and even moderately priced packages will perform hundreds of operations. It is the goal of this chapter to introduce the user to the main functionality that may be useful in a wide range of applications. It is important to note that there is no standard terminology for tools (operations) among GIS packages, i.e. the name of tools discussed in this chapter will undoubtedly differ among the various packages. In addition, this chapter is presented using a number of broad "functional categories". Thus, while tools are discussed here under particular headings, this does not mean they could not be considered as applying to other functional groups. A further introductory point is that some of the functionality of the GIS operations might best be performed using either the raster or vector format. In most cases, attention is drawn to the preferred modelling format, but it is worth noting that many proprietary GISs are already programmed to use the most efficient format. Finally, it is assumed that all data to be used for GIS work has been validated and edited so that the user is confident that the data are as reliable as possible (see Section 5.3). For more information on GIS operations and functionality, see for example, Chrisman (2001), Chang (2004), Bolstad (2005), Heywood, Cornelius and Carver (2006), Delaney (2007) and Longley *et al.* (2011).

Before examining the types of tasks that GIS may perform, it is worth recalling that in order to perform any task the GIS software is dependent on its ability to be questioned or queried. The GIS analyst must have questions to which she/he requires answers, and these questions must be answerable using the tools available in the GIS. Querying is the act of searching attribute and location information stored in a spatial database and, as was shown in Section 5.5.3, the database management system (DBMS) within a GIS software package allows users to ask conditional questions of the data (tabular or spatial). Therefore, using so-called structured query language (SQL) and based on the information provided in Box 5.4, it is possible to ask questions such as "What is the proportion of fish caught in water having a flow velocity of 5 to 10 kilometres per hour?" Similarly, based on an extended version of Table 5.1, users could ask the software to "List all ports in the Federative Republic of Brazil where wooden vessels are registered", or more complex queries such as "What is the relationship between the length of fishing vessels in the Federative Republic of Brazil and the construction material used?" A spatial query might be "Show me the locations of vessels over 30 metres in length that are more than 12 years old." The reader can see that the GIS is

[172] It is certain that some of the pre-processing tasks discussed in Section 7.2 could be carried out in CAD (computer-aided design) or other remote sensing, drawing, photography and design packages.

making the best use of the attribute information contained in Table 5.1. As described in Section 5.5.3, SQL queries rely upon the fact that the DBMS of most GIS have the ability to perform numerous "operations" on data, such as Boolean logic, arithmetic operations, geometric operations, and various statistical or algebraic operations, all of which are designed to allow the user to manipulate the data in any way desirable.

In the rest of this chapter it will be important to realize that all of the functions that the GIS can perform will rely on this ability to ask suitable questions, and that these questions can only be answered if the appropriate data are accessible to the tools and the DBMS that are integrated in the GIS. Finally, it is the intention of this chapter only to describe what the typical functions are that GIS packages may perform; no attempt is made to tell readers how to perform these functions, i.e. as this will vary with the GIS software being used.

7.2 DATA PRE-PROCESSING AND TRANSFORMATIONS

This section covers some of the "preliminary functional" areas that most GIS packages should perform, i.e. those that are concerned with data pre-processing, data transformations and data manipulation. These are all necessary functions that can be applied to data sets, either in their raw or mapped form, which aim to change the data to suit the area, scale, theme, etc., of the specific GIS task being undertaken. This section discusses:

- data or map pre-processing
- generalization
- classification and reclassification
- buffering
- overlaying

While a great deal of time might be spent on the collection or creation of data for GIS projects and applications, it is very rare that data will be in a suitable form to answer the question being examined without first being manipulated. Pre-processing, therefore, allows the user to take the data collected and then adjust, update, refine or alter the data as necessary. Most GIS packages provide several tools to prepare data for use in analysis, though these tools will vary by software package. The ability to do the majority of pre-processing in the GIS provides users with the ability to experiment with the data in order to find out which type of output best suits individual project needs. Although this section describes mainly "pre-processing" functions that are often necessary to get the digital data into a useful state, in many cases these transformations might also represent the final output from the GIS project. For example, the "overlaying" function (see Section 7.3) can be effectively used to produce extremely informative new mapping information. Here, only the most important pre-processing and transformation functions available are discussed.

7.2.1 Data or map pre-processing

At a very basic level, digital maps and data sets may require a variety of obvious manipulations in order to best suit the task being undertaken. Most of these functions would also be available in other graphics or remote sensing packages. A range of the most basic pre-processing functions is given in Box 7.1.

GIS software often provides a range of more advanced transformation or pre-processing capabilities, and these are detailed in Box 7.2. These processes will be performed directly to the mapped output before the new output is stored in the database, and some of the processes may be applicable to remote sensing output as well as to GIS.

BOX 7.1

Examples of basic pre-processing functions available in most GIS or graphics programs

The following pre-processing functions may need to be applied to any spatial data set or digital map in order to make it available for a specific GIS project:

- **Delete** – Usually required in order to reduce a data set to suit a specified area, scale or theme. Individual entities can also be deleted.
- **Cut, clip or crop** – It is often possible to simply cut or crop mapping boundaries to suit a defined project area.
- **Move** – when changing scale it might be preferable to move entities to their more precise locations. Some entities may have been incorrectly located.
- **Recode** – If map layers are merged it might be necessary to establish new classes or coding for entities.
- **Dissolve** – It may be necessary to remove specific boundary lines, e.g. when two maps have been merged.
- **Update** – It will always be necessary to update maps or data sets.
- **Zoom** – It is very useful to be able to move in or out from mapped scenes, thus effectively changing scale. However, this might not be advantageous if data has only been captured at a small-scale.
- **Join or merge** – Allows neighbouring mapped areas to be merged into a single mapped area.
- **Rotate** – Allows a map to be conveniently viewed from any direction.
- **Labels** – Labels may need to be repositioned or changed in order to reflect different map designs or layout requirements.

BOX 7.2

Transformations that may be directly applied to digital maps

Unlike the pre-processing functions described in Box 7.1, these pre-processing transformations provide the capability to directly improve mapped images or to alter them in ways that might be necessary for specific GIS tasks. These transformations are unlikely to appear in more general graphics software.

- **Edge matching** – This function allows neighbouring maps in any series having the same scale (and usually theme) to be exactly matched up (registered) along their edges.
- **Projection change** – Because the world is spherical, there is no way to display the curved surface of the world on a flat map without distorting it. There are numerous ways to project the curved data to a flat surface, and, therefore, it must be ensured that the GIS recognizes the projection method used (see Section 3.3.4 and Figure 7.1). For excellent introductions to projections, please refer to Snyder (1993) and Iliffe (2008).
- **Datum (coordinate) transformation** – Similar to projection change, it is important that GIS can recognize a range of georeferencing systems (Section 3.3.4). Most modern GIS packages have "behind-the-scenes" functions to change between coordinate systems.
- **Rubber sheeting (warping)** – There are various reasons why maps might suffer from distortions, especially those derived from aerial photographs or scanned images, but it is important that they can be overlayed, if necessary, and they can be registered to appropriate geo-coordinates. Thus, rubber sheeting allows maps to be "contorted" as necessary so that the whole mapped area is adjusted to accurately locate control or registration points.
- **Orthorectification (geometric correction)** – This process corrects inevitable spatial distortions in satellite or aerial imagery caused by the topographic shape of the landscape, and is necessary if these images are to be used in mapping or GIS-based analyses.
- **Image enhancement** – This includes a range of techniques whose purposes are to improve satellite imagery so that images are clear and are well defined.
- **Structure conversion** – It is important that GIS packages have the ability to switch between working in vector or raster modes. Sometimes this is done automatically according to the GIS tool being used, but it can be user controlled. Figure 7.2 explains the procedure. It can be seen that there is some information loss if this procedure is carried out.

Figure 7.1 illustrates the importance of one of these transformations, i.e. that of projection change. Here, it can be seen that, for comparison purposes, the continent of Africa has been drawn using three different projections. All three versions of Africa in this image are perfectly accurate and yet, because of the projections used, they are clearly different from each other, with some countries appearing to occupy very different geographic locations.

FIGURE 7.1
Comparison of three different map projections of Africa

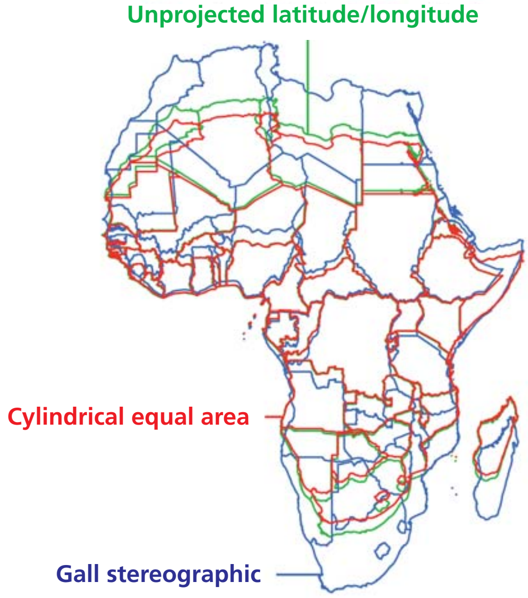
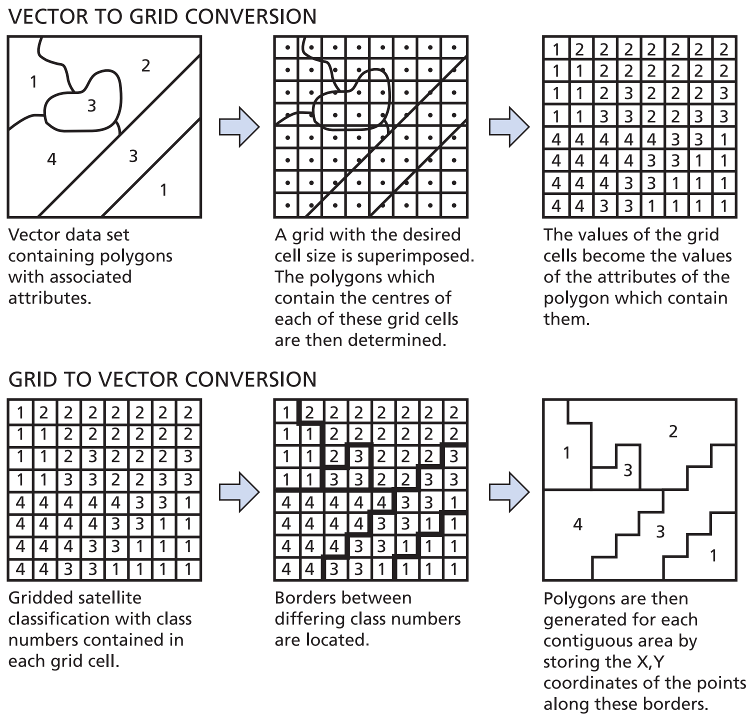


FIGURE 7.2
The vector to raster and raster to vector conversion process



Source: Meaden and Kapetsky (1991).

7.2.2 Generalization

Generalization is the abstraction, reduction and simplification of features so that they can be more easily used for particular mapping purposes. Thus, a major problem in cartography is that mapping at different scales requires different levels of detail to be captured at each scale. Box 7.3 shows the types of information that may reasonably be shown at three mapping scales. Details that are captured at a large-scale cannot possibly be shown on a map that is redrawn at a small-scale because individual mapped features would be too small. Likewise, the information captured at a small-scale often looks coarse and imprecise on a map redrawn at a large-scale because not enough detail will have been recorded.

BOX 7.3
Typical information shown on topographic maps at different scales

Large scale (1: 1 000 to 1: 10 000)

- plot boundaries and land parcels
- house or building outlines
- footpaths, grass verges, road widths
- small jetties

Medium scale (1:25 000 to 1: 100 000)

- all main roads and rail tracks
- all rivers over perhaps 3 metres in width
- most patches of woodland
- urban area shapes but perhaps not each residential road
- small villages and hamlets shown as dots
- contours at perhaps 20-metre intervals

Small scale (1:250 000 to 1:1 000 000)

- most towns as dots plus the location of larger villages only
- main rivers over perhaps 20 metres in width
- main roads and railways only
- contours at perhaps 100- to 250-metre intervals

Most GIS packages have several tools that fall under the heading of "generalization". Figure 7.3 shows brief examples of how a river, a group of buildings and patches of woodland might be generalized. Generalization typically includes the elimination of smaller features, the merging of features, the simplification of lines and a reduction of complexity, and is most appropriate when moving from large-scale towards a smaller scale. Figure 7.4 shows how "linear generalization" may be performed by a "line thinning" algorithm within the GIS software. Here, the original digitized outline of a river is shown in blue. In the first version of the river, the line thinning algorithm in the GIS will have reproduced the river's outline based on perhaps every tenth digitized location captured during the original digitization process, and thus is rather crude but appropriate for smaller-scale maps. The second river outline may be based on every fifth digitized location and is more accurate and suitable for larger-scale maps.

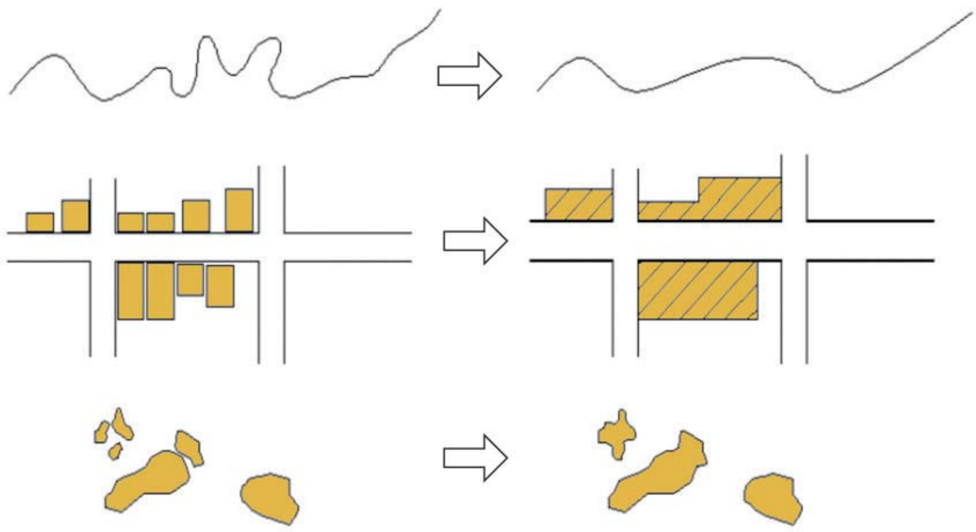
It should be noted that there are two classes of generalization:

(i) **Graphical generalization.** This is concerned with generalizing the graphical features on maps, i.e. those consisting of any points, lines and polygons.

(ii) **Semantic (or conceptual) generalization.** This is concerned with the actual entities that are considered necessary for mapping at different scales, e.g. at a large scale there may be houses, apartments, shops and factories, but at a small-scale the map may only show "buildings".

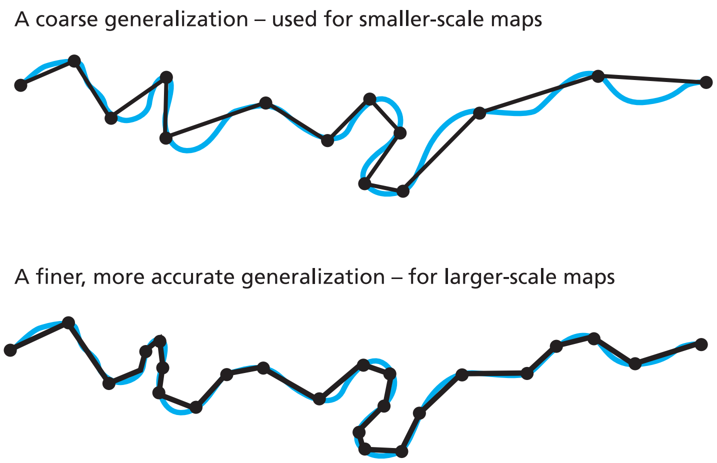
As well as generalization based on vectorized points, lines and polygons, it is possible to generalize rasters. Here, the GIS software may use an algorithm that calculates a mean value of, for instance, a central cell plus its eight surrounding neighbour cells, and the new raster will have a cell size equal to that original block of nine cells. This would create a more generalized map with the benefit of approximately an 88 percent reduction in data storage. As with most cartographic processes, there are no strict "right or wrong" methods regarding generalization and it will be up to the GIS operative to make sensible choices. Further details on generalization can be obtained from Laurini and Thompson (1992), Robinson *et al.* (1995), Li (2007) and Harvey (2008).

FIGURE 7.3
Examples of pre- and post-generalization in mapping



Source: ICIMOD (2011).

FIGURE 7.4
Line thinning at two levels of generalization



Source: Modified from Sinfogeo (2012).

7.2.3 Classification and reclassification

Classification and reclassification are subsets of generalization. The classification of data is necessary as a means of simplifying (generalizing) the complex real world and classification can be applied to each of the various types of data discussed in Box 3.5. Classification is the division of data into a specified number of classes using one of several classification methods, and Table 7.1 lists five common methods for classifying numeric data.

Figure 7.5 illustrates three of these classification methods in more detail. The histograms plot the number of counties in the United States of America on the vertical scale and the percentage of the population of each county who is more than 65 years old on the horizontal scale. Each example classifies the counties into ten classes, and these classes are then mapped such that the colour corresponds to the class. The top example divides the data into equal intervals, meaning that percentages shown on the horizontal scale are divided equally (perhaps 20 percent–30 percent; 30 percent–40 percent; 40 percent–50 percent, etc.). The middle example divides the data into what are termed "Jenks natural breaks", based on recognizable breaks in the data distribution (see Slocum *et al.*, 2005, for a full explanation of this method). The lower example divides the data into classes that each contain the same number of counties.

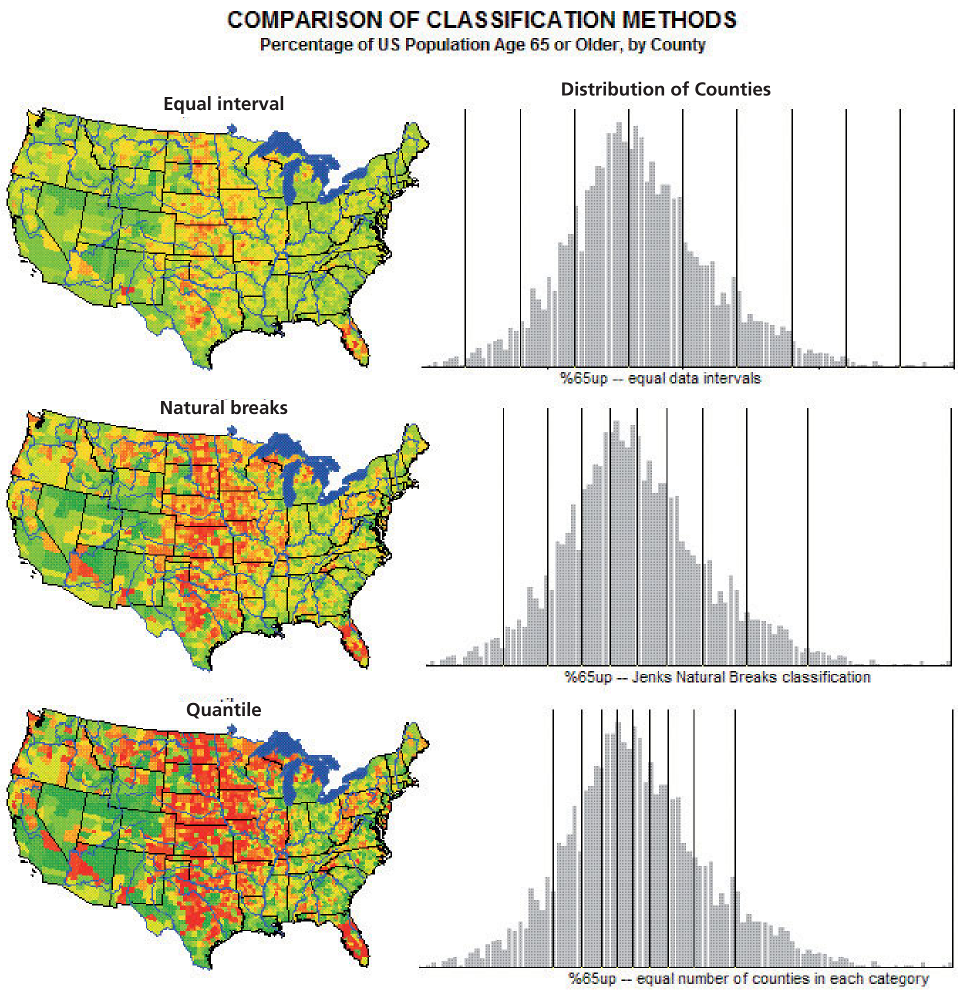
TABLE 7.1
Five methods to define class intervals for numerical data

Classification method	Description
Equal interval	Divides values into groups with an equal range of values.
Quantile	Creates classes that have the same number of features in each class being mapped.
Standard deviation	Finds the mean and then creates class breaks based on standard deviations above and below the mean until all values are contained.
Natural breaks (Jenks)	An algorithm defines classes based on natural break points in the data.
User defined	The user establishes class breaks at their own discretion.

Regardless of which classification method is used, the effect is to change the look of the data being displayed and often the spatial patterns highlighted. Data classification can also be used to create new data. For vector data, it is as simple as selecting the features that fall into the new class and then assigning a new value to those records that correspond to the new class. When working with raster data, it is possible to similarly create new data from an existing data set by classification, which is known as reclassification. Here, users can simply assign a new value to a cell or they can assign new values to a range of cell values. Table 7.2 shows the reclassification of data whereby the original population classification densities have been reassigned a new value (or coding). There are no specific rules regarding how many classes the data should be divided into, but recommendations usually say that five to seven classes are preferable for numerical data. If nominal data are being used, i.e. classes based on named categories such as soil or vegetation types, more classes can be used within the limits of easy colour and/or shading recognition. Finally, most proprietary GIS have menus or dialogue boxes that allow users to make easy classification selections, including choice of value ranges and colours or colour ramps.[173] For more information on classification, see Krygier and Wood (2005), Slocum *et al.* (2005) and Diaz (2006).

[173] Colour ramps are logical progressions of colour that depict ranges going from high to low values. These ramps may not logically apply to nominal values.

FIGURE 7.5
A comparison of three important methods of classifying data



Source: Mackenzie (2011).

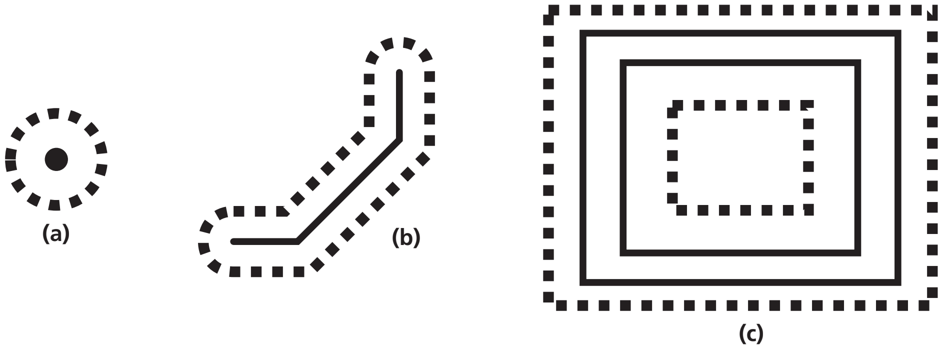
TABLE 7.2
Example of a reclassification table

Population density (inhabitants/km^2)	Reclassification coding	Possible interpretation
0–30	1	Low density
31–60	2	Moderate density
61–90	3	Fairly high density
91–120	4	High density

7.2.4 Buffering

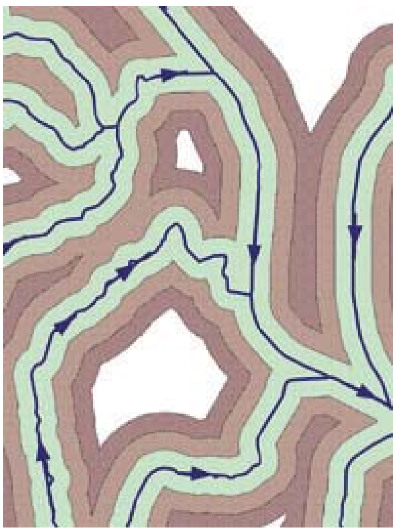
A buffer is a polygon created at some user-specified distance around a point, line or polygon feature. Figure 7.6 shows examples of buffers generated around the three main feature types. Notice that for polygons buffers may be drawn inside or outside any specified feature. Most GIS packages allow the user to create multiple buffers around a feature, as demonstrated by the three equal distance buffers created along sections of a stream network in Figure 7.7. Users are able to specify the number of buffer zones they wish to create as well as the distance increments at which the software creates the new buffers. The distances at which buffers are drawn, or the number of buffers used, are usually arbitrary decisions based on an "educated perception" of their need. For example, it would be possible to define mangrove areas as buffer zones (e.g. 50 m from the shrimp farms) to mitigate the potential impacts for wastewater discharges from shrimp farms. Clearly, some buffers can be more accurately defined than others and, indeed, some GIS allow for the drawing of variable buffers along portions of the same line or polygon.[174]

FIGURE 7.6
Buffers formed around (a) points, (b) lines, and (c) polygons



Buffers are the basis for much GIS analysis. For instance, if the land area shown in Figure 7.7 contained a number of mapped point sources of pollution, the GIS could provide an answer to the question "How many sources of pollution in the area are within 200 m of a stream?" The answer would simply be the number of points that intersect the 200-m wide buffer. More complex buffering algorithms exist that allow for differential movements or distances around a point source. For instance, if an oil spill occurs in an area of mixed geology, the oil may seep through some rocks at faster rates than others. If the seepage rates are known, then buffers can be calculated to show where (and how far) the oil will have reached after any specified time interval.

FIGURE 7.7
Multiple buffers surrounding part of a stream network



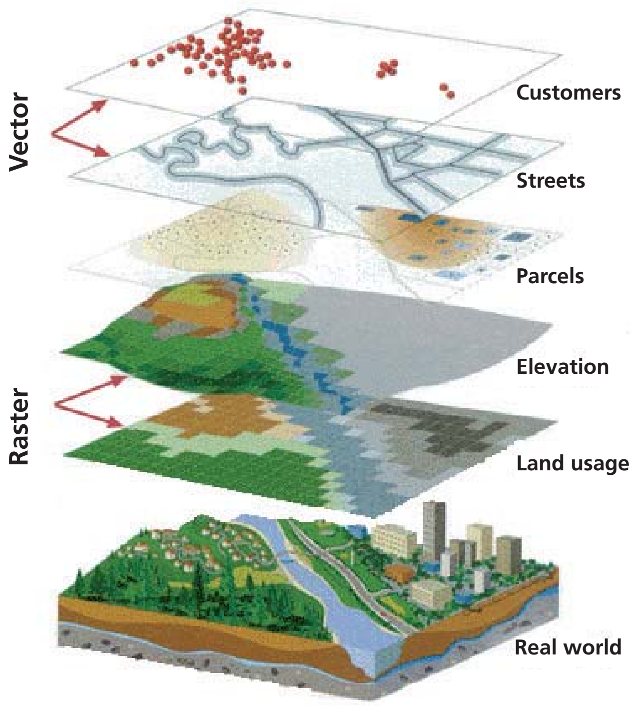
Source: United States Geological Survey (2007).

[174] This is particularly useful where lines represent features having variable widths, e.g. rivers.

7.3 OVERLAYING

Overlaying is basically the integration of mapped data from two or more different sources within the same area, and it is arguably the most powerful function of a GIS. Any mapped area of the earth's surface can be subdivided (classified) into any number of different thematic "layers". Thus, a typical map will conventionally show rail lines, the road network, forested areas, urban areas, the river network, the coastline, etc., and each of these themes can be mapped separately. Figure 7.8 illustrates that it is also possible to have different layers containing raster or vector maps, and perhaps topographic maps, historical maps, land use maps, remotely sensed images, etc. Any separate mapped layer can be overlaid with any other layer (or layers) as long as it is in the same projection and covers the same area. If, however, a raster layer is overlaid by a vector-based layer (or vice versa) with the intention of analyzing or integrating the data, then one or other layer would typically need to be converted (see Figure 7.2). Any new map produced will need to be named, filed and stored before it can contribute to further overlaying or other types of analysis.

FIGURE 7.8
Selected mapped layers for a specified area using points, lines, polygons, vectors and rasters



Source: Heard (2010).

Performing overlays using vector data can be computationally intensive because of the huge number of mathematical operations that will typically be performed in the course of the analysis. Furthermore, GIS operatives need to be cautioned that when doing overlays of vector data sets, there is often the problem of generating "false (or sliver) polygons". These are often due to the fact that the individual layers being overlaid were digitized separately and thus the points, lines or polygon boundaries on each map do not match up exactly (see Figure 5.3). Extensive editing may be needed in this case. Raster-based overlays are typically much simpler for the GIS to perform because individual cells are directly overlaid on other cells, although similar problems arise when the rasters have different cell sizes or origins. Raster overlay and the use of weightings are at the heart of map algebra (see later in this section).

A main purpose of overlaying is to see what relationship(s) might exist between different themes (layers). For instance, it is highly likely that there will be a relationship between soil type and land use, and GIS can tell the user facts about the closeness of this relationship. Other purposes for overlaying are described as follows:

(i) Creation of new features. It may often be useful to create a more complex map from existing data. For instance, data might be available for a specific area showing both “soil types” and “main vegetation classes”. By overlaying and merging these two data sets a new map can be created showing “soil with vegetation classes”.

(ii) Allocation of weightings. Sometimes layers are overlaid and merged in order to find the optimum location for some type of commercial activity. For instance, Figure 1.6 showed a map designed to seek optimum locations for shrimp production in western Democratic Socialist Republic of Sri Lanka. Fourteen layers were overlaid and merged to create this map and each was assessed as being of different importance to the success of shrimp production. Each layer was given a relative numerical weighting and this value was automatically assigned by the GIS to every pixel in that layer in the raster database. The 14 weighted layers were then merged in order to provide the final mapped output. The assignment of weightings can be rather arbitrary and, in fact, can be one of the most difficult parts of the analysis, but in many cases weightings can be agreed by a panel of experts.

(iii) Map algebra. Just as in mathematics where algebraic formulae have been designed to help with more complex computations, similar processes can be used in raster-based GIS. Basically this means that a formula can be developed, usually for modelling purposes, that allows the user to carry out a range of mathematical, e.g. addition, subtraction and multiplication, or algebraic manipulations to the data in order to achieve some goal. Figure 7.9 provides a very simple illustration of the basis upon which map algebra works. Most of the output achieved by the CHARM 2 team (see case study 10.4.1) utilized quite complex map algebra within the overlay process[175]. Map algebra functions are extremely powerful and allow the user to analyze and generate new data based on data they may already possess. A detailed description of map algebra functions is beyond the scope of this technical paper; for more information, see Arlinghaus and Griffith (1996), Batty and Longley (2003), O’Sullivan and Unwin (2003), de Smith, Goodchild and Longley (2007) and Bivand, Pebesma and Gomez-Rubio (2008).

FIGURE 7.9
Illustration showing simple map algebra function

6	4	2	6
2	8	6	6
6	4	8	8
4	6	2	6

+

3	2	1	3
1	4	3	3
3	2	4	4
2	3	1	3

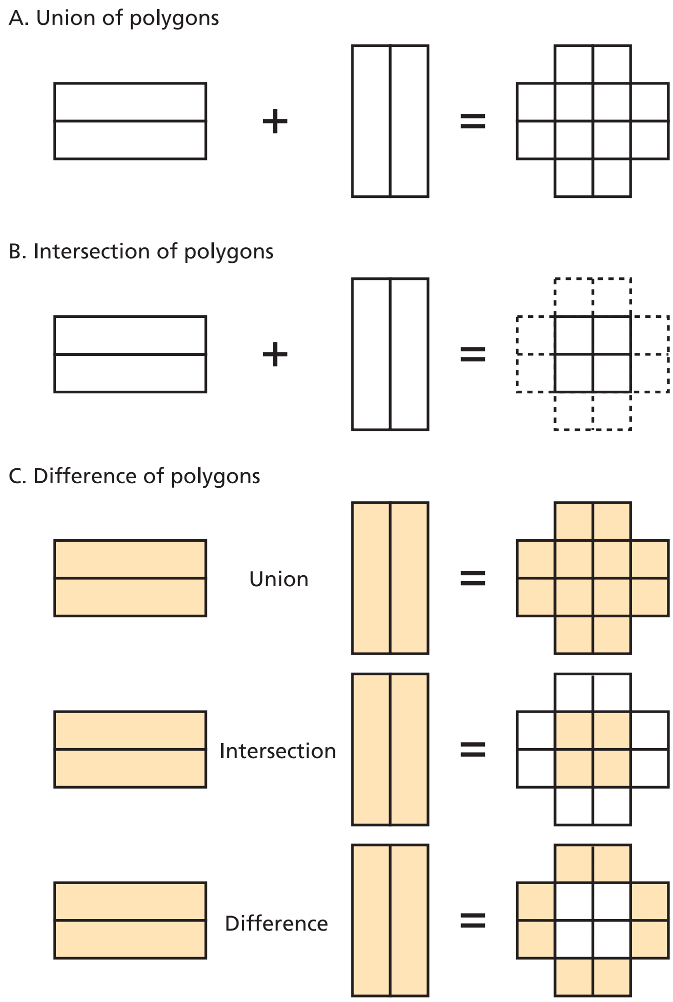
=

9	6	3	9
3	12	9	9
9	6	12	12
6	9	3	9

For most overlay operations, it is possible to perform a range of post-overlay procedures. This means that any resulting map can be edited in various ways so as to retain only desired information. For instance, Figure 7.10 (A) illustrates the overlaying (or union or merging) of two sets of polygons, which retains all the areas from both sets of polygons. Figure 7.10 (B) shows the intersection of two sets of polygons, which retains only the areas that are common to both data sets (see Lo and Yeung, 2002, for additional

[175] Map algebra is fundamental to the science of spatial statistics.

FIGURE 7.10
Overlay operation combines an input and overlay polygon



information). Figure 7.10 (C) shows the "difference" overlay operation, which subtracts the second set of polygons from the first set.

The simple overlaying of a polygon layer on top of a point layer can yield useful information about distributions. For example, if data are available to map survey results showing the distribution of a fish species in a particular area, then this point distribution can be overlaid by a vector map showing bottom sediment classes. The GIS can then calculate the numbers, the proportion and the density of the species within each sediment class.

Finally, it is worth considering the fairly complex range of analyses that may be performed by using a combination of buffering and overlay procedures. Again using Figure 1.6, which has many of its 14 layers based on buffering, the GIS-based map could be overlaid with a map of population density (by classes), and it would be possible to ask questions such as "How many people live within areas that are most suitable for shrimp farming?" or "What is the relationship between areas that are unsuitable for shrimp farming and the population distribution?

7.4 MEASUREMENT

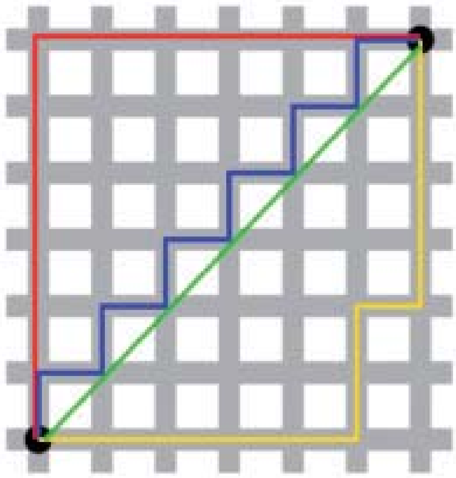
GIS software is capable of performing many types of measurement, including simple enumerations or counts, linear distances, areas, perimeters, volumes, directions and angles, plus a range of less frequently used measurements such as "cost" surfaces, weighted mean points, slope angles, directions, stream sinuosity, ratio of area to perimeter for polygons (edginess) and travel time distances. It is important to remember that various factors can affect the accuracy of measurements, including the projection of the data, whether the GIS accurately calculates areas and distances using different geographic coordinates, the precision and accuracy at which the data were collected, and the fact that the data typically do not exactly match the real world features (i.e. the real world may have curved edges, or fuzzy edges where one feature type gradually changes to another, while the GIS assumes clear boundaries made of straight lines). Because all forms of measurement are performed very differently in raster-based GIS compared with vector GIS, it is instructional to examine measurement under these two headings.

7.4.1 Raster-based measurement

If a raster is projected so that the units are linear (e.g. metres or feet), then line measurement using rasters is simple given that the cell (pixel) size is known. A measurement either horizontally or vertically along the raster columns or rows is simply the number of pixels multiplied by the width of a pixel. However, any other raster-based measurement will be more complex. Raster-based distances that diagonally cross the rasters (Figure 7.11) are 1.414 times as far as straight vertical or horizontal distances, so the green line is 8.5 distance units compared with a vertical or horizontal (red lines) measurement of 6 units. Figure 7.11 also illustrates that some raster-based measurements utilize so-called "Manhattan" distance (blue line) whereby distances are measured by traversing along an imaginary line going "across and up" the side of every pixel, thus increasing the real distance by approximately 30 percent from the straight diagonal distance, i.e. to 12 distance units. So, rasters are not a good basis for length measurements of linear distances. However, Figure 7.11 shows that rasters can easily be used to accurately calculate perimeter length (e.g. 6 × 6 = 36 distance units) and polygon area (6 × 6 = 36 aerial units). The same principle used to calculate area can be applied to measurements of spatial volume, i.e. width × length × depth.

Geographic (also known as unprojected) rasters are not defined in linear units (such as metres or feet) but rather as angular units (degrees), and thus are considerably more difficult to measure from and requires that the GIS knows how to handle geographic units. The basic problem is that the raster cells only look square when viewed in an X/Y plane but, in fact, the cells form trapezoids on the actual surface of the earth (Figure 7.12). Furthermore, the shape of the trapezoids depends on the latitude of the cell, with cells becoming narrower as they approach the poles.

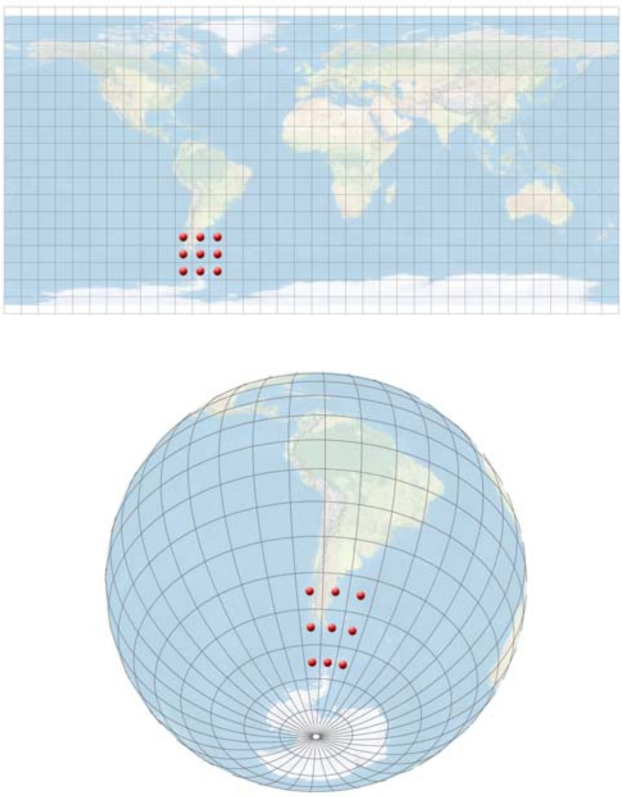
FIGURE 7.11
Raster GIS measurement showing diagonal distance (green); Manhattan distance (blue); and other random distances from start to finish (red or yellow)



Note: Red, blue and yellow lines are all the same length to show that whichever logical route is taken from one black dot to the other the travel will be the same distance.

Source: Ask.com (2012).

FIGURE 7.12
Trapezoidal raster cells in an unprojected raster

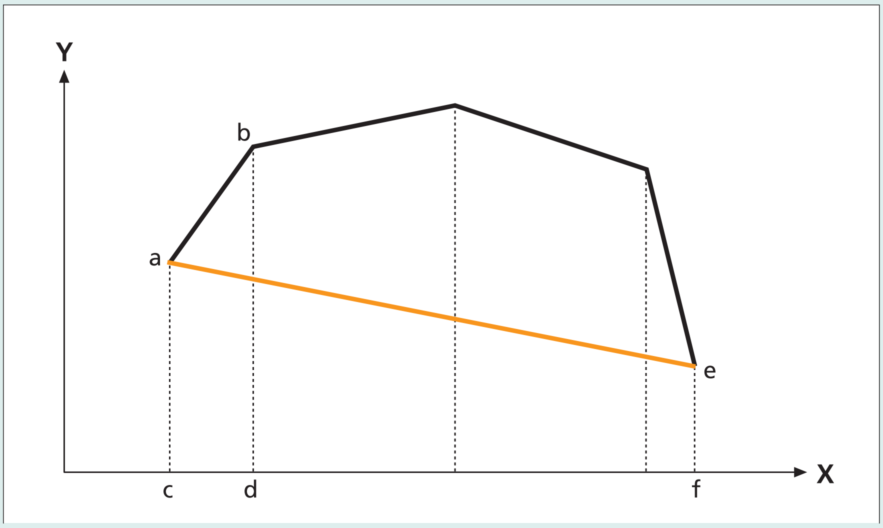


7.4.2 Vector-based measurement

Vector-based GIS provides a much more accurate basis for measurements of distance, area and centrality because the vertices, segments and edges are precisely defined. Measurements on projected data require simple Euclidean geometry, and the distance between any two points can easily be calculated using the Pythagorean theorem.[176] Euclidean geometry is also used to calculate perimeters or areas, with most GIS software using the so-called trapezoidal method (explained in Box 7.4) to calculate area.[177] More advanced GIS functions can incorporate the three-dimensional surface of the landscape to calculate the lengths and areas of vector features on hilly terrain.

The Pythagorean theorem and the trapezoidal methods, however, only work with projected data because these methods assume the vector features lie on a flat plane. Unprojected vector data (i.e. in latitude/longitude coordinates) lie on the curved surface of the planet and, therefore, require more complex methods (drawn from spherical and spheroidal geometry) to calculate distance, area and centrality. Most GIS systems use Vincenty's method to calculate the great circle distance[178] and direction between any two points (Vincenty, 1975).

BOX 7.4
Method used by GIS to calculate the area of vector-based polygons



The polygon consists of four heavy grey lines plus a brown line forming the fifth side. Trapezia are dropped from each edge to the x-axis and their areas are calculated, i.e. for trapezium a,b,d,c the area is the length c,d times the average of height a,c and height b,d. The areas for the four trapezia that meet with the x-axis are summed. The area of the trapezium e,a,c,f is then calculated and the result is subtracted from the sum of the four trapezia.

In general, if the two polygon vertices used in the trapezium move to the right (as in trapezium a,b,d,c), then the area of the trapezium is added to the total. If the two polygon vertices move to the left (as in trapezium e,a,c,f), then the area of the trapezium is subtracted from the total.

Source: Adapted from Longley *et al.* (2005a).

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176 See Purplemath.com (www.purplemath.com/modules/distform.htm), which provides detail on the Pythagorean measurement of length.

177 Information on this can be found at Geocomputation (www.geovista.psu.edu/sites/geocomp99/Gc99/076/gc_076.htm).

178 The great circle distance is the shortest distance between any two points on the surface of a sphere measured along a path on the surface of the sphere (as opposed to going through the sphere's interior).

Although vector-based measurement methods are generally more accurate than raster-based methods, they are more computationally demanding. Often vector objects can be composed of thousands of segments and can, therefore, easily require tens or hundreds of thousands of mathematical operations to calculate areas, lengths or centroids. This is especially the case with unprojected data or when the vector object approximates a curved line (like a circle). Curves are generally approximated using many short straight-line segments and, therefore, typically have large numbers of vertices and segments. Longley *et al.* (2005a), Dale (2005) and DeMers (2008) provide good detail on various facets and means of measurement in GIS, and the first of these publications makes the important point that most GIS distance measurements tend to result in underestimations of the true distances.

7.5 SPATIAL RELATIONSHIPS

Most modern GISs offer a wide range of spatial relationship functions. In this section, the various ways in which objects or areas are associated in space are described. The types of questions for which answers are sought may be as follows:

- Are there any "spatial patterns" across the landscape?
- Are distributions of features or objects random or regular?
- Are there density variations of features and what might this be related to?
- What is the degree of association between any features or objects?
- Have there been temporal or spatial changes in distributions across space?

It is easy to see how answers to these questions could have a profound influence on fisheries and/or aquaculture management, notably in terms of the appropriate scale or level of detail in which to carry out a project, or in deciding on the best sampling or data collection strategies. To derive answers to these types of questions, the broad range of GIS functions will each be examined under those headings that are conventionally applied, though different authors or software packages may have alternative preferred names. It should be mentioned that, according to the density and distribution of sampling information held, it might be necessary to utilize interpolation methods in order to gain additional data. These methods are described in Section 7.5.3.

7.5.1 Measures of centrality

Most readers will be aware that in statistics or mathematics there are various concepts of "centrality" such as the mode, the mean and the median. As these measures represents centrality in the single dimension, so there are various concepts of centrality in two dimensional space. Here, two useful methods of establishing centrality using GIS are briefly described, i.e. establishing central points and constructing Thiessen polygons.

Establishing central points

Knowledge of spatial centrality can be useful in several ways. For instance, because it minimizes the average distance that customers may have to travel, there are many reasons why a central location can give economic advantages for businesses. Thus, retail outlets prefer central locations and processing plants may wish to locate in a location that is central to their raw material sources. This latter point may be particularly important to both fisheries and aquaculture where fish processing is now a large-scale commercial activity.

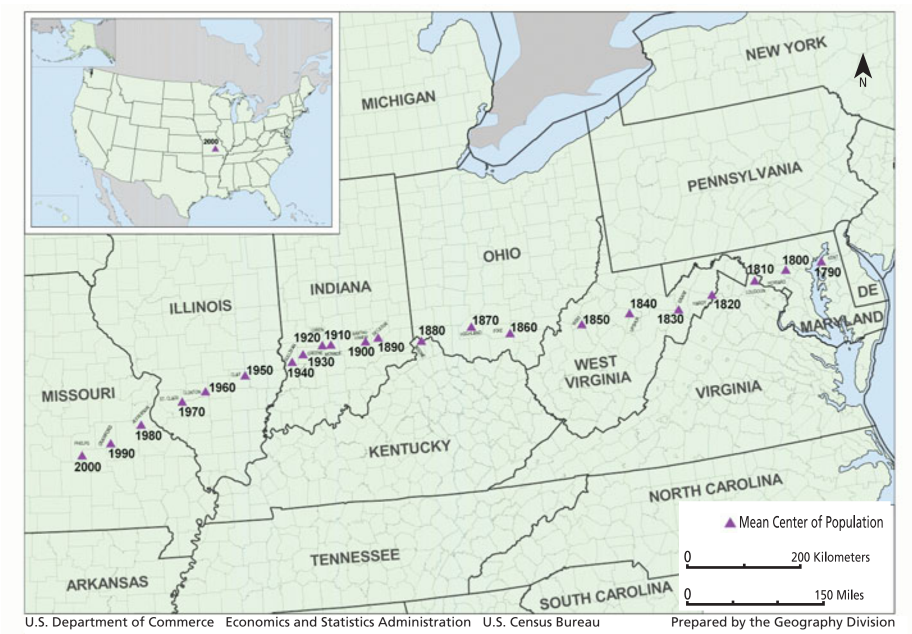
Most GIS packages have the functionality to locate various forms of centrality. One measure of centrality is that of locating the central point of a polygon – the so-called "centroid", or mean centre position[179]. This point can be envisaged as the point at which an imaginary cardboard cut-out of the polygon would be able to balance on the point of a pin. In vector analysis, centroids are sometimes used as "handles" that facilitate

[179] It is also the point that minimizes the sum of squared distances.

the default position for placing map labels, and they may be used in several analysis operations, for example, when performing an operation like distance calculations, the software will find the centroid of the polygon and use that point from which to do any measurements. Centroids are also used in raster analysis, for example, when determining a water flow path, centroids are used to generate lines representing this path.

Centrality can also be thought of as the spatial centre of gravity. This means that for many distributions of points within a given area the distribution will show some level of clustering. The centre of gravity will be the point within the given area around which the distribution is best centred. For instance, in an unpublished dissertation, Meaden (1978) calculated the centre of gravity of catfish farms in the lower Gulf States of the United States of America for successive years from 1970 to 1976. During this period, the author found that the centre of gravity migrated about 70 miles south-eastwards from near Indianola to near Benton in Mississippi state. On a longer time scale, Figure 7.13 shows how the centre of gravity for the population living in the United States of America has moved westwards from a position in Maryland in 1790 to a position in Missouri in 2000. A variation of the straight forward centre of gravity is the "weighted mean centre". This means that the items forming the distribution may not all be of equal importance, and therefore more "important" items may be allocated a weighting before the centre of gravity is calculated. Almost all measures of centrality are most efficiently calculated using vector-based GIS.

FIGURE 7.13
The mean population centre of the United States of America (1790 to 2000)



Source: Jacobs (2009).

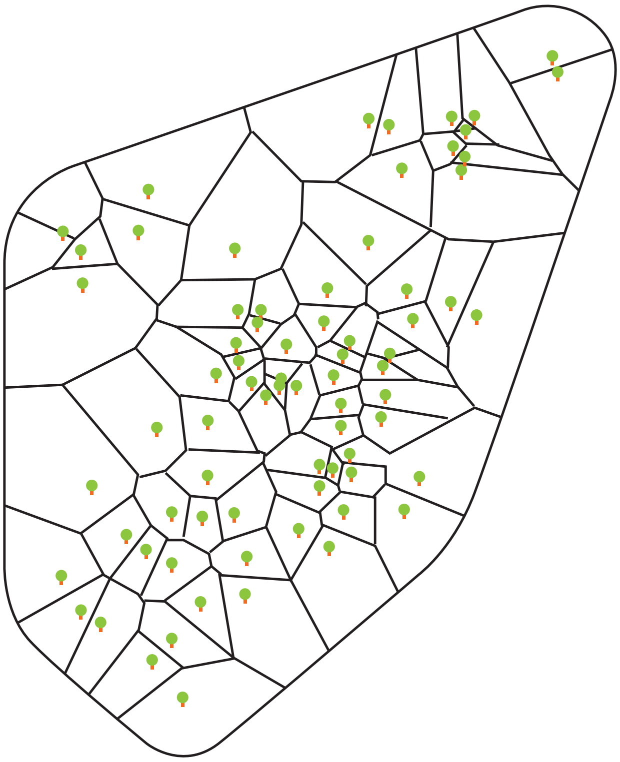
Thiessen polygons (or Voronoi diagrams)

Another measure of centrality that can be performed by GIS is the creation of proximal polygons, better known as Thiessen polygons[180] or Voronoi diagrams. Using this method, users can input point data and then use the GIS software to generate polygons that surround each of the points. Figure 7.14 shows an example of the polygons created

[180] These polygons are named after Alfred Thiessen, who in 1911 devised a method for best assigning single data values (in this case to rain gauge readings) to areas on a map where data collection points are highly irregularly placed.

by a Thiessen polygon operation. This type of operation can be useful for delineating territories or regions of influence. Note that the measure of centrality being established here is an answer to the question "From where I am situated, which is my closest central point?" So, the central point is likely to represent some kind of service centre, or the points of the data set could represent seafood distributors, and the Thiessen polygons might show their potential market areas based on distance from the distributor.

FIGURE 7.14
An illustration of Thiessen polygons



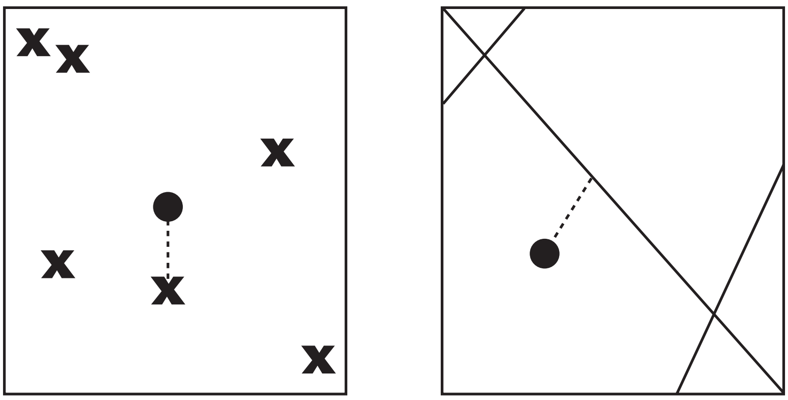
Source: Chou (1997).

Thiessen polygons are not intended to have a regular shape or to form a tesselation of identical shapes. They are intended to divide the landscape into polygons around a set of points, with each polygon constructed around a single point in such a way that all the area within that polyon is closer to that point than to any other point. Figure 7.14 shows that there is no place within any of the polygons that is closer to another point than it is to the polygon point. The only time Thiessen and/or Voronoi polygons would have a constant size and shape would be if the points were distributed in a regular array.

7.5.2. Measures of proximity

Proximity analysis is concerned with the distances between different features, and the numbers of a feature *a* that may be near to a feature *b*. GIS analysts may often want to know the nearest feature to some other feature (such as the nearest market to a fish farm, or the nearest fishery to an oil spill). Figure 7.15 illustrates the basic "nearest feature" proximity operation, and it is easy to see how this function can be expanded to identify all the features within a specified distance, or perhaps

FIGURE 7.15
Examples of the point-to-point and point-to-line proximity operations



the nearest x feature to a specified point. Typically, users may perform a variety of proximity analyses as a step in their overall analysis process, meaning that the results of this type of analysis may generate data, often displayed in the form of tabular or graphical output, for use in other analytical operations or GIS output.

Quadrat counts or points and/or lines in polygons

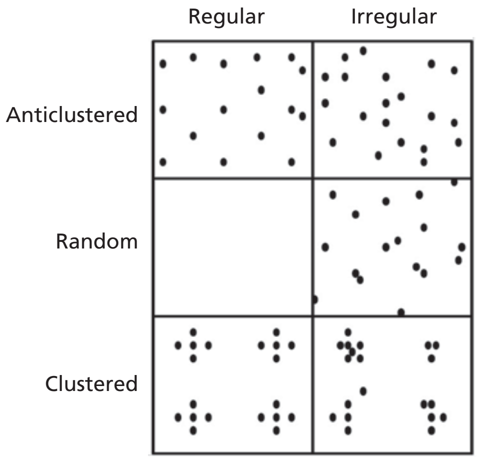
The measurement of proximity differs between feature types. Proximity between polygons can be assessed by calculating the shortest distance between polygon perimeters or by computing the distance between the centroids of the polygons (see Section 7.4) (Chou, 1997). The distance between points is established by simple measurement between points.

One of the issues with using any "count within polygon" method is determining the size and placement of the polygon being used.[181] Count operations make use of buffering techniques, so if the user wanted to know "How many fish farming operations are within x kilometres of a fish processing or fish meal plant", then a buffer would be drawn at the required distance around the plant so that the count could be made by the GIS.

Point pattern (or nearest neighbour) analysis

Another type of spatial proximity analysis is examination of the point pattern of the data, with a view to gaining insights into underlying causes of these patterns. These points could be fish hatcheries, cities, etc., and they can represent features of varying scale. As shown in Figure 7.16, point patterns can be classified as being regular or irregular (organized or disorganized) and these could be subdivided into anticlustered (or uniform), random or clustered.[182] In practice, the points representing the distribution of any single object can vary from being absolutely regularly spaced through to being absolutely clustered. However, these patterns are very much determined by the scale or resolution of the study, i.e. what appears to be a random distribution at a very large scale (small area) may in fact be a clustered distribution at a small scale (large area).

FIGURE 7.16
Possible spatial distribution patterns in point data



Source: Cole and King (1968).

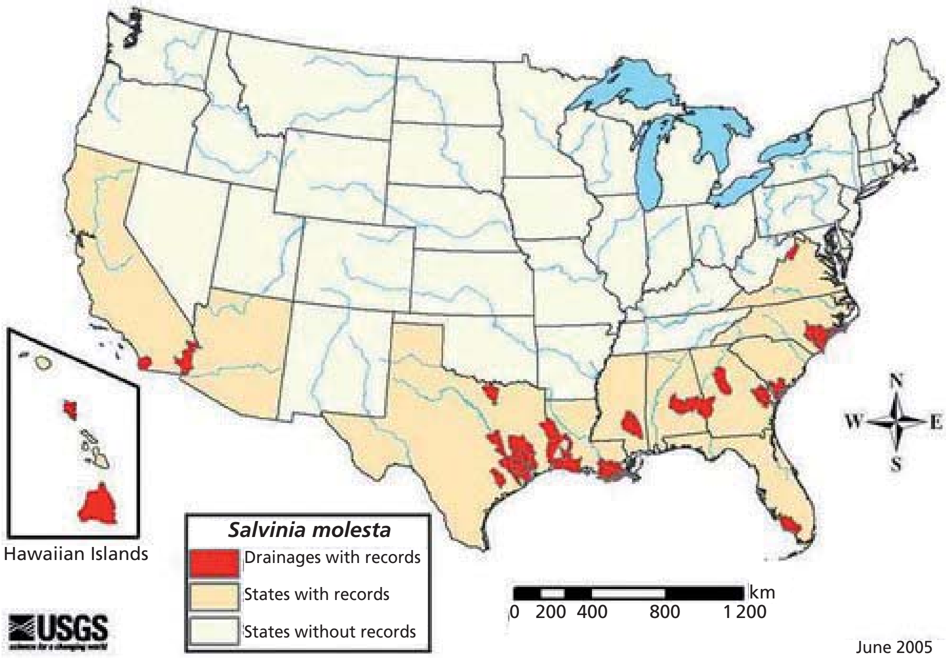
[181] This is part of the family of "modifiable areal unit" problems highlighted by Openshaw and Alvanides (1999) whereby GIS (and other software) output results can be severely compromised according to factors such as the spatial scale of study, the size of aereal units, the number and position of class boundaries, the location (placement) of polygons or cells on the map, etc. See also Reynolds (1998) available at www.badpets.net/Thesis/index.html.

[182] The box "Random/Regular" in Figure 7.16 is blank because it would be impossible to have a "Regular/Random" point distribution pattern.

Figure 7.17 shows that the occurrence of the invasive pond weed *Salvinia molesta* in the United States of America appears to be clustered mainly in the south-eastern portion of the country, but, obviously, an examination at a local level would suggest that the aquatic weed is more randomly distributed.

Most GIS are able to perform a statistical test on point distributions called the "nearest neighbour analysis", the result of which gives a numeric value giving a relative indication of the degree of regularity, randomness or clustering of the points within a specified area, plus a probability value indicating whether the pattern is statistically different from a perfectly random distribution. This analysis can be performed using either vector- or raster-based GIS functionality. A look at the distribution of fish ponds in many areas shows a fairly high degree of clustering, and this is likely to be around areas that have good soils for water retention, or where fish food sources are available or close to fish processing facilities. If marine species are found to show clustering in an area, it can be invaluable to try to ascertain what independent spatial factor is the cause of the clustering.

FIGURE 7.17
The distribution of the invasive weed *Salvinia molesta* in fish ponds in the United States of America

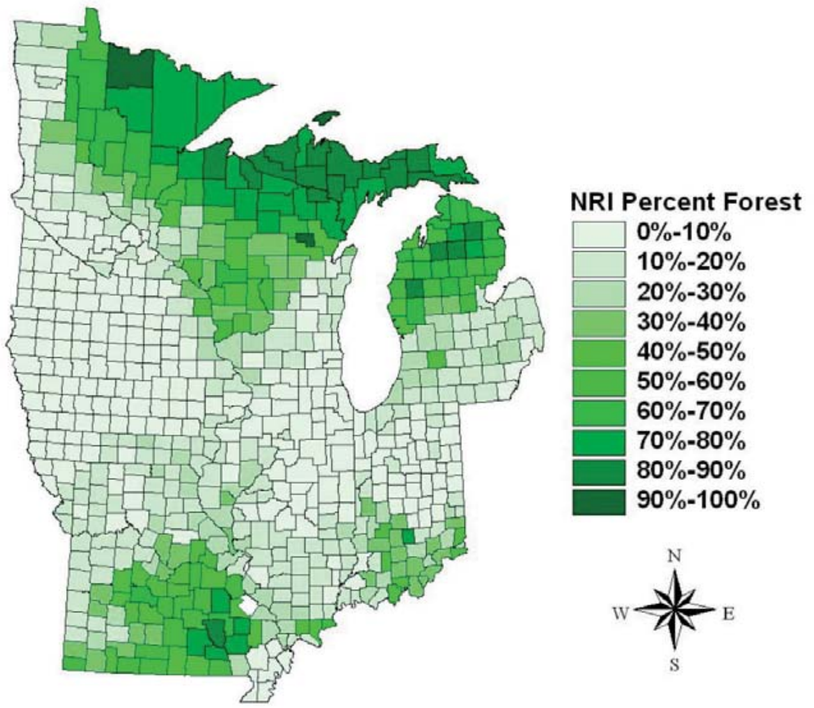


Source: Toledo-Bend Guide (2005).

Contiguity and spatial autocorrelation

In a similar way to point distributions, polygons may also be distributed in various patterns that range from uniform through random to clustered. However, with polygon distributions there is more interest in attempts to measure the dispersion of polygons in terms of their contiguity or spatial autocorrelation. Contiguity refers to whether polygons showing the same type (or classification) are more or less likely to be adjacent to one another. Consider the forest cover shown in Figure 7.18. Here, it is clear that counties having similar proportions of forest cover are frequently contiguous (next to) counties having the same proportion of forest cover. The other extreme would be the pattern seen on a chessboard where none of the black or white squares share boundaries with a similar colour. So a greater degree of contiguity means that a much more regular polygon dispersal pattern could be mapped. DeMers (2008) describes how a useful measure of contiguity is the "joint count statistic", which indicates either how many similar polygons are co-joined or the relative number of polygons that are contiguous within a defined area. Contiguity is important in the natural world because it can indicate how easy it is for plants or animals to move or migrate within favourable environments.

FIGURE 7.18
Distribution of forest cover by county in the north central United States of America



Source: Rutherford (2012).

Similar to a measure of contiguity, most GIS software can provide a measure of the similarity between neighbouring cells or polygons, i.e. by use of the Moran or Geary statistic. This measurement is called spatial autocorrelation. For example, elevation data tends to have high spatial autocorrelation, e.g. the elevations at two locations close to each other tend to be similar.

Using Figure 7.18, the question could be posed "What proportions of cells having 40–50 percent forest cover are adjacent to polygons having the same density of forest cover?" Clearly, the spatial distribution of forest density shows a high positive degree of spatial autocorrelation, i.e. polygons that are close to each other tend to have similar forest densities and, therefore, the landscape has a locally homogeneous forest distribution. When such a relationship is noticed, then it is often useful to look for the underlying causes. In the case of forest cover, it is likely that neighbouring counties tend to share similar climatic and soil conditions, which directly affect forest density, though it might also be related to the fact that the land may be unsuitable for alternative uses. As indicated earlier, extreme negative spatial autocorrelation would be exhibited by the colour pattern of squares on a chessboard. Like the nearest neighbour analysis, measurements of contiguity or spatial autocorrelation are scale dependent.

7.5.3 Measures of statistical surfaces

In this section, the concern is with measuring any of a range of so-called "statistical surfaces". A statistical surface can be thought of as any section of the earth's surface (including the seabed) that has an interval or ratio numerical value attached to it indicating a value on the z-axis (vertical). Surfaces can be mapped and come in two general forms – those relating to: (i) the human environment; and (ii) the physical environment. Measurements of the z-axis of the human environment might include average incomes per unit area, number of people per household, number of fish markets per districts and rates of fish consumption per country. Measurements of the physical environment might include height above sea level, mean air temperatures, depth to the water table and ocean depth. All of these measurements (and countless others) can be measured and mapped.

All of these examples can also be described as being either "spatially continuous" or "spatially discrete". Spatially continuous data are those where a value can be allocated to any place, and values might continuously vary over space. These data sets are usually best represented by rasters. For example, it is possible to measure the ocean temperature at any location, so an infinite number of continuous measurements could be made. Discrete data, by contrast, only occur where the object (factor) being measured is located, e.g. the postcode, the household and plant types. These types of data can be represented by either raster or vector formats, but the vector format is used more often because it precisely defines the area in question.

These statistical surfaces showing the distribution of any feature can be relatively smooth or very rugged. For instance, a surface showing air temperatures or ocean water salinity is likely to be very smooth because these factors only change very gradually through any spatial area. By contrast, a mapped surface showing the distribution of a single fish species might be very rugged, with surface values varying significantly over short distances. Although this statistical surface data can be used in a range of GIS analyses, two main kinds of analysis are specifically examined: interpolation and trend surface analysis.

Interpolation

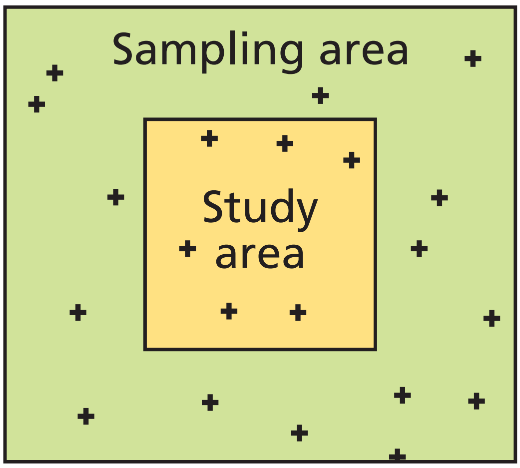
Interpolation is the process of estimating values of properties at unsampled locations based on known values in surrounding areas (existing sampled observations). Because of the usefulness of estimating missing data values, it is important that GIS has the tools to estimate these.

Interpolation is based on the fact that it is possible to predict or estimate missing values inside a set of numbers by using numbers on either side of the gap. Interpolation can be applied to spatially continuous surfaces and it generally relies on spatial autocorrelation, i.e. the idea that things closer together are more similar than things further apart. For example, to make a temperature map it is not likely that there will be sample points (observations from weather stations) at regularly spaced intervals, but it is likely that nearby temperature readings will be very similar to each other. A good sample set for interpolating a surface should have enough points to represent the important details of the surface. The sample set should also be able to represent changes in the surface as well as the dips and troughs of the surface. There are several different interpolation methods, or, to be more precise, interpolation algorithms that the software implements to create these estimations.

Interpolation may be described as being either "global" or "local". Global interpolation methods use a single mathematical function for every available sampled point in a region to create the estimation of any cell or point value it is looking for. This type of interpolation is typically used if values are fairly consistent over the area being studied. However, when creating, for instance, an elevation surface (e.g. a contour map) using point sample data, there may be features in the real world that could skew the estimation of the surface. Thus, the presence of a large canyon a short distance away could unduly influence any sample values generated if it is taken into account. To avoid this problem, the "local" interpolation method uses only a local sample of the available known points to complete the estimation. Therefore, the use of a local method that excludes distant irrelevant values produces an interpolation result that more closely resembles the real world.

It is the responsibility of the user to understand the nature of the data being collected to know whether or not a global or local method would produce the most accurate results. It is also important to note that the samples used to interpolate any surface should extend well beyond the area to be estimated. Having the sample data extending outside of the study area decreases what is known as the "edge effect", i.e. without sample data outside the study area the values estimated along the edge of the study area are likely to be skewed. Figure 7.19 shows an example of properly collected samples in relation to the study area to be interpolated.

FIGURE 7.19
Correct sample point strategy when using interpolation methods within a defined study area

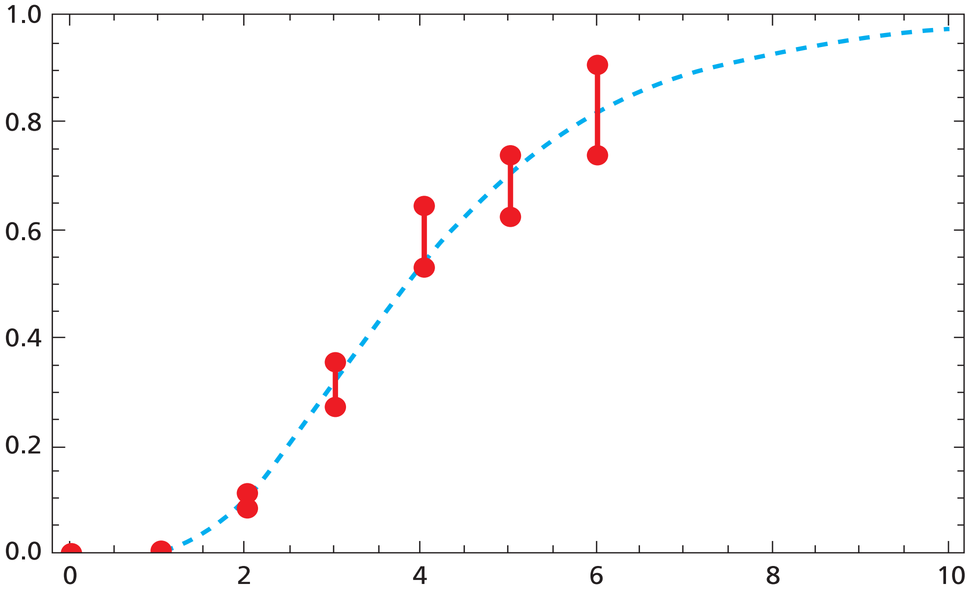


Another way of classifying interpolation methods is by whether they use linear or non-linear techniques. Linear methods of interpolation assume that values across a surface change in a regular arithmetic progression, e.g. 10, 20, 30, ?, 50, 60…etc., and it is easy to interpolate the missing value here as "40". Values across a surface rarely change in an exact form, but linear interpolation methods might be the safest method to use when there is any degree of uncertainty.

Other distributions may change in a logarithmic or exponential form (Figure 7.20). From this figure, distributions can be interpolated from the best-fit line that for a value of 4.5 on the "x" axis, the value on the "y" axis would be 0.6. A final interpolation method illustrated here is that known as inverse distance weighting. This method assumes that those known sampling points that are located nearest to a missing data point will probably have more influence in determining any missing value than known points located at a distance. So, in calculating a missing value, the near points are allocated a weighting that is higher than those that are further away. An example of the use of inverse distance weighting interpolation is shown in Figure 7.21, which shows estimates of commercial values of all groundfish species for all locations in the New York Bight, United States of America. Here, the interpolation was based on the known values of groundfish caught at each haul site (blue dots) and from these values weighted interpolated estimates could be obtained for the whole exploited groundfish marine area.

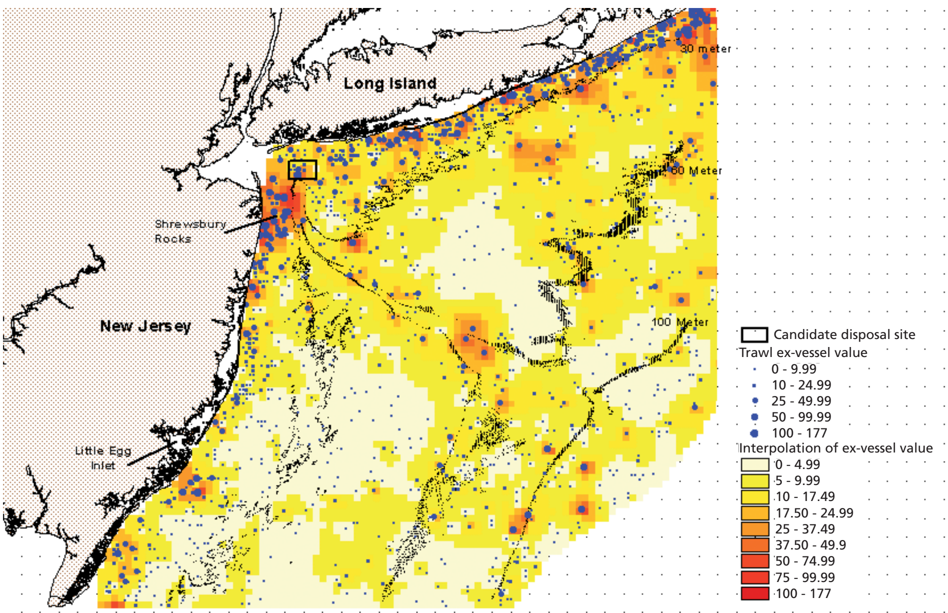
There are a number of other more specialized interpolation methods that rely on complex mathematical procedures that go beyond the scope of this technical paper, for example, kriging and the drawing of splines. Some of these are illustrated and discussed at Spatial Analysis Online (www.spatialanalysisonline.com/output). Most

FIGURE 7.20
Interpolation based on a sample appearing to show an exponential distribution



Source: Stack Overflow (2012).

FIGURE 7.21
An inverse distance-weighted interpolation of the commercial values for groundfish in the New York Bight, United States of America



Source: Nuckols III (2012).

GIS packages will have several interpolation methods available for use with point, line or area data. For more information on interpolation, see Dubois (1998), Longley *et al.* (2005a), de Smith, Goodchild and Longley (2007) and DeMers (2008). For more advanced texts on different types of kriging, see Chilès and Delfiner (1999) and Cressie (1993).

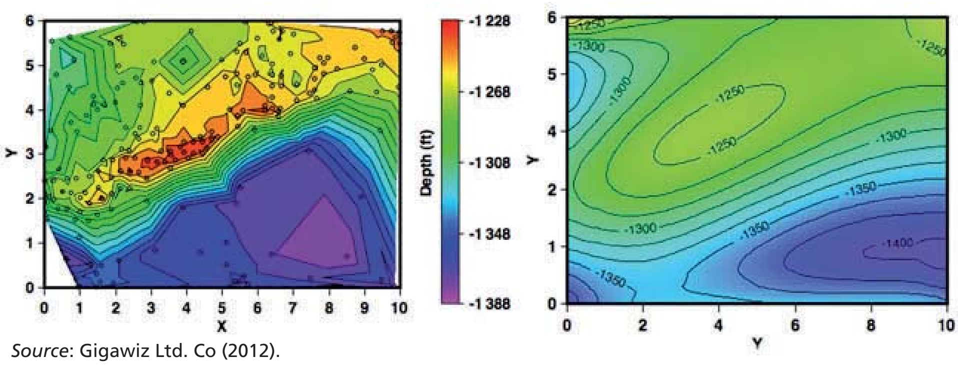
Trend surface analysis

Trend surface analysis is a frequently used global form of interpolation. The term "global" in this case does not mean that it covers the entire globe or is used all over the world, but rather that the entire landscape being analysed is described by a single equation or polynomial model.[183] This is in contrast to "local" interpolation techniques (such as inverse distance weighted, splines and kriging, mentioned above), which interpolate the surface at any location based on data points in the nearby neighbourhood. Local methods will use a different set of data to interpolate any point in the study area, while global methods use all the data to generate a single equation that describes the entire study area.

The trend surface method creates maps that may be used to identify general patterns of regional trends without being skewed by localized anomalies that often have no overall pattern. A way to envisage the trend surface is to think of it as the three dimensional equivalent of the conventional "best-fit" line, which may be drawn through a two dimensional set of data points. However, instead of a single line being drawn, a whole "surface" is drawn based on a polynomial model.

For example, suppose that detailed quantitative data are sampled allowing for the mapping of a fish species throughout a regional sea. For mobile species such as fish, each individual data sample is likely to vary, perhaps quite significantly, between neighbouring samples. When mapped, the data might look highly irregular and the map might mask underlying trends. However, through the use of trend surface analysis, it is possible to obtain a generalized map for the regional sea showing a broader trend of the species distribution. For most species, this would show a high fish distribution in areas where habitat conditions were favourable and the map might show declining fish quantities with distance from the highest count area(s). It is frequently useful to compare the trend surface map with the original data sampling map so as to, for instance, compare the differences in recorded fish density at any x, y location on the maps, or to identify areas where fish densities are seen to be particularly high, i.e. identifying anomalous fish numbers. Because fish are constantly on the move, it is quite likely that a trend surface map of fish distributions is more reliable than any actual sampling made on a particular day. Figure 7.22 shows an application of trend surface analysis to sea-water depths. The left-hand map illustrates the seabed depths calculated from the numerous sampling points shown. The right-hand map shows the overall trend of sea depths in the same area. Trend surface mapping can easily be accomplished by most GIS. Details of how it is undertaken are not discussed, but further information can be found in Lo and Yeung (2002) and Heywood, Cornelius and Carver (2006).

FIGURE 7.22
A trend surface to show the general trends of sampled water depths



Source: Gigawiz Ltd. Co (2012).

[183] For details on polynomial model, including examples of alternatives to polynomial trend analysis, please refer to Chapter 13, Section 2 of Legendre and Legendre (1998).

7.6 NETWORK AND SPATIAL INTERACTION ANALYSES

In this section, attention turns away from an examination of phenomena that are distributed over continuous surfaces, concentrating instead on potential GIS analyses that focus on linear patterns in the landscape. These analyses are frequently described as network analyses, though this section also includes other considerations of spatial allocation within networks, such as gravity modelling, which is not network analysis per se but which is usually dependent on networks. Section 5.8.4 explained in some detail how networks are modelled for GIS purposes, and it also pointed out that networks could represent a wide array of routes or pathways. Figure 5.18 illustrated a typical network structure consisting of links and nodes[184], information on these being retained in the database management system of a GIS through the use of topological tables. In this section, spatial interaction via gravity models, routes and pathways via forms of connectivity analyses, spatial allocation and service areas, plus some analyses of river and stream networks are described. Users of network analysis should be aware that not all GIS packages have the tools necessary to work with networks. For example, Environmental Systems Research Institute's (ESRI) ArcGIS has a geometric network data model, but it is primarily for use by utility companies, and ESRI's ArcHydro data model is designed for hydrologic modelling (mainly river networks).

7.6.1 Gravity models

In a topological network of links and nodes, it might be assumed that each node is of equal value or importance. While for some networks this might be true, in the majority of cases this is far from the real world situation. If the case of towns or cities is considered, then it is clear that larger urban centres are likely to provide more shops, jobs, markets and other facilities. Similarly, larger lakes are likely to attract more wildfowl or fishers. It is easy to envisage that a hierarchy can be produced that assigns a value to town nodes or to lake nodes according to their size or to their "attraction capacity". The value may be in terms of population, or number of shops or number of boat-mooring places, etc., and the higher the value assigned, the greater will be the "gravitational pull" of any node.[185] Effectively, this means that people are usually prepared to travel further to get to a larger "node" because that node is able to offer a greater range of services or other attractions.

Figure 7.23 shows a large central place (G) with a population of 55 000. It is surrounded by various towns (A to F) that have populations varying from 7 000 to 30 000 and that vary in distance from the central place between 13 and 44 kilometres. Most GIS contain algorithms that can calculate the likely number of people who will utilize the facilities in the larger central place and the likely break-even distance threshold between each town and the central place. By linking the six distance thresholds, it is possible to derive a market or service area that surrounds the central place. Calculations to establish the market area can be simply based on distance, but there are many other calculation methods. For instance, it could be based on travel times,travel costs, the number of shops in each urban area or on the specific services offered. From a fisheries or aquaculture perspective, this form of analysis might be useful in detecting the optimum location for fish processing plants, i.e. relative to the disposition of aquaculture production, or maps such as Figure 7.21 could compare values of groundfish at different ports relative to the distance necessary to travel to fishing grounds. Clearly, what has been described here is a simplification of the real world, because in reality there might be many other factors that influence the interactions between centres.

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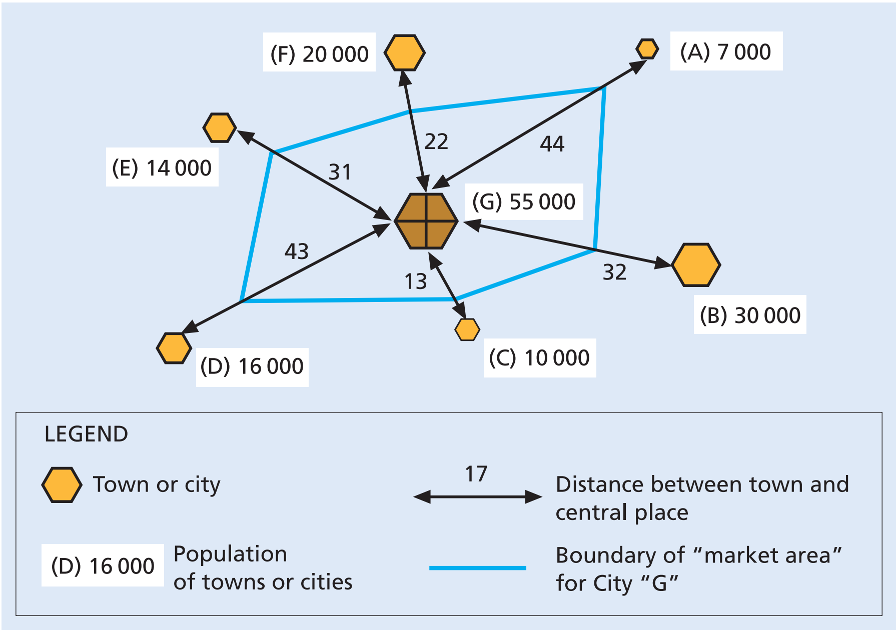
[184] Links and nodes are described in section 5.8.4.

[185] Gravity models utilize Newton's law of gravity, which states that the force of attraction of two bodies is proportional to the product of their masses but inversely proportional to the squared distance separating them.

FIGURE 7.23
Likely market area for city "G" based on calculations using a typical gravity model within a GIS



7.6.2 Optimum routes and pathways

There are a number of different types of network analyses that can be performed relating to optimizing routes along networks or pathways, and these are sometimes described under the general heading of "connectivity analyses". The main types of network analyses are described as follows.

Shortest path analysis

Recall from Section 5.8.4 that routes or pathways can comprise not only transport routes such as roads, rail, air and tram, but also pipelines, cables, sewers, electricity grids, etc. Shortest path analysis aims to find the quickest or shortest route between two nodes (or which have the least impedance, as explained in Section 5.8.4). This is the type of analysis used when consulting Web-based travel planners or when getting directions from an in-vehicle navigation system. The analysis, which is based on a network such as Figure 5.18, uses an algorithm that finds the best route along a network from an origin to a destination (Fu and Rilett, 1998). The algorithm looks at the topological table associated with the network that details any impedance that might be found between two nodes, and the software looks at all possible routes between nodes to determine which has the lowest aggregate impedance values. For instance, using Figure 5.18, it is possible to easily calculate that to get from node "B" to "F" there are three apparently logical route choices, but each would have total impedance values as follows:

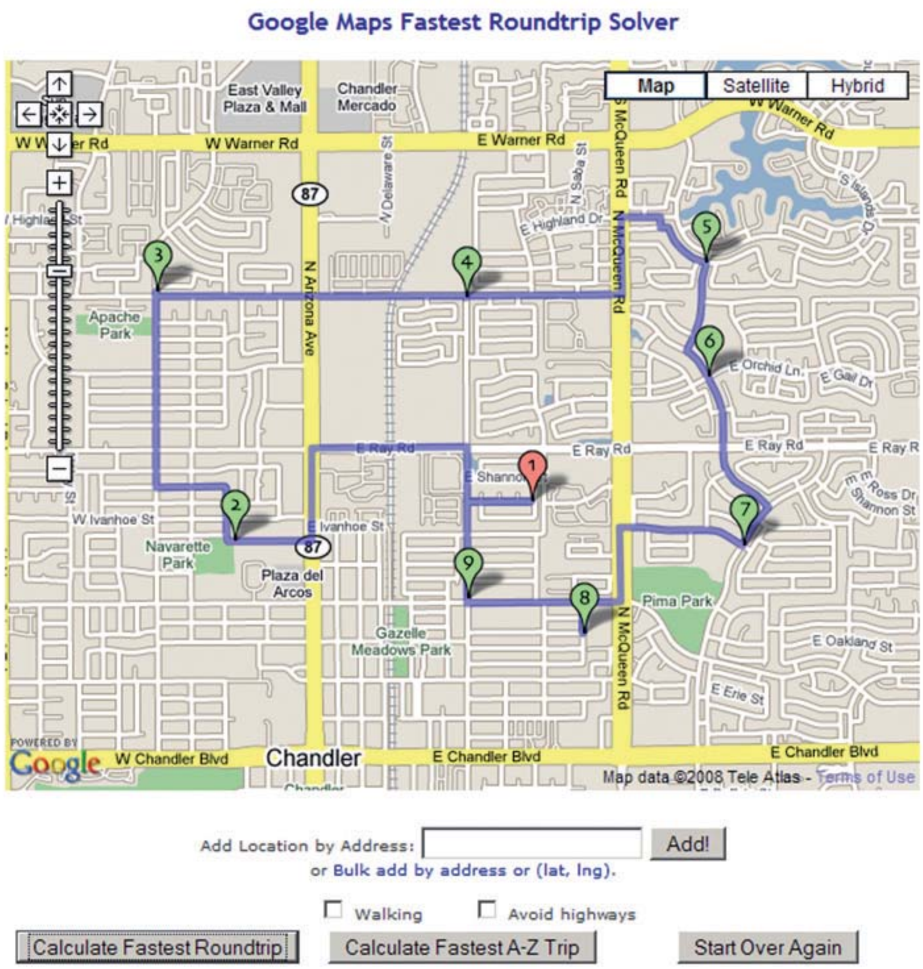
(i) Route B, A, C, G, F = impedance values 4 + 5 + 3 + 4 = 16.
(ii) Route B, D, C, G, F = impedance values 3 + 2 + 3 + 4 = 12.
(iii) Route B, D, E, F = impedance values 3 + 7 + 5 = 15.

From these calculations, it can be seen that the second choice above would seem to offer the best option because it has the lowest total impedance value, in this case aggregate travel time. However, impedance can take many forms, so while option (ii) might be preferable in terms of the lowest cumulative impedance, if the impedance were changed to reflect public transport costs or actual distance travelled, then this route might not be the cheapest, shortest or the quickest.

The "travelling salesman problem"

Closely linked to shortest path analysis is the so-called "travelling salesman problem". For example, numerous delivery companies are required to make x number of deliveries per day, delivering to centres (nodes) that may be widely scattered. Most GIS network analysis programs have the capability of working out the optimum delivery route taking into account any desired set of impedance values. From a fisheries perspective, it might be extremely useful to establish the optimum daily route for the collection of landed fish catches. There is now an interactive Web site (http://gebweb.net/optimap) where users can utilize Optimap, which is linked to Google Maps, in order to calculate any optimum round-trip problem involving visits to a maximum of 24 locations. Figure 7.24 gives an example of the output from Optimap where, from a start location at "1", nine sites have been visited using the shortest possible routeway.

FIGURE 7.24
Illustration of the travelling salesman problem solved by the use of Google Maps in Optimap



Source: Free Geography Tools (2009).

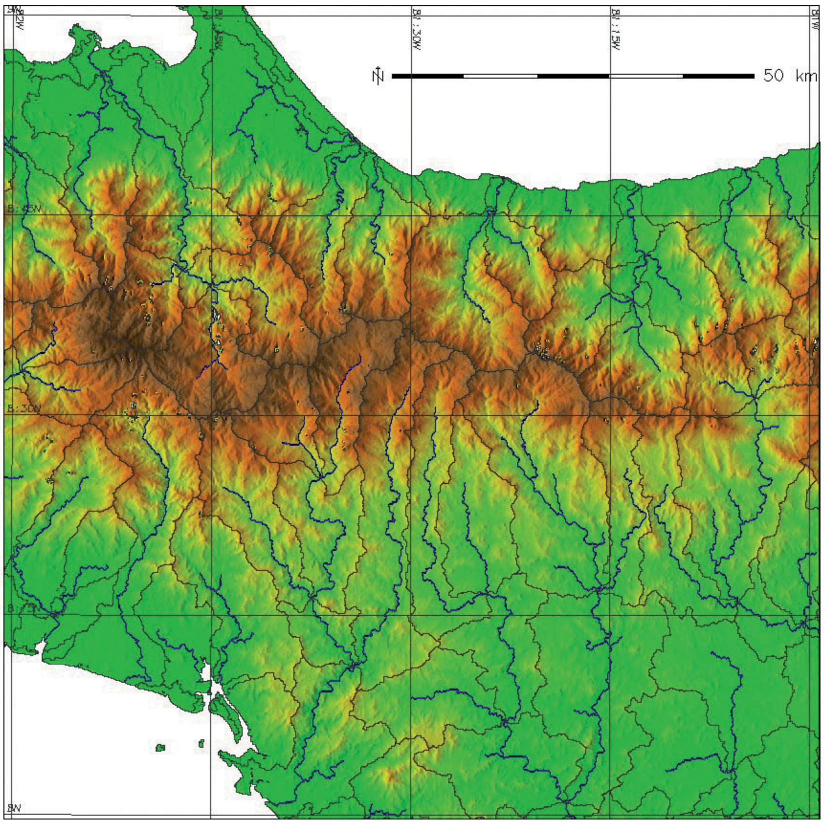
Drive time analysis or service area definition

It is frequently useful to map the region that is within a certain drive time of some central location. This type of analysis is commonly done to determine the most efficient placement of such locations as commercial businesses or emergency response services. Hospitals can use this information to determine the likely number of patients residing within their service areas. If fish farmers make direct deliveries to customers, they could calculate their potential customer base by identifying the region (service area) that is within a 60-minute travel time from their farms. From any given point on the network, a GIS can calculate the likely travel distance achievable in a given unit of time, or alternatively, it can spatially distribute a network of service centres in an efficient manner.

7.6.3 River and stream networks

Figure 7.25 provides a vector cartographic illustration of an oriented network, in this case the stream networks in a portion of the central part of the Republic of Panama. Here the landscape is dominated by a dense network of streams that generally radiate outwards from a core highland area. Given this stream network, and working in either raster or vector formats, a wide range of different modelling investigations can be accomplished, as is shown in Box 7.5. All the modelling described can be directly relevant to both inland fisheries and to aquaculture site location considerations. For instance, with respect to detecting flood storage areas, it can be envisaged that a similar modelling process can be used to determine optimum sites for the building of dams or reservoirs. An increasing proportion of the latter are likely to be utilized for fisheries or aquaculture, especially if water quality can be maintained.

FIGURE 7.25
The stream network in a portion of the central part of Panama



Source: Mitasova (2006).

BOX 7.5
Examples of directed (oriented) network modelling relating to rivers or streams

The following network modelling examples can be mostly accomplished using either vector or raster data structuring.

- **Calculating flow direction and water accumulation –** Rasters containing elevation values (i.e. digital elevation models, or DEMs) enable the GIS to calculate water flow direction. By using known rates for a particular rainfall event and geographic area, then it is possible to calculate approximate water concentrations along stream stretches or at particular points on the network.

- **Deriving stream catchments –** Raster DEMs allow river water catchments to be delineated, i.e. as connected high points between basins.

- **Detecting flood storage areas –** Using both triangulated irregular networks (TINs) and stream network information, areas with the potential for holding excess flood waters can be delineated. With increasing urbanization along rivers, this is more frequently a problem that needs addressing

- **Probability of flooding –** Again, with increasing population pressures and changed rainfall patterns, there is the need to identify which areas along a river are likely to be flooded. This is known as inundation modelling.

- **Rate of pollution dispersal –** If known quantities of point-source pollutants enter a stream, their trajectory and likely dispersal rates can be calculated. Similar modelling can be done relating to sediment dispersal.

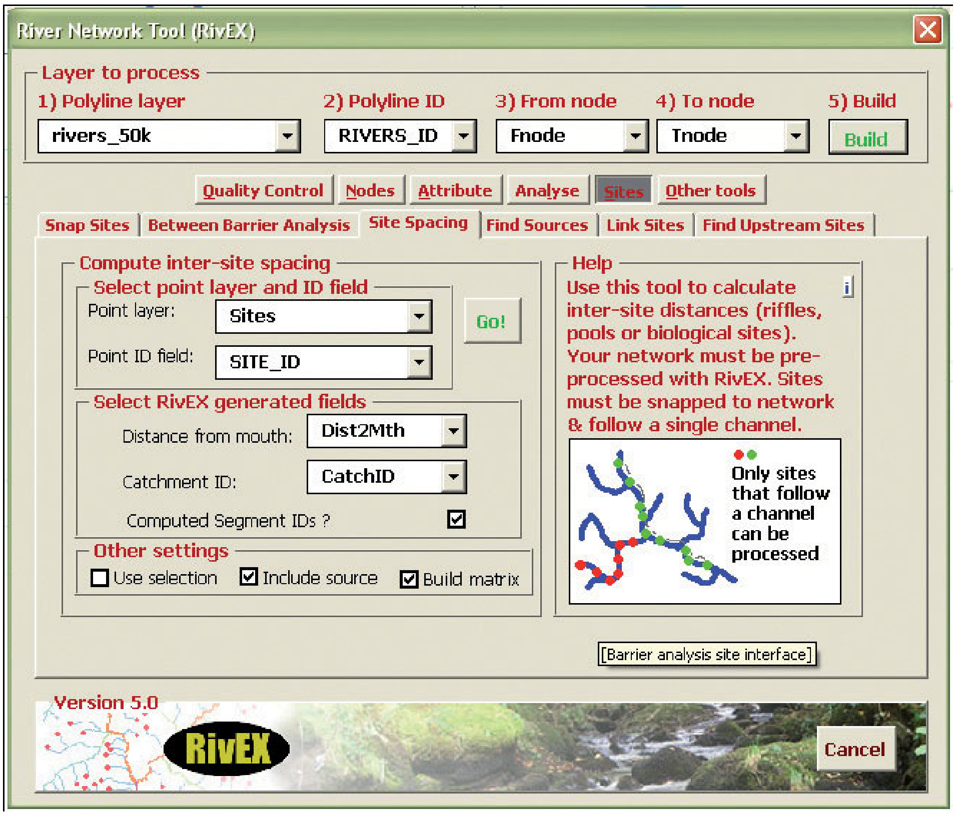
- **Managing water extraction –** Knowledge of river networks, water flow rates and water demand allows for the GIS-based management of water extraction.

- **Creating stream networks –** If digital data on stream networks are not available, then TINs or DEMs can be used to create the likely stream network.

- **Peak flow prediction –** Given a storm event over a part of a river catchment, then the peak flow in a stream can be modelled in terms of time and location.

Most proprietary GIS packages available today can perform a range of network analyses, but if network analyses are going to be important for future anticipated GIS work, the user should check the exact functionality before investing in the software. For example, ESRI's ArcGIS includes specialized tools designed specifically for hydrologic networking. There is also a wide range of separate network analysis software available online that can be linked to GIS. See Spatial Analysis Online (www.spatialanalysisonline.com) and Spatial Hydrology (www.spatialhydrology.com/software_hydrostat.html) for two gateways to hydrologic tools listing approximately 100 software packages for modelling hydrology. Examples of low cost or free GIS-based river analysis software capability are: www.rivertools.com, http://grass.itc.it and www.rivex.co.uk. Figure 7.26 provides a screen shot from RivEX Version 5.0 showing one of the many capabilities that the software provides. For more information on network modelling, see Lo and Yeung (2002), Vieux (2004) and de Smith, Goodchild and Longley (2007).

FIGURE 7.26
Screen shot of the RivEX GIS software for modelling stream networks



Source: RivEX (2011).

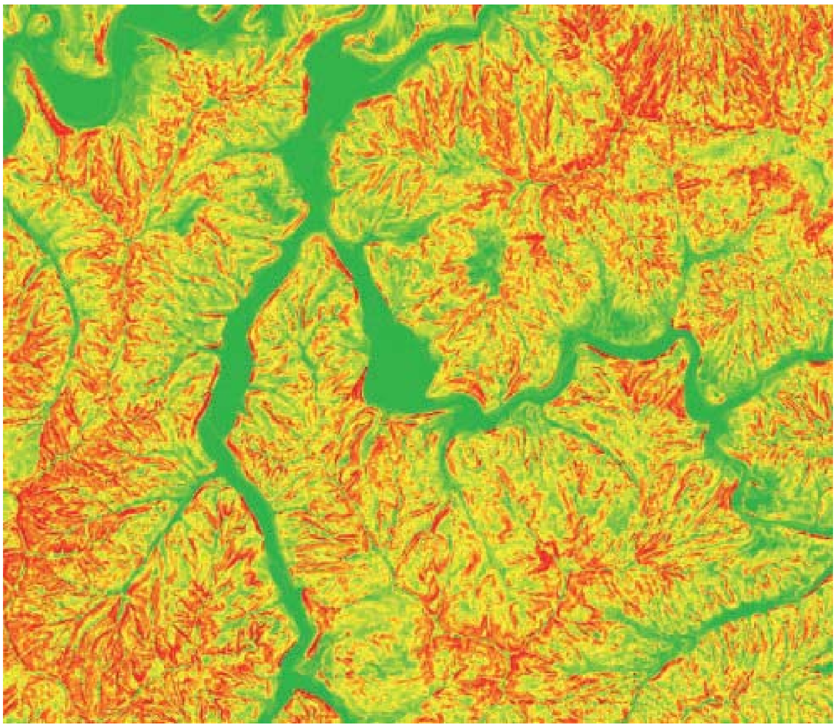
7.7 TOPOGRAPHIC SURFACE ANALYSES

Topographic surface analysis is concerned with describing and accounting for various attributes associated with the shape of the earth's surface. To perform topographic analyses, various types of data must be collected and stored, and these typically include point elevations, angle of slope, aspect of slope, curvature of the landscape and hillshades, through the use of triangulated irregular networks (TINs) or digital elevation modelling (DEMs). For more information on the TINs and DEMs that form the basis of topographic surface analyses, see Section 5.8, which also gives the range of analyses that can be performed by GIS. Here, the range of analyses are classified under: (i) gradient (slope) and aspect; (ii) visibility (viewshed) analyses; and (iii) watershed and river flow analyses. This section does not consider contour derivation (interpolation) as this has been reviewed in Section 7.5.3.

7.7.1 Gradient (slope) and aspect analyses

Gradient (or slope) is a measure of the rate of change in elevation between points in the terrain (O'Sullivan and Unwin, 2003). This gives the user a percent of elevation change between the points, or the actual angle of the slope, or the ratio of the amount of vertical rise compared with the amount of the horizontal distance between the two points, e.g. a slope could be 1 unit in 10 units. It is also possible for the GIS to "calculate" the slope in terms of its length. Different GIS packages use different algorithms to make their calculations of slope. This type of analysis could be of significant use in seeking areas suitable for aquaculture pond locations, and this is well illustrated in Figure 7.27 where only areas of green shading are likely to be of use for pond locations.

FIGURE 7.27
Illustration of GIS output using slope analysis in an area near Harlan, Kentucky, United States of America

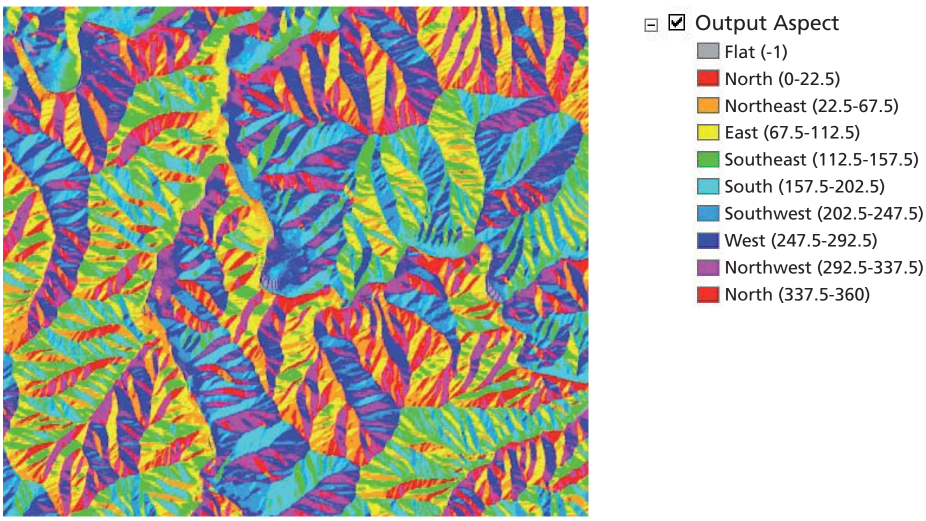


Note: Green areas are flat, yellow are intermediate and red are steep.

Source: Nelstead (2009).

Aspect measures the direction that the slope is facing – also called the slope's orientation. Direction is represented in degrees starting from 0, which represents north, and proceeding clockwise around to 360 degrees. In Figure 7.28, which illustrates aspect, the legend displays both a colour showing the direction which the slope is facing, as well as the compass degrees from north.

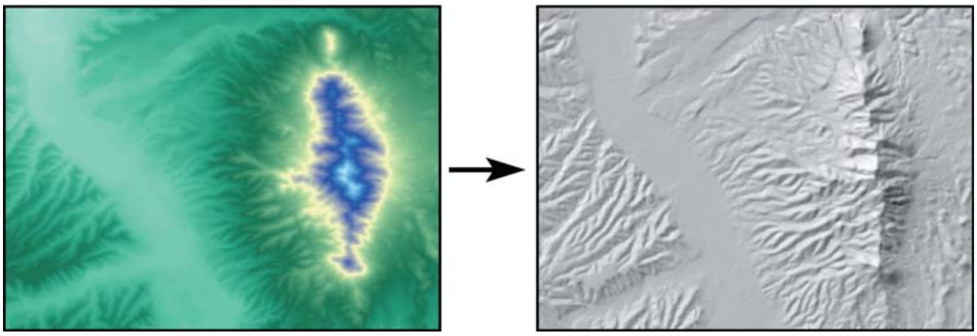
FIGURE 7.28
Illustrating aspect for the same area shown in Figure 7.27



Source: Nelstead (2009).

A variant of aspect representation is that of hillshading (Figure 7.29). Here, the GIS assumes that the sun is in a designated position in the sky (in terms of direction and angle of inclination), and GIS output is obtained showing the areas of the land that would then be in shade or in sunlight. It is clear from the "Hillshade" output map that the sun is shining from a north-west direction – hill slopes facing south-east are the most heavily shaded. Aspect can be extremely important in terms of the amount of solar radiation, wind or rainfall received and the consequent effects on microclimates, habitats, length of the growing season, and so on.

FIGURE 7.29
Hillshade obtained from a raster digital elevation modelling (DEM)



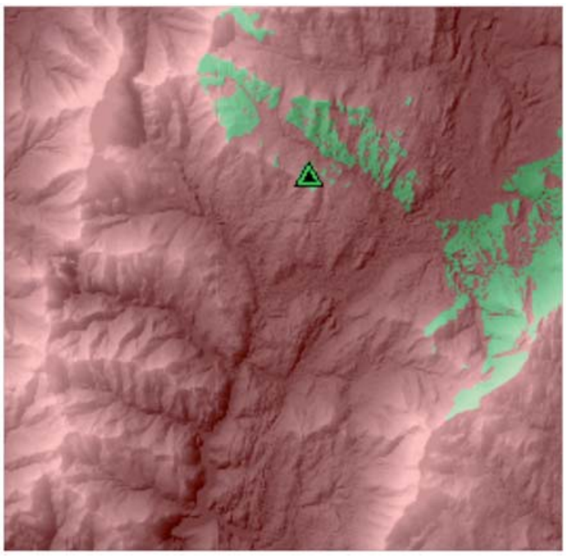
Source: Jenness (2011).

7.7.2 Visibility (viewshed) analysis

Visibility analysis allows the user to determine what is visible from certain locations based on surrounding elevations, such as hills, valleys and mountains. The software does a so-called "line-of-sight" analysis from an observation point to every cell in a raster layer in order to calculate what cells would be visible or not visible from that point. This binary data set makes it very easy to visualize the results of the analysis. Thus, Figure 7.30 shows in green all the areas of a landscape that would be visible from the location indicated by the triangle. Depending on the size of the data set and the number of observation points, a visibility analysis can be time and computer intensive.

Visibility analysis may be very useful for aquaculture site selection. When siting a new aquaculture facility, government agencies may require that the visual impact is kept to a minimum. To do this, the farmer can create a viewshed analysis from various observation points near the proposed site to visualize the potential impact the facility might have on the surrounding area.

FIGURE 7.30
Visibility analysis showing areas (in green) visible from the located triangle



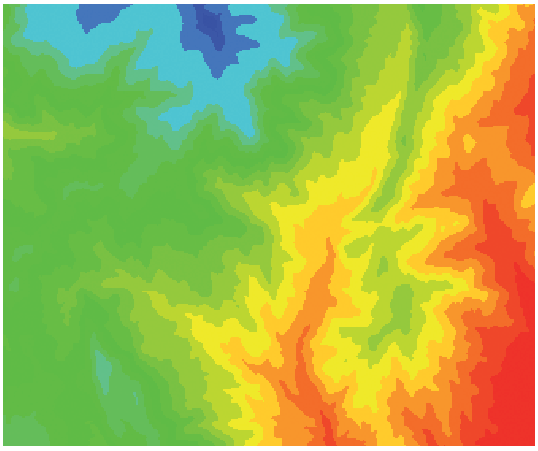
Source: Neteler and Mitasova (2007).

7.7.3 Watershed and river flow analysis

Some modelling relative to water flow has already been described in Box 7.5, but here the basis on which the GIS performs its analyses is described. GIS may be used to examine the characteristics and likely stream flow in river catchments. For workers in inland fisheries or aquaculture, this could be an important area for spatial analysis. The main types of GIS work that can be accomplished include:

- defining water catchment areas (watersheds or river basins);
- determining catchment boundaries;
- determining subcatchments and so-called "pour-points"[186];
- establishing stream networks (or stream ordering);
- calculating likely water flow directions;
- defining likely water flow quantities (or water accumulation);
- calculating stream lengths.

FIGURE 7.31
Raster elevation data in a hypothetical area

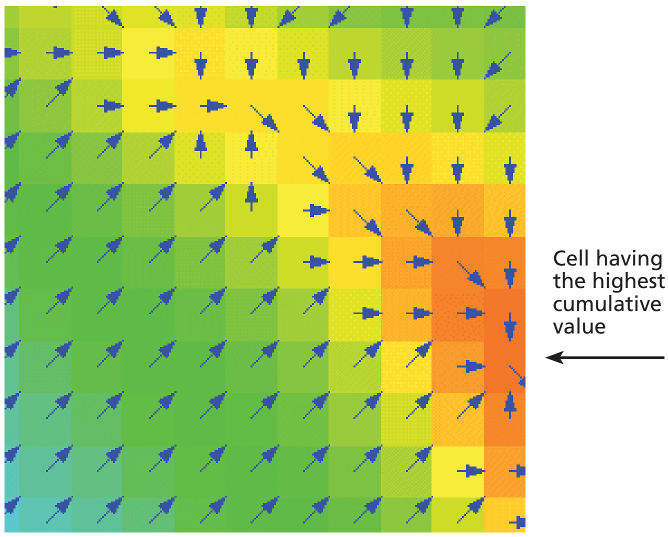


Source: Nelson, Jones and Smemoe (1997).

Examining watersheds mostly involves the use of elevation raster data to determine where water would flow and accumulate given the topography. The broad principles upon which water flow and analysis works are described using Figures 7.31 to 7.33. Figure 7.31 shows a raster DEM with low areas coloured red and higher elevations coloured progressively with yellows, greens and finally to blues at the highest areas.

Given that every pixel will have its own value, and that water will always flow downhill using the steepest gradient, the GIS is able to examine the pixel value for each pixel plus its eight surrounding pixels to determine where rainfall water (or snowmelt) is likely to flow, i.e. the surrounding pixel having the lowest elevation value. Figure 7.32 shows predicted water flow directions for each pixel in an enlarged sub-area of Figure 7.31. Thus, it is clear that water is flowing generally from blue areas towards the red colour pixels. The pixel values allocated to any cell in Figures 7.32 may now relate to the cumulative number of cells through which water has flowed to get to that cell. So, the cell indicated as having the highest value has accumulated (received) water from 113 cells is shown on this map extract.

FIGURE 7.32
Predicted water flow direction across a section of the hypothetical area shown in Figure 7.29

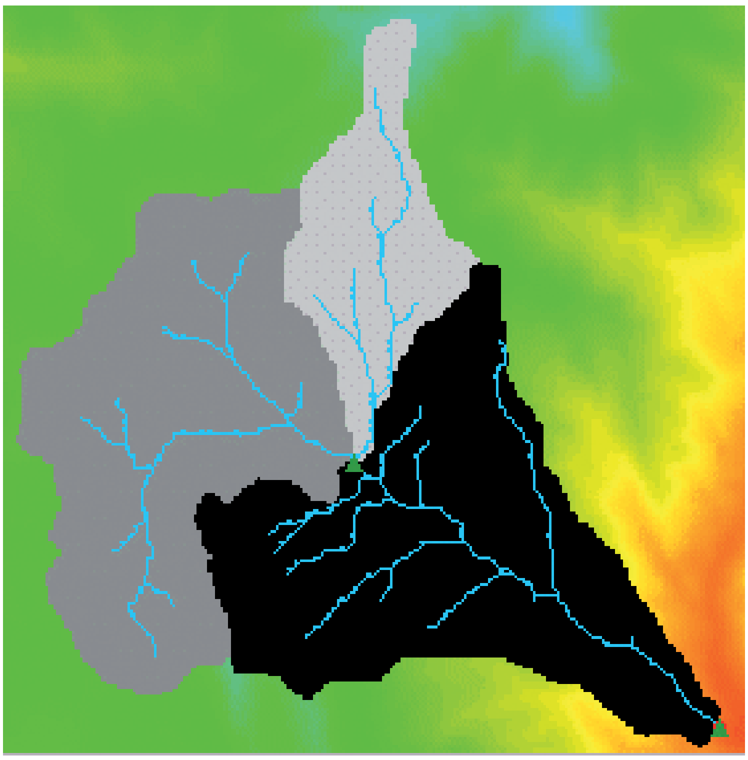


Source: Nelson, Jones and Smemoe (1997).

[186] A "pour-point" is the point where one subcatchment meets the next subcatchment. This will be at the lowest point in the subcatchment.

Where relevant, each pixel will accumulate water from neighbouring higher value cells. Once cells have accumulated water from more than x number of cells (a threshold value), then the GIS can be programmed to start drawing in the likely path of the river.[187] Figure 7.33 shows (in light blue) the likely river network in the main part of the same area as covered by Figure 7.31. It also shows that this particular river catchment can be divided into three main subcatchments, with "pour-points" occurring at the sites of the olive green triangles. At the "pour-point" in the lower right-hand corner, the river depicted clearly merges with a larger river that is not shown but which would be flowing down the valley (red area) sited near the lower right-hand side of the map. The main catchment boundary is also clearly shown. It can be seen that the GIS has produced information that potentially allows any of the bullets listed at the start of this Section (7.7.3) to be evaluated and discussed. The reader may appreciate that this account simply outlines the basics of water flow and river catchment analysis. For further information, see Nelson, Jones and Smemoe (1997), Maidment (2002), Chang (2004) and DeMers (2008). For examples of watersheds analysis as applied to inland fisheries and aquaculture, see the African Water Resource Database (AWRD) by Jenness *et al.* (2007a,b).[188]

FIGURE 7.33
The main river catchment and subcatchments identified by the GIS for the area shown in Figure 7.29



Source: Nelson, Jones and Smemoe (1997).

[187] The value of x will depend upon what size river the GIS operator wishes to consider.

[188] The African Water Resource Database includes some 5.5 GB of data plus a set of data and custom-designed GIS-based tools covering many aspects of inland fisheries and aquaculture. Concepts, application case studies and a technical manual and workbook are also provided.

7.8 CUSTOMIZATION AND SCRIPTING

Even the best GIS will not have every tool and function that the user could want. Most users have questions that cannot be answered simply with the tools at hand and may require a long series of functions strung together. Some questions require complex statistical analysis that simply cannot be answered at all with the available tools.

A good GIS will provide a means for users to create their own functions and tools. This may be a simple macro function. Macros are collections of frequently used commands that are grouped together in a file. Instead of entering commands individually, users can call the macro and the commands stored therein will be executed automatically, and then the user is able to run several tools in sequence without having to set up each tool individually each time. Macro functions are especially useful for repetitive functions, or functions that have to be done on a regular basis. For example, a common function in both terrestrial and benthic habitat analysis is to categorize the landscape by slope position (i.e. find the ridgetops, midslope regions, valley bottoms and flat areas). This process uses a statistic called the Bathymetric Position Index in marine environments and Topographic Position Index in terrestrial environments (Weiss, 2001), and it involves several steps including calculating slopes from a DEM or bathymetric data set, a neighbourhood analysis, map algebra and multiple reclassifications based on multiple data sets. The steps are relatively intuitive and straightforward, but repetitive and tedious and prone to error if done manually. It is much easier to run this type of analysis in a macro.

The most advanced GIS software will allow the user to write sophisticated tools using the most current software programming languages, such as C++, C#, Java, Python or VB.NET. Such tools give users the ability to do any type of analysis on the data, limited only by their imagination and ability to write the algorithms. Many high-end GIS packages have enthusiastic user groups of people who write and share custom tools, and often provide them free online. With experience in GIS it seems that most functions are possible.

An example of a script for inland fisheries is one developed by de Graaf *et al.* (2003) to conduct a linear regression analysis between the number of fishers and the number of gillnets in villages around a lake. Another example is the African Water Resource Database (AWRD) (Jenness *et al.*, 2007a,b). The AWRD includes an extensive collection of custom-made tools[189] to analyse watersheds, surface waterbodies and aquatic species, and includes many additional tools to assist with general statistical analysis, cartography and creating and editing metadata.

[189] Scripts and macros generally just run an analysis. The AWRD tools include many other internal aspects, including graphical user interface (GUI) windows, buttons, graphics and user interface parameters, that make them a lot more sophisticated and user-friendly than simple scripts. The technical name for the functions provided in the AWRD are “tools”, “command buttons” and “dialogs”, and these call a number of background scripts to gather analysis parameters and to run the analysis.

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

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8.1 INTRODUCTION

Aquaculture is a very broad endeavour when considered by environment, techniques, administration and economics, i.e. just to mention a few of its many facets. For example, aquaculture statistics are compiled by FAO by production and value, by environment (marine, brackish water, freshwater), by organisms cultured including fishes, shellfishes, reptiles, amphibians and plants (scientific and common names), and geographically by nation and continent. Additionally, aquaculture cannot be considered as an activity unto itself. For example, it is often associated with fisheries not only in terms of the species that are both fished and cultured, but more closely in terms of fisheries that are aquaculture dependent for most of their stock, i.e. historically a variety of salmon and trout species.

The rapid growth of aquaculture, already referred to in Chapter 1, has brought with it a great variety of environmental, social and economic issues. It is important to note that issues in aquaculture have two main sources: those stemming from aquaculture itself and those that affect aquaculture owing to external activities or events. No matter what the origin, each of these issues possess a number of components that vary by location and, therefore, can be addressed by spatial analyses. In this regard, GIS and remote sensing have been used to address the "what, where and how?" of aquaculture production activities since the early 1980s, but there is now considerable impetus to use spatial analyses to expand coverage of issues to "for whom, and with what social, environmental and economic consequences?" as obligatory, additional questions to be investigated in conjunction with the development and management of aquaculture.

The main thrust of this chapter is to provide measures of the status of GIS as it is employed to address spatial issues in the development and management of aquaculture. Because remote sensing and mapping are very closely associated with GIS, they are implicitly included when reference is made to GIS herein. This chapter covers GIS applications to aquaculture in a general way, i.e. as there is easy access to the details of the applications themselves, or to the abstracts of them, through FAO's GISFish portal.[190] The breadth of GIS applications is measured in relation to the spatial issues being addressed and by the geographic distribution of applications. Several approaches are taken for this purpose. The first approach summarizes recent reviews of GIS applications in aquaculture followed by an account of the main spatial issues being addressed, i.e. based on the GISFish aquaculture database. A second approach, closely associated with the first, summarizes the status of GIS applications to aquaculture in terms of the geographic distribution of the applications based records in the GISFish aquaculture database and on the Aquatic Sciences and Fisheries Abstracts (ASFA). The final approach illustrates, via selected in-depth case studies, a range of applications and their associated issues.

[190] GISFish: www.fao.org/fishery/gisfish.

8.2 RECENT REVIEWS DEALING WITH SPATIAL ISSUES IN AQUACULTURE

The spatial issues in aquaculture to which GIS has been applied can be classified as: (i) development of aquaculture; (ii) aquaculture practice and management; (iii) training and the promotion of GIS; and (iv) multisectoral development and management that includes aquaculture. Each of these main categories has subcategories of issues associated with them, and GISFish provides a continuously updated count on the numbers of applications relating to each of the sub-issues (Table 8.1).

TABLE 8.1
Number and percent of main issues and sub-issues addressed among 391 GIS applications to aquaculture in the GISFish database (1985–2012)

Issue	Number	Percent
Development of aquaculture	**209**	**53**
Suitability of site and zoning	111	28
Strategic planning for development	79	20
Anticipating the consequences of aquaculture	15	4
Economics	4	1
Aquaculture practice and management	**124**	**32**
Inventory and monitoring of aquaculture and the environment	83	21
Environmental impacts of aquaculture	27	7
Restoration of aquaculture habitats	8	2
Web-based aquaculture information system	6	2
Training and the promotion of GIS	**32**	**8**
Training	9	2
Promotion	23	6
Multisectoral development and management that includes aquaculture	**26**	**7**
Management of aquaculture together with fisheries	9	2
Planning for aquaculture among other uses of land and water	17	4
Total	**391**	

Note: The "Web-based aquaculture information system" sub-issue could be a sub-issue of any of the main issue headings. However, most of the applications using Web-based information were focused on aquaculture practice and management per se.
Source: FAO (2012d).

The earliest reviews of GIS applications in aquaculture were conducted by Meaden (2001), Kapetsky (2004) and Kapetsky and Aguilar-Manjarrez (2004), with the latter covering the time period from 1985 (when such GIS applications first appeared) to 2002. Reviews of spatially related issues of GIS applications in aquaculture have been made in several contexts. Mapping, remote sensing and GIS applications applied to marine aquaculture, organized by the main spatial issues listed in Table 8.1, were covered by Kapetsky and Aguilar-Manjarrez (2007) with example applications being described. GIS applications and their related issues as described by Kapetsky and Aguilar-Manjarrez (op. cit.) were separately tabulated according to those pertaining to finfish cage culture (13 applications) and to shellfish culture (24 applications). By handling mapping, remote sensing and GIS applications separately, the important role of each in spatial analysis for development and management of aquaculture was emphasized.

More recently, the status of GIS, remote sensing and mapping applications in aquaculture was reviewed from an ecosystems viewpoint by Kapetsky, Aguilar-Manjarrez and Soto (2010). The purpose of the review was to gauge the spatial analytical experience that could be brought to bear on the ecosystem approach to aquaculture (EAA) and to draw attention to technical and geographic gaps. The indicators used to evaluate spatial experience were the number of applications associated with each spatial issue (identical to those in Table 8.1), the kinds of ecosystems being studied by the applications, or in which they were carried out (e.g. ponds, river basins) and the scales encompassed by the applications (local to global) in the three main environments of brackish water, inland and marine. Regarding the issues addressed, it was concluded that GIS applications in the development of aquaculture and the aquaculture practice and management domains were fairly common, but that the economics sub-issue was rarely addressed. Also, applications in the main issue of multisectoral planning and management were infrequent, possibly reflecting the poor integration of aquaculture into land and water use planning. An important gap was found in the lack of experience in dealing spatially with the social and economic components of ecosystems. It was emphasized that promotion and training are issues aimed at increasing the capacity to use spatial tools, particularly with the purpose of more broadly promoting and propagating the spatial awareness that goes beyond the usual technical scope of training. Regarding the spatial scales that GIS addressed, it was recognized that, although GIS has the built-in capability to accommodate any scale, most of the applications in all three environments were carried out at the large scale, i.e. in relatively small areas, corresponding to local activities or to farm and aquaculture zone scales in EAA terms.

8.2.1 The development of aquaculture

Altogether, GIS aimed at development of aquaculture accounted for more than 50 percent of all applications, and the sub-issues most frequently addressed were: (i) suitability of the site and zoning and (ii) strategic planning for development (Table 8.1). GIS applications in this main issue category are carried out as a prelude to aquaculture development. Recent new thinking (Kapetsky and Aguilar-Manjarrez, 2013) conceives of aquaculture potential, zoning and siting, together with an estimation of carrying capacity, as development activities that follow a temporal and spatial hierarchical progression beginning with estimating potential and ending with siting (Table 8.2). In terms of spatial scope and the number of factors considered, estimating aquaculture potential has the broadest reach, but it includes only the more general factors. Zoning is intermediate, and site selection is the narrowest in spatial scope. Carrying capacity estimation has to be considered at all stages of development and management. Estimating potential, zoning and siting will need to be repeated as culture systems are developed for new species or as culture systems are modified for species already under culture.

The siting and zoning sub-issues of Table 8.1 relate directly to the concepts of Table 8.2. The sub-issue of "Strategic planning for development" closely corresponds to estimating the potential for aquaculture. Likewise, the sub-issues "Anticipating the consequences of aquaculture" and "Economics" relate to carrying capacity when carrying capacity is broadly interpreted in environmental, social and economic terms. The low number of applications addressing the economics sub-issue calls attention to a very serious gap when it is considered that all development activities in the commercial sector are driven by economics, including many of those that are government subsidized.

An example of estimating potential at the global level is the spatial analysis of offshore mariculture potential by Kapetsky, Aguilar-Manjarrez and Jenness (2013). The main objective was to assess the potential for the expansion of mariculture from present nearshore locations to offshore areas. An underlying objective was to identify countries with no mariculture but that appear to have high offshore mariculture potential. The study was comprehensive of all maritime nations and the results were comparable among them. The analytical approach located and spatially integrated those environmental factors that are essential to sustain offshore mariculture: (i) areas in which it is technically and economically feasible to place culture installations; (ii) areas that promote fast growth of fish and molluscs; and (iii) locations that minimize competing and conflicting uses while taking advantage of possible complementary uses of adjacent space. The culture systems were sea cages and longlines and the corresponding

TABLE 8.2
Sequential steps for the development of aquaculture

Steps	Estimating potential	Zoning	Siting	Estimating carrying capacity
Main purpose	Plan strategically for development and eventual management	Regulate development; minimize competing and conflicting uses; maximize complementary uses of land and water	Reduce risk; optimize production	Sustain culture; protect environment/ecosystem
Spatial scope: administration	Global to national	Levels 1 and 2 subnational	Farm or farm clusters	Farm or farm clusters
Spatial scope: ecosystems	Main environments (freshwater, brackish, marine)	Ecosystem	Portion of ecosystem	Aquaculture ecosystem
Ecosystem approach to aquaculture (EAA) scale	Global	Watershed or waterbody	Farm	Farm to watershed or waterbody
Executing entity	Organizations operating globally; national aquaculture departments	National, state/provincial/ municipal governments with aquaculture responsibilities	Commercial entities	Regulating agencies
Data needs	Basic, relating to technical and economic feasibility, growth and other uses	Basic environmental, social and economic sets	All available	Data to drive models
Resolution	Low	Moderate	High	High
Results obtained	Broad, indicative	Directed, moderately detailed	Specific, fully detailed	Moderately to fully detailed

Source: Kapetsky and Aguilar-Manjarrez (2013).

technical criteria were depth and current speed. The economic criterion considered the area within 25 nautical miles of a harbour, and implicitly took into account time and travel costs between an onshore support facility and an offshore grow-out installation having reliable access to the sea. Three species were used to indicate potential: cobia (*Rachycentron canadum*), Atlantic salmon (*Salmo salar*) and blue mussel (*Mytilus edulis*). Additionally, areas for integrated multitrophic aquaculture (IMTA)[191] of Atlantic salmon and blue mussel were located. These species were selected as indicative of offshore mariculture potential because of their commercial importance and well-established culture practices. Also, the two fish species represent "fed" aquaculture while the mussel is an example of "extractive" culture. Taken together, the production of these species spans all the climate zones in which mariculture is currently practised. Areas favourable for growout of all three species were identified using temperature ranges from mariculture research and practice, and chlorophyll-*a*

[191] For a detailed description of integrated multitrophic aquaculture, see Soto (2009).

concentrations were also used to indicate areas with adequate food availability for the mussel. Marine protected areas (MPAs) were used in the modelling process to draw attention to competing, conflicting and complimentary uses. MPAs vis-à-vis mariculture may fall into any of these use categories. MPAs provide a relevant illustration of uses of marine space other than for mariculture because of their global coverage in international and national waters. Mariculture potential was estimated in terms of the surface areas meeting the criteria for successful fish production. The results indicated that there is much unrealized mariculture potential both among nations already practising mariculture and among those yet to develop it.

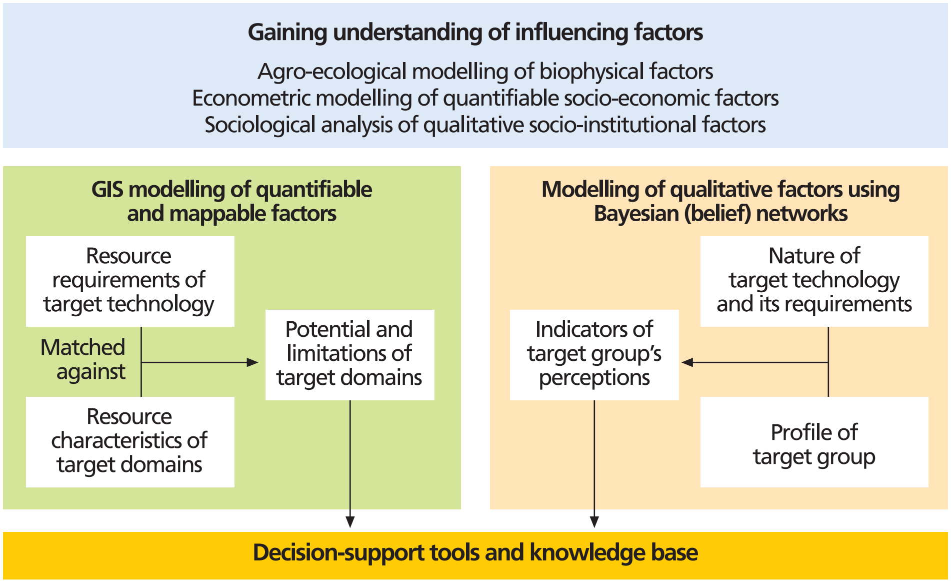
Another example of a study with a global reach is an assessment of the vulnerability of aquaculture-related livelihoods to climate change (Handisyde *et al.*, 2006). The study used a range of national scale and higher-resolution raster data in combination with a hierarchical modelling approach to assess the climate-induced vulnerability of aquaculture-related livelihoods. The assumption was that vulnerability is a function of sensitivity to climate change, exposure to climate change and adaptive capacity. In total, eight different assessments of vulnerability were produced at the country level: (i) general vulnerability; (ii) vulnerability in terms of food security; (iii) vulnerability based on economic importance of aquaculture; (iv) vulnerability with emphasis on adaptive capacity; (v) vulnerability of freshwater aquaculture to inland flooding; (vi) vulnerability of freshwater aquaculture to drought; (vii) vulnerability of brackish-water aquaculture to cyclones; and (vii) vulnerability of mariculture to cyclones. GIS was used to highlight areas where livelihoods are most likely to be affected. Rather than aiming for a single final output, a range of models was produced with the objective of addressing production in freshwater, brackish and marine environments in relation to a number of potentially changing climate trends and extremes. Results pointed to high vulnerabilities among countries in Asia where most of aquaculture production takes place. A follow-up study with methodological improvements is under way.

An example of estimating potential for aquaculture at the national level is the four-country research project (detailed in Kam *et al.*, 2008) to determine recommendation domains[192] for promoting the development of freshwater pond aquaculture aimed at improving household food security and the livelihoods of smallholder farmers. The results of this work have been summarized as a case study by Kapetsky, Aguilar-Manjarrez and Soto (2010). The research project adopted an analytical framework, as depicted in Figure 8.1, that integrates the various multidisciplinary components into a knowledge-based analytical and decision-support system to provide an informed basis for recommending particular aquaculture practices and technologies. The framework served as the basis for using the GIS and Bayesian network[193] modelling techniques developed by the project to analyse the data collected on the quantitative and qualitative influencing factors. The combination of the GIS and Bayesian network tools identify places and sets of conditions for which a particular target aquaculture technology is considered feasible and advantageous to promote, while also identifying the nature of constraints to aquaculture development and thereby shedding light on appropriate interventions to realize the potential of the target areas (Figure 8.2).

[192] Recommendation domains are places having sets of conditions for which a particular target aquaculture technology is considered feasible and therefore advantageous to support.

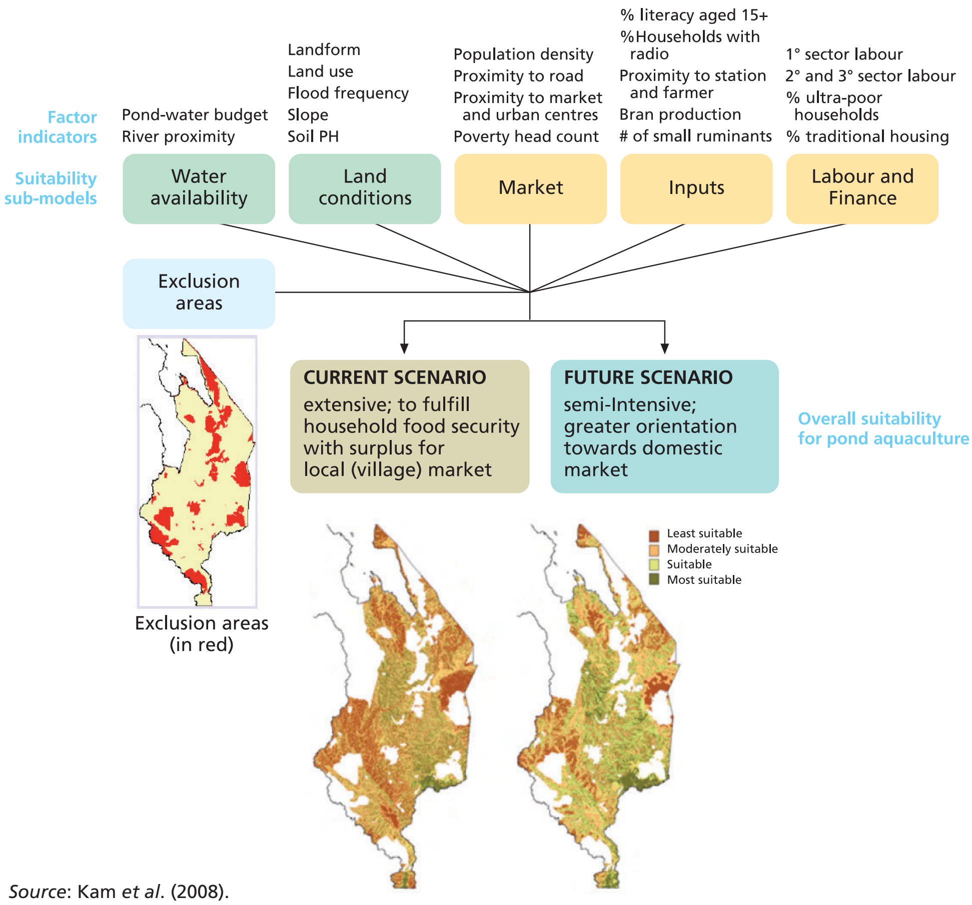
[193] Many factors that determine whether a particular aquaculture technology is sustainably adopted – particularly social, cultural and institutional factors – are not readily quantifiable, let alone mapped. In many situations, these "soft" factors have an overriding influence on technology adoption yet are excluded from GIS analysis and modelling. GIS modelling was therefore complemented in the project with another set of modelling tools based on Bayesian networks, which can incorporate factors of a qualitative nature that influence farmers' perceptions about a particular aquaculture technology (for detailed information, see Kam *et al.* (2008) at www.worldfishcenter.org/resource_centre/WF_1047.pdf.

FIGURE 8.1
Framework for developing and using decision-support tools for determining recommendation domains for freshwater pond aquaculture



Source: Kam *et al*. (2008).

FIGURE 8.2
Overall suitability for pond aquaculture for the southern region of Malawi



Source: Kam *et al*. (2008).

Note: How the "suitability submodels" are derived and modelled so as to arrive at both a current scenario and a future scenario are described in detail in Kam *et al.* (2008).

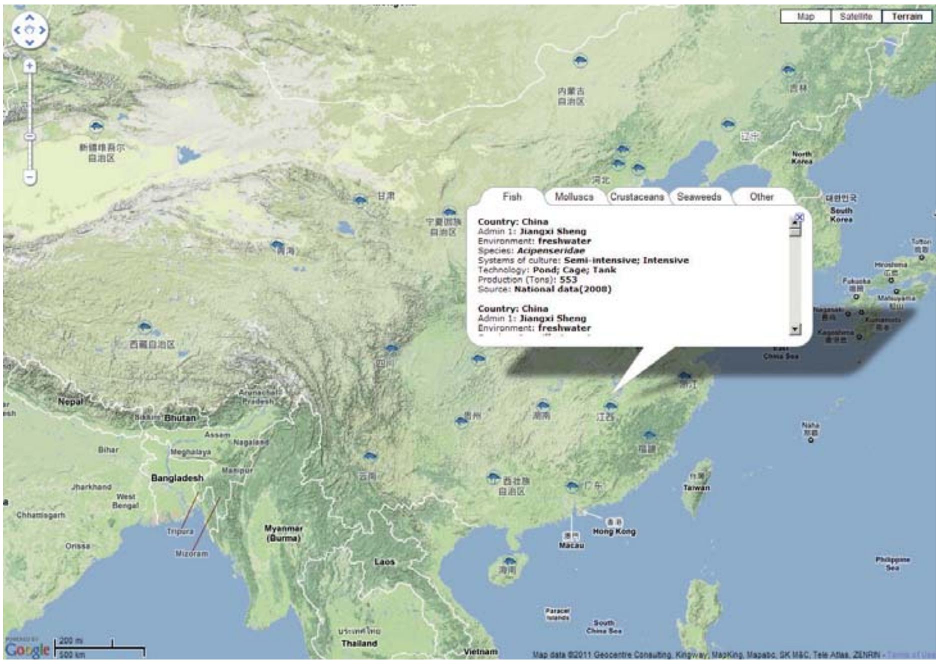
8.2.2 Aquaculture practice and management

Applications of GIS aimed at aquaculture practice and management accounted for about one-third of the total applications in GISFish, and "inventory and monitoring of aquaculture and the environment" was the most frequently addressed sub-issue (Table 8.1).

An inventory assessment of existing aquaculture facilities in an area is an indispensable component for the management and regulation of aquaculture and for its further spatial expansion, and the periodic monitoring of land-use developments is essential where aquaculture and other development activities are occurring at a rapid rate. Both inventory and monitoring activities are required in order to address the other sub-issues of "environmental impacts of aquaculture" and "restoration of aquaculture habitats". Inexpensive opportunities for inventory and monitoring have been greatly advanced by relatively high-resolution imagery from earth browsers such as Google Earth. FAO's FIRA has created a Web site, the National Aquaculture Sector Overview(NASO) map collection[194], which is a collection of Google maps for a selection of countries showing the location of existing aquaculture sites and their characteristics mainly at an administrative level (state, province, district) and in some cases at an individual farm level depending on the degree of aquaculture development.

Aquaculture data for the NASO maps is collected using a Microsoft Excel submission form. The completed forms, once validated by FAO, are then used to create the NASO maps. The form allows for rapid data entry from compilers and easy data retrieval by users, and maps are accessible online through a browse map page or through a "Search by Country" page; an "Advanced Search" is also available. The NASO map collection currently consists of maps for 18 countries and new maps are added as they become available. The collection is important because it places aquaculture in a spatial domain that is easily accessible to nearly everyone, and it is a development that could have huge positive effects on the flow of reliable statistics and information about aquaculture for its improved development and management. The

FIGURE 8.3a
NASO map of China at an administrative level



Source: FAO (2012c).

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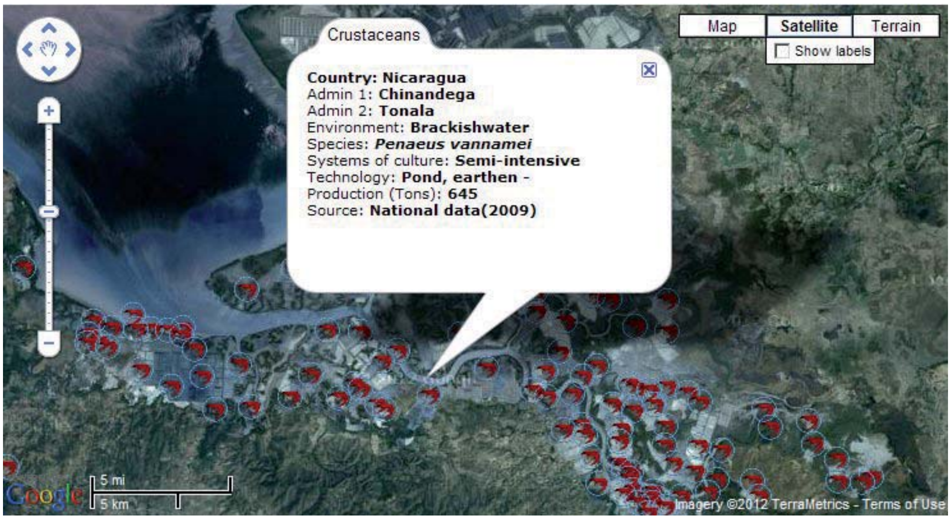
[194] National Aquaculture Sector Overview (NASO) map collection: www.fao.org/fishery/naso-maps/naso-home/en.

NASO collection is in its early stages, but it clearly provides potential for monitoring the status and trends of aquaculture development, addressing site selection and zoning issues, and improving the operational management of aquaculture. The NASO map for the People's Republic of China is illustrated in Figure 8.3a. The map illustrates information that has been aggregated at an administrative level. Figure 8.3b illustrates a NASO map for the Republic of Nicaragua at an individual farm level showing the locations of shrimp ponds.

FIGURE 8.3b
NASO map for part of Nicaragua at an individual farm level



Note: Icons presented in red colour represent individual shrimp farms.

Source: FAO (2012c).

Fish farming cages are also clearly visible through Google Earth's satellite images (Figure 8.4). University of British Columbia, Canada, researchers have used them to estimate the amount of fish being cultivated in the Mediterranean. In the Mediterranean Sea, ocean fish farming is prevalent, and using satellite imagery available through Google Earth, stationary cages can be seen off the coasts of 16 countries. Using this tool, the University of British Columbia researchers demonstrated that a few trained scientists now have the capacity to ground truth farmed fish production data reported by the Mediterranean countries. With Google Earth, they could examine 91 percent of the Mediterranean coast and counted 248 tuna cages (circular cages 0.40 m diameter) and 20 976 other fish cages within 10 km of the shore, the majority of which were off the Hellenic Republic (49 percent) and the Republic of Turkey (31 percent). Combining satellite imagery with assumptions about cage volume, fish density, harvest rates and seasonal capacity, they made a conservative approximation of ocean-farmed finfish production for 16 Mediterranean countries. Their overall estimate of 225 736 tonnes of farmed finfish (not including tuna) in the Mediterranean Sea in 2006 is only slightly more than the FAO reports. The results demonstrate the reliability of recent FAO farmed fish production statistics for the Mediterranean as well as the promise of Google Earth to collect and ground truth data (Trujillo, Piroddi and Jacquet, 2012).

Environmental impacts of aquaculture have many facets as spatial issues. One of them is the public perception of the consequences of aquaculture development. Another spatial issue is the environmental impact of one or many aquaculture installations on other land or water users in the same area. An example is an environmental impact

FIGURE 8.4
Example image from Google Earth showing a fish farm off the coast of Greece

Note: Location: 38°19'19.21"N; 24° 3'14.33"E

Source: Image © 2012 DigitalGlobe, © 2012 Google

assessment project conducted in the Republic of the Philippines in Bolinao Bay to increase the organization and representation of farmers so that "clusters" of farms could be effectively monitored and managed, thus helping to avoid the classic boom and bust cycle prevalent in small-scale aquaculture. This project, based on work by Palerud *et al.* (2008), Legovic *et al.* (2008) and White (2009), has also been encapsulated as a case study in Kapetsky, Aguilar-Manjarrez and Soto (2010). The fundamental problem addressed by this project was that there was little planning, management and control of aquaculture development in Bolinao Bay. The solution involved a range of activities including GIS use and an assessment of carrying capacity, plus zoning along with the development of zone committees, cluster-level environmental assessment and monitoring, training/awareness, capacity building and institutional strengthening. The environmental impact assessment was addressed by proposing three types of surveys for monitoring the impact of aquaculture, i.e. low cost through intermediate to fully scientific surveys that differed in terms of cost, complexity and accuracy, but all of which might give a good indication of the level of aquaculture impact. Using a depositional model TROPOMOD[195], two and three rows of cages were tested and compared for each of the six aquaculture zones (Figure 8.5a). The area of high and severe impact was found to occupy the majority of the zone area and little room was available between rows for remediation of impacts (Figure 8.5b). Thus, in all aquaculture zones except zone 4, two rows of 18 cages were found to be optimum. As larger cages were present in zone 4, two rows of 12 cages were recommended.

From a GIS viewpoint, this study shows how a number of models can be coupled with GIS to identify zones, estimate the maximum number of cages in a zone, estimate the minimum distance between zones, and undertake scenario testing to identify management options for minimizing the impact of aquaculture.

[195] TROPOMOD is a particle tracking model used for predicting output, movement and deposition of particulate waste material (with resuspension) and the associated benthic impact of fish farms.

FIGURE 8.5a
Aquaculture zones 1 to 6

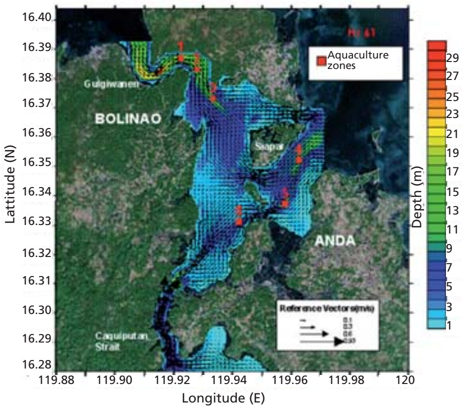
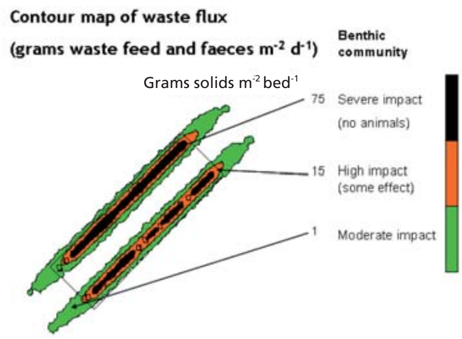


FIGURE 8.5b
Definition of severe, high and moderate impact for the SABBAC zone modelling. There are two rows of cages shown and different colours represent different amounts of waste flux (grams waste feed and faeces depositing on the bed per m² per day)



Note: SABBAC is a length of coastline in Pangasinan, Philippines covering the Municipalities of Sual, Anda, Bolinao, Bani and Alaminos City.

Source: Palerud *et al.* (2008).

Regarding the Web-based aquaculture information system sub-issue of "aquaculture practice and management" (Table 8.1), traditionally inventories of aquaculture facilities have been confined to production installations. However, for a holistic understanding of the industry and for planning for development and regulation, all of the commercial components of aquaculture require inventories and monitoring, including transporting, processing and marketing facilities as well as seed production. One specific need for a Web-based aquaculture information system is for the comprehensive identification and characterization of existing production areas and individual sites in order to track production from the producer through the chain of processing, transporting and marketing to the consumer. More generally, all of these components need to be spatially placed in their respective administrative jurisdictions, as well as in their social, economic and ecological contexts. Additionally, aquaculture support services, whether commercial or governmental, need to be accounted for spatially in terms of their areas of operations and specific services so that delivery of services and feedback are rapid and are properly channelled. These functions are within the domain of an "Aquaculture Management Information System", of which a Web-based GIS could be the backbone. FAO currently has a Technical Cooperation Programme project under way in the Kingdom of Thailand that encompasses a number of these functions (Aguilar-Manjarrez and Miao, 2011), and AkvaVis (see Section 8.4.2) also embodies other functions of a Web-based aquaculture information system particularly with regard to transparency of information and public participation in management via the Internet.

8.2.3 Training and the promotion of GIS

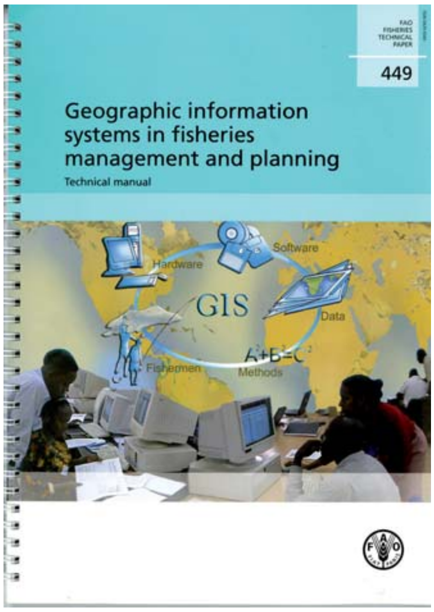
A lack of appreciation of the importance of spatial matters by aquaculturists and other practitioners has been identified as a problem and/or issue that GIS training and the promotion of GIS can help to address. Altogether, GIS training and promotion made up 8 percent of the current applications in GISFish with "promotion" receiving the most attention (Table 8.1).

GIS training and the promotion of GIS in one sense can be seen as one and the same issue in that promotion of the various applications of GIS in aquaculture can be considered as a training exercise aimed at managers and decision-makers as well as at technical staff. Indeed, an important mission of this technical paper is to promote GIS by engendering an interest in its applications to a wide range of problems in aquaculture faced by managers and decision-makers. To this end, Section 4.8 devotes significant advice on where further guidance and training can be obtained.

Both the FAO Fisheries and Aquaculture Department Aquaculture Branch (FIRA) and the Institute of Aquaculture at the University of Stirling, Scotland,[196] have been active in promoting the use of GIS and remote sensing as applied to aquaculture since 1985. Promotional activities at FIRA have been carried out through training, projects, field missions and oral presentations and publications. The Fishery-Aquatic GIS Research Group, established in Japan in 1997, also promotes GIS and spatial analyses in fishery and aquatic sciences, with its primary activity being to organize the triannual "International Symposium on GIS/Spatial Analyses in Fishery and Aquatic Sciences", which includes aquaculture, and to publish its proceedings.

A training manual by de Graaf *et al.* (2003) provides "hands-on" step-by-step guidance on the use of GIS software for inland fisheries management and planning, and aquaculture is also included (Figure 8.6). The manual is aimed at fisheries biologists, aquatic resource managers and decision-makers in developing countries who do not have any knowledge of GIS. It by no means covers all possibilities of GIS; it merely touches upon some of the most important features for fisheries management and planning, but it is useful for a broad range of fishery and aquaculture applications. The manual was written for use with the Environmental Systems Research Institute's (ESRI) ArcView 3.x and Spatial Analyst software[197]; it includes two CD–ROMs with spatial data for exercises and has been tested in the Republic of Uganda, the Republic of Namibia, and the Republic of India.

FIGURE 8.6
Technical manual on GIS in fisheries management and planning



Source: de Graaf *et al.* (2003).

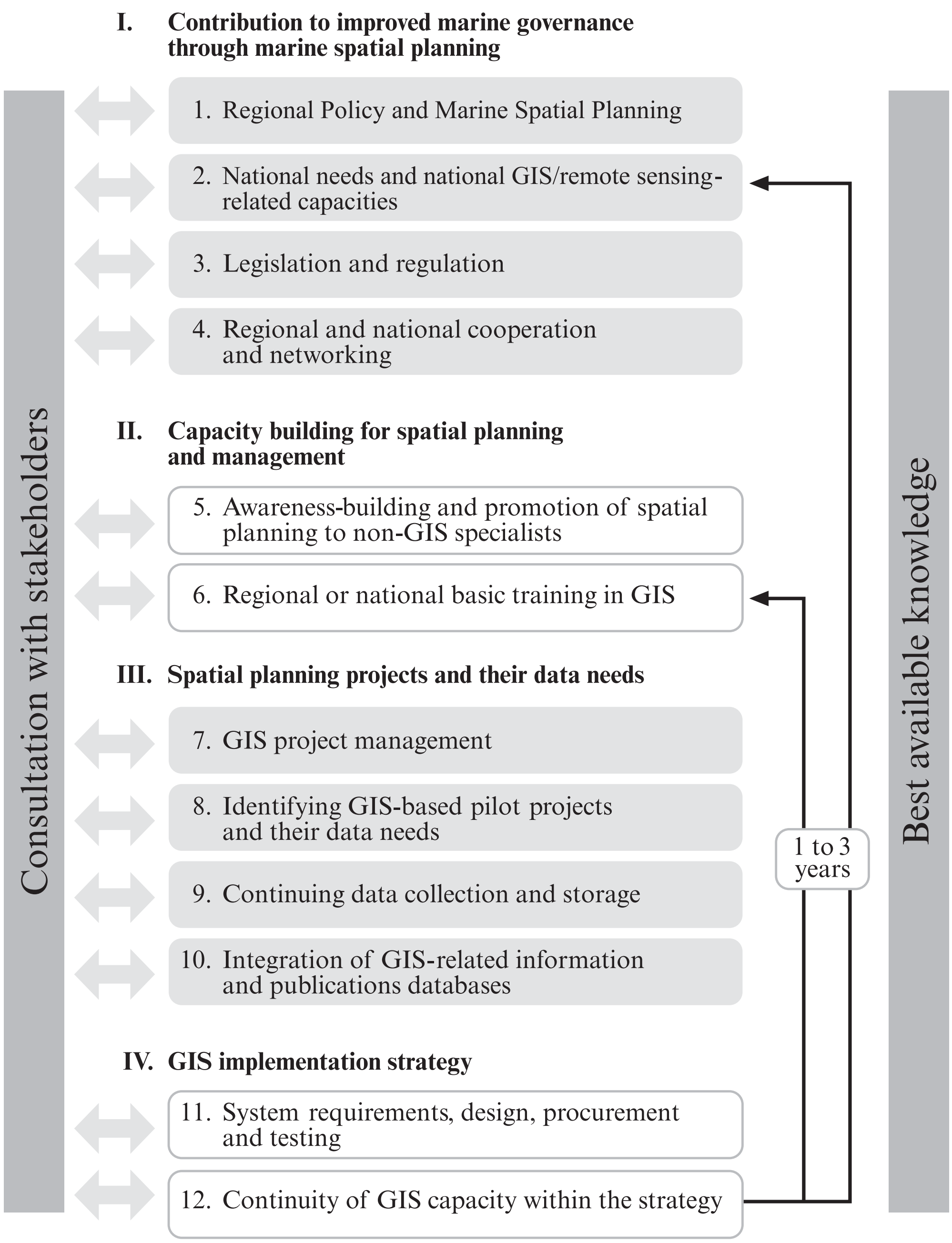
[196] Institute of Aquaculture at the University of Stirling: www.aqua.stir.ac.uk/GISAP/gis-group.

[197] ArcView 3.x is now discontinued. However, the examples provided in this manual could be replicated using the most recent ArcGIS software.

8.2.4 GIS for multisectoral development and management that includes aquaculture

This main issue addresses the role of GIS in establishing aquaculture in the context of competing, conflicting and complementary uses of land and water space. The attention this issue has received relative to other issues, only 7 percent of the total (Table 8.1), is an indication of the minimal extent to which planners and decision-makers have taken aquaculture into account in the general context of development.

FIGURE 8.7
Implementation of the strategy process



Source: FAO/Regional Commission for Fisheries (2011).

In many cases, especially in the coastal zone or in estuaries or larger bodies of inland water, aquaculture and fisheries use the same resources and are practised in the same or adjacent space. Additionally, both pursuits have many interests and needs in common, not the least of which is an environment having ecological, social and economic components that allows both activities to remain sustainable. This sub-issue can be illustrated comprehensively by a proposal for a regional programme to implement a spatial strategy for the simultaneous management of marine fisheries and aquaculture in the Middle East Gulf Region, as detailed by FAO/Regional Commission for Fisheries (2011). Although the approach is regional, elements of the spatial strategy pertain to individual nations and their government institutions and commercial entities, i.e. to the extent that the strategy could be used as a framework for a combined national strategy for spatial planning for marine fisheries and for aquaculture development. Indeed, elements of the strategy could contribute to the wider regional marine spatial planning that will be necessary in the future for many of the more "congested" marine areas. Figure 8.7 shows a schematic diagram of the strategy illustrating that it consists of four programme components and 12 elements. Two actions are fundamental throughout the strategy process: (i) to collect and use the best available information; and (ii) to have broad stakeholder participation. The process, steps and potential starting points are described in this figure.

The sub-issue of "Planning for aquaculture among other uses of land and water" (Table 8.1) addresses the place of aquaculture among other users of land and water, and it goes beyond those considerations necessarily required collectively by fisheries and aquaculture. Ideally, there are several important roles for GIS relating to this sub-issue. One role is to establish where aquaculture can best be established while taking a detailed account of other uses of the land and water, i.e. so that conflicts are eliminated, competition is minimized, and complementary uses of the aquaculture space are thoroughly explored. A second role is to effectively communicate these results to high-level decision-makers.

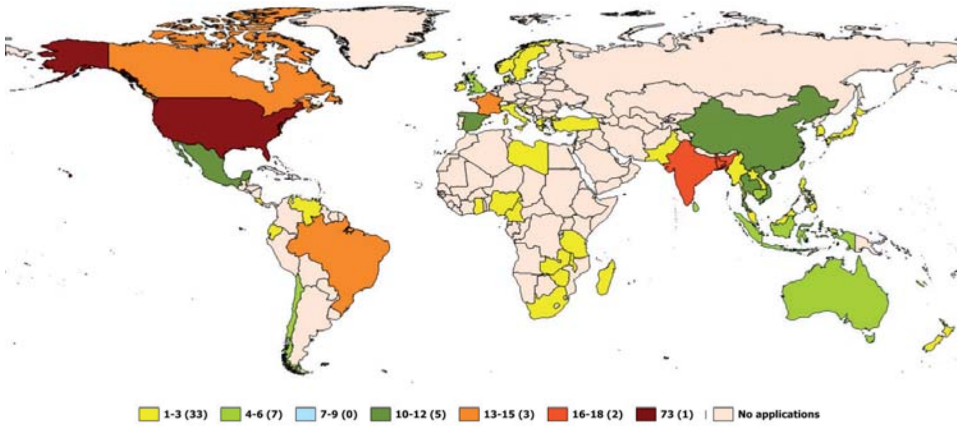
8.2.5 Trends in addressing aquaculture issues using GIS

A positive trend in addressing aquaculture spatial issues is that it is becoming more difficult to associate any one GIS application in aquaculture with any one issue or sub-issue. This means that spatial analyses for aquaculture are becoming broader in scope to the point that multiple issues are more frequently being addressed by any single project. In a recent review (Kapetsky and Aguilar-Manjarrez, 2013), attention was called to applications that incorporate multiple species, multiple models at different scales, including economic models, varied temporal scales for the simulation of consequences of management options, and the possibility that they could be adapted to address issues at different scales in other countries. GIS is used to provide the spatial components for the modelling of key variables by providing input values via a spreadsheet or database, as a platform for communication between different models, in the verification of data and of model results, for visualization and for spatial analyses. Despite such progress, there is a need for a greater focus on spatially defining and integrating the environmental, economic, and social components of aquaculture development, practice and management.

8.3 THE GEOGRAPHIC DISTRIBUTION OF GIS APPLICATIONS TO AQUACULTURE

Along with the types of spatial issues in aquaculture addressed by GIS, the geographic distribution of the applications is also of interest. For example, it is important to know the level of experience with GIS on a country basis so that technical assistance and training can be allocated in a way that might be appropriate to country needs and capacities. One such indicative measure was the number of applications to aquaculture by country in the GISFish aquaculture database in December 2009, and this was depicted as a thematic map by Kapetsky, Aguilar-Manjarrez and Soto (2010) (Figure 8.8). The results were quite skewed, with more than half of the countries having only one to three recorded GIS applications but with very few countries having many applications, i.e. indicating that the GIS experience is far from evenly distributed. Moreover, although 51 countries were represented among the 298 GIS applications, at that time there were 163 countries having some recorded aquaculture production. This result suggests that there are many aquaculture practising countries that are not employing GIS to address aquaculture issues even when taking into account the bias toward the English language inherent in the GISFish aquaculture database and/or that many countries are simply not writing about and publishing their aquaculture GIS work. Even countries with a high aquaculture production, such as Japan, the Kingdom of Norway, and the Republic of the Philippines, publish very few studies relating to aquaculture where GIS has been a significant input.

FIGURE 8.8
The geographic distribution of GIS applications among countries



Source: Kapetsky, Aguilar-Manjarrez and Soto (2010).

A similar measure of the extent to which GIS applications in aquaculture are spatially distributed is based on the number of records from ASFA using "GIS" and "geographic information systems" together with "aquaculture" and "mariculture" as search commands for the period 1996 to 2010 (Table 8.3). In comparison with the GISFish analysis, fewer applications were found in ASFA, but the relative rankings among countries is similar. This is not surprising as ASFA focuses on scientific literature that has appeared in books, journals and conference proceedings while GISFish includes the grey literature from technical reports and trade publications as well as ASFA records.

An additional background area indicating the status of GIS applications to aquaculture is that of where much of the major and innovative work in aquaculture GIS (in terms of the institutions) is being conducted. Box 8.1 gives a general overview of some of the major organizations that are pursuing work in aquaculture GIS. The main institutions are in Europe; however, there are now institutions in the Republic of Chile, the Republic of Ecuador, the Republic of Ghana, the Republic of India, the Sultanate of Oman, the Republic of Peru and the Republic of South Africa where applications of GIS to aquaculture research projects and to management are innovative.[198] It is worthwhile visiting the Web sites of the institutions periodically to learn about work in progress or to view technical reports that may contain innovations not yet published in journals.

[198] See "Country initiatives" in NASO maps collection (www.fao.org/fishery/naso-maps/country-initiatives/en), and Kapetsky, Aguilar-Manjarrez and Soto (2010), Box 7.1, p. 115.

TABLE 8.3
Country or marine area of application for 350 literature records on papers covering GIS + geographic information systems + aquaculture + mariculture in FAOs ASFA database (1996–2010)

Region	Country of application	Number of applications
North America	United States of America	107
	Canada	12
Latin America and Caribbean	Mexico	3
	Brazil	3
	Peru	2
	Chile	2
Caribbean Sea + Gulf of Mexico		17
Asia and Pacific	China	24
	India	17
	Sri Lanka	9
	Viet Nam	8
	Bangladesh	7
	Indonesia	6
	Thailand	6
	Australia	6
	New Zealand	4
	Japan	4
	Philippines	2
Indian Ocean		1
Africa		9
	South Africa	2
Europe	France	8
	Spain	4
Baltic Sea		3
	Norway	3
	Italy	2
	Portugal	1
	Denmark	1
	Finland	1
North Atlantic		1
North Sea		1
No specific area		74
Total		**350**

Source: FAO (2012b).

BOX 8.1
Overview of major organizations carrying out aquaculture-related GIS research and projects

Clearly this box can only be illustrative and it is beyond the scope of this publication to give the exact range or number of institutions carrying out aquaculture-based GIS work.

- **Brazil.** The Universidade Santa Úrsula conducts aquaculture and GIS research in the marine and coastal environment. Different types of GIS projects include studies for aquaculture site selection (tilapia, *Litopenaeus vannamei*, bivalves), habitat suitability (marine turtles), stock evaluation (sea cucumbers – *Isostichopus badionotus*). Also species fragility in environments undergoing rapid changes, such as coastal areas and wetland homes to the annual freshwater killifish (*Rivulidae - Sympsonicthyes*).
- **Brazil.** The Universidade Federal de Santa Catarina, Centro de Filosofia e Ciências Humanas, Programa de Pós-graduação em Geografia conducts PhD work related to GIS e.g. use of GIS for the management of mariculture
- **Canada.** Hatfield Consultants Partnership (Hatfield) was established in 1974. The company capitalizes on its remote sensing and GIS group capabilities to provide a range of remote sensing and GIS products and services that complement and support traditional environmental assessment and monitoring services. Since its inception, the company has focused in particular on providing innovative and cost-effective environmental management solutions to the fisheries and aquaculture sectors.
- **France.** The Institut français de recherche pour l'exploitation de la mer (IFREMER) – French Research Institute for Exploitation of the Sea – carries out projects relating to remote sensing and GIS in the coastal zone.
- **Italy.** The FAO Fisheries and Aquaculture Department Aquaculture Branch (FIRA) develops methodologies, technical guidelines, technical papers, reviews, training materials, georeferenced information systems such as GISFish and GIS applications to aquaculture.
- **Japan.** The Fishery-Aquatic GIS Research Group was established in 1997, and is a non-profit organization located at the Environmental Simulation Laboratory Inc., Kawagoe, Saitama, Japan. The objectives of this group's activity is to promote GIS and spatial analyses in fishery and aquatic sciences through developing marine GIS software and organizing the triannual International Symposium on GIS/Spatial Analyses in Fishery and Aquatic Sciences and to publish its proceedings. The Graduate School of Fisheries Science at the Hokkaido University also carries out much innovative GIS work on fisheries and aquaculture.
- **Malaysia.** The World Fish Center has developed methodologies that apply remote sensing and GIS techniques, linked to environmental and socio-economic modelling, to support aquaculture and fisheries research, planning and management. Applications have included developing GIS-based decision support tools for identifying recommendation domains for small-scale aquaculture, and using remote sensing and GIS for community-based participatory planning of coastal livelihoods rehabilitation in post-tsunami coastal areas of Aceh province in Sumatra.
- **Spain.** The Dirección General de Pesca y Acuicultura, Consejería de Agricultura y Pesca conducts studies on integrated coastal zone management for the Andalucia region in the Kingdom of Spain.
- **Thailand.** The Fishery Information Technology Center at the Department of Fisheries, Thailand, develops and maintains computer networking, GIS, management information systems, and fisheries data collection and statistics reports for end users in Thailand. Current projects are: inventories of aquaculture and fisheries structures; fish cage identification and inventory; vessel monitoring systems; fishing gear detection; and flood management
- **United Kingdom.** The Institute of Aquaculture, University of Stirling, Scotland, has a small GIS group working on GIS and remote sensing applications in aquaculture. Its programme has taken two directions: the strategic evaluation of large regions for aquaculture exploitation and development, and the use of GIS in detailed facility location within a site. GIS-based environmental impact modelling is also being developed, with special emphasis on coastal zone management. GIS and remote sensing are incorporated into their M.Sc. programmes and GIS and remote sensing have been provided for a range of overseas institutions.
- **The United States of America.** There are a number of entities that use GIS for aquaculture including the Office of Aquaculture, National Oceanic and Atmospheric Administration, as well as regional fisheries bodies such as the Gulf States Marine Fisheries Commission. In addition, many of the states have their own fishery-aquaculture GIS units (e.g., North Carolina) and there are companies dedicated to the application of GIS and remote sensing in aquaculture (e.g., Consultants in Fisheries and Aquaculture Sciences and Technologies (C-FAST, Inc.).

8.4 CASE STUDIES

Case studies allow for the easy comprehension of what are often advanced and detailed research activities with practical applications. They are also a valuable complement to journal articles and technical publications because not only do they call attention to a wide variety of applications that have contributed to solving important issues that affect the sustainability of aquaculture, but they also provide information usually lacking from scientific papers and reports, namely, in what ways, and with what commitments of time and specialized personnel the work has been completed, as well as lessons learned that are helpful to assess the time and resources required to undertake similar investigations.

A source of case studies of GIS, remote sensing and mapping applications in aquaculture is the published case studies page of GISFish[199]. There are currently 14 case studies and new ones are added as innovative material becomes available. In addition to the presentation of the application in the case study format, there are links to the publications upon which the case study was based. Another source for case studies are those assembled and interpreted from an ecosystems viewpoint by Kapetsky, Aguilar-Manjarrez and Soto (2010). The purpose of these case studies was twofold, the first being to show the relevance of GIS capabilities to the EAA principles and the second was to illustrate by actual application examples ways in which GIS, remote sensing and mapping can contribute to the implementation of the EAA.

The following case studies were selected from a number of different sources including those described above. These case studies not only illustrate the technical capacity of GIS applications in aquaculture, but they also address issues that are of global to local importance and that span environmental, social and economic considerations.

The four case studies selected also needed to be as varied as possible and therefore include a variety of GIS-based techniques and degrees of complexity. The studies provide:

- a sophisticated and holistic example from a developed world area where a fairly large group of research workers were deployed (Sections 8.4.1);
- a sophisticated example also from a developed world area involving the use of a Web-based decision-support system (Section 8.4.2);
- a less sophisticated study also in a developed world area involving the use of remote sensing data (section 8.4.3);
- a fairly basic study carried out by a Ph.D. level student using precollected data and looking at defining aquaculture potential in Ghana (Section 8.4.4).

8.4.1 Sustainable options for People, catchment and Aquatic Resources (SPEAR)

Original publication reference: Ferreira, J.G., Andersson, H.C., Corner, R.A., Desmit, X., Fang, Q., de Goede, E.D., Groom, S.B., Gu, H., Gustafsson, B.G., Hawkins, A.J.S., Hutson, R., Jiao, H., Lan, D., Lencart-Silva, J., Li, R., Liu, X., Luo, Q., Musango, J.K., Nobre, A.M., Nunes, J.P., Pascoe, P.L., Smits, J.G.C., Stigebrandt, A., Telfer, T.C., de Wit, M.P., Yan, X., Zhang, X.L., Zhang, Z., Zhu, M.Y., Bricker, S.B., Xiao, Y., Xu, S., Nauen, C.E. & Scalet, M. 2008. SPEAR: *Sustainable options for People, catchment and Aquatic Resources: the SPEAR project, an international collaboration on integrated coastal zone management*. 180 pp.

Spatial tools: GIS, remote sensing, models.

Main issue addressed: Environmental impacts of aquaculture.

Duration of study: 2004–2007.

Personnel involved: The SPEAR team consisted of 35 experts from different countries around the world with a wide range of expertise ranging from tools, systems, aquaculture, ecosystem modelling, screening modelling and management.

Target audience: Coastal zone water managers, planners and licensing authorities.

[199] Case studies page of GISFish: www.fao.org/fishery/gisfish/id/1014.

Introduction and objectives: The SPEAR project was financed by the European Union INCO-DEV programme (www.biaoqiang.org). It was a follow-up to the experiences gained in the Sustainable Mariculture in Northern Irish Loughs Ecosystems (SMILE) project (2004–2006) for determining environmentally sustainable carrying capacity for shellfish aquaculture for Irish loughs (Ferreira *et al.*, 2007).

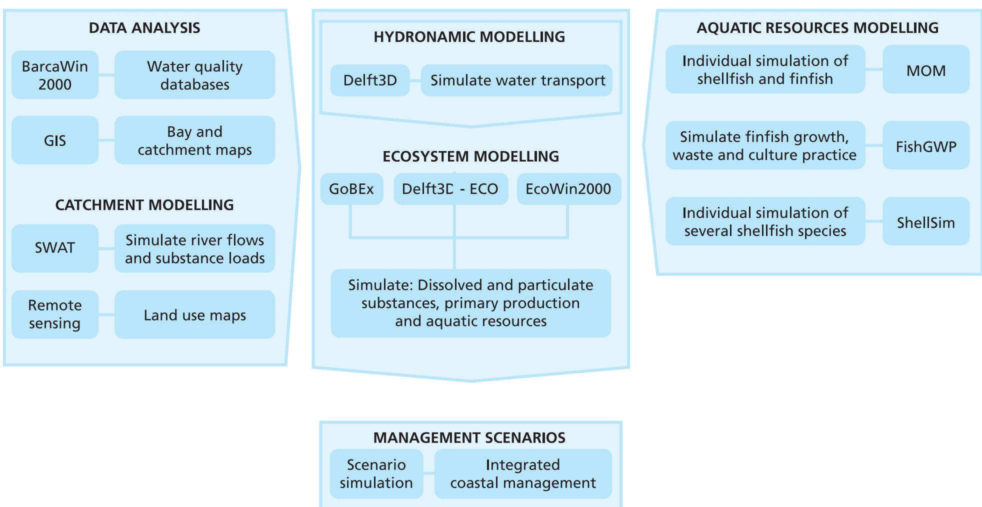
The general objective of SPEAR was to develop and test an integrated framework for management of the coastal zone, using two test cases where communities depend primarily upon marine resources of which a large component is aquaculture of finfish, shellfish and seaweeds, often in integrated multitrophic aquaculture (IMTA).

This case study does not aim to provide an exhaustive account of all the research executed in SPEAR, and the reader is directed to the official project Web site (available in English at www.biaoqiang.org and in Chinese at www.spear.cn). A digital copy of the SPEAR book is available on the site, together with links to databases, models, reports and all other resources made available by this research.

Methods and equipment: Two contrasting coastal systems in the People's Republic of China were used as study areas. Sanggou Bay is in a rural area in the north, and Huangdun Bay is an industrialized area south of Shanghai that is subject to substantial human pressure at both local and regional levels.

The overall SPEAR framework accounted for watershed interactions, ecological structure and human activities. The interdisciplinary study used combined natural and social science approaches and addressed the complex scaling issues inherent in integrated management. The main objectives of model development at the ecosystem scale were to: simulate the ecosystem processes on a multi-year scale for each bay; simulate the aquatic resources produced in the bays; develop the socio-economic components to dynamically integrate this framework; and to calibrate and validate the research model suite. A key feature of the general modelling approach was to integrate the various models in order to develop a robust ecosystem modelling framework where GIS and remote sensing play an integral part (Figure 8.9).

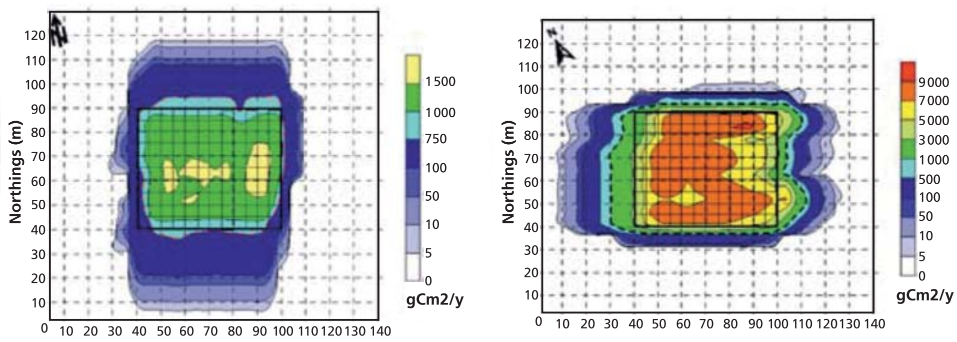
FIGURE 8.9
General modelling framework used in SPEAR ecosystem models



Source: Ferreira *et al*. (2008).

Results: SPEAR focused on both research and screening models. The latter, useful for a fish farmer, farm manager or coastal manager, are employed to support decisions and are featured herein. For example, at the local scale, screening models[200] may be used to look at aquaculture yields, local impacts of fish farming and water quality. A good illustration is the particulate waste distribution model developed for fish culture in Huangdun Bay (Figure 8.10) using GIS, which provides a footprint of the organic enrichment beneath fish farms. The footprint can be used to predict changes to benthic biodiversity through empirically derived calibration curves. Such enrichment footprints are used for the environmental regulation of cage fish farming in many countries.

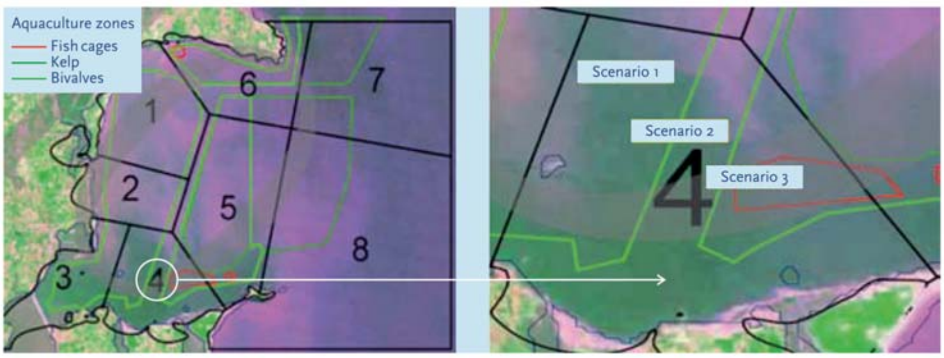
FIGURE 8.10
Screening model for carbon input to sediments from fish culture in Huangdun Bay under ambient current flow conditions (left), and for the same production level under slower hydrodynamic conditions (right)



Source: Ferreira *et al*. (2008).

Figure 8.11 illustrates one of the management scenarios from the project. The farm selected as a demonstration site is located in Box 4 of Sanggou Bay, where Pacific oyster (*Crassostrea gigas*) raft culture, Japanese flounder (*Paralicthys olivaceus*) and pufferfish (*Fugu rubripes*) cage culture coexist. There, three scenarios were posed all of which concern different ways to spatially distribute oyster culture among the other

FIGURE 8.11
Box layout of Sanggou Bay, China, and the location of FARM simulation area



Source: Ferreira *et al*. (2008).

[200] The distinction between research models and screening models is related to the data requirements, complexity of use, difficulty/ease in interpreting the results, runtime and post-processing required, and target audience. Research models are considerably more costly to build and run, require inputs from multiple users, are useful for detailed analytical work, and tend to be used by scientists or others who are experts in the particular issue and model. While screening models are less costly, they consist of rapid assessments and should in principle be usable by anyone with a working knowledge of the issue at hand.

cultures and the effects of these distributions. Overall, scenario 3 provided both the highest profit from production activities and the highest potential income when also considering the environmental costs of nutrient treatment, or (alternatively) the resale value of nitrogen credits as a catchment management option.

Discussion, conclusions and recommendations: From a technical standpoint, outputs from the SPEAR project represent the state-of-the-art in coastal management, featuring Web-based models, hybrid ecological-economic approaches, and management tools that can be used at a variety of scales. Technological developments will mean that the tools themselves will evolve fairly rapidly, but the underlying scientific paradigms are expected to change more slowly.

In summary, GIS was used throughout the project in several key roles:

- In decision support as the geographic component of key variables and results to support the decision-making process.
- In modelling, by providing input values relevant for parameterization and calibration, by serving as a platform for communication between different models and by allowing a first approach at 2D validation processes, for allowing the use of spatialized assessment of model results.
- In visualization at several stages of the project for basic mapping purposes to facilitate the understanding and interpretation of relevant inputs and results, and by performing spatial analysis of model results. However, most models used in this project were not fully integrated within the GIS software. This was done in a follow-up project, "Understanding Irish Shellfish Culture Environments", on the carrying capacity in Ireland, where an application in ArcGIS was used to run the various models (J.G. Ferreira, personal communication, 2011).

Challenges and benefits from the case study: This project is valuable because it is a holistic assessment of aquaculture on the basis of people, planet (i.e. environment) and profit. The challenge of bringing the various components of the people-planet-profit equation together as a holistic indicator of sustainable carrying capacity in coastal areas appears both achievable and appropriate for integrated coastal management. From a GIS viewpoint, this project is noteworthy in a number of ways: (i) it represents a good example of integration of spatial data across different scientific disciplines; (ii) it is novel because it combines models running at widely different time and space scales for different ecosystem components as a requirement for scaling and as co-validators of each other, lending confidence to the outcomes; and (iii) it included a socio-economic viewpoint using the MARKET model. Also valuable are the set of management scenarios proposed by the project team, including the stakeholders, that clearly illustrate the role and value of GIS.

As a follow-up to SMILE and SPEAR, the Institute of Marine Research (IMAR) has been working with others on individual shellfish modelling over the past two years. In particular, IMAR has developed a new model called AquaShell, which aims to include the minimum set of equations required to successfully simulate bivalve growth, and it has implemented it for the blue mussel, grooved carpet shell clam and Pacific oyster (J.G. Ferreira, personal communication, 2011). The model has been applied to oyster cultivation in the Republic of Chile using the following approach: (i) a coastal system was screened for potential shellfish aquaculture areas using GIS; (ii) the FARM model, using AquaShell to simulate individual growth, was applied to examine the feasibility of production in those areas and at appropriate sites; and (iii) an optimization analysis was carried out for production, profit and environmental effects (Silva *et al.*, 2011).

At the system scale, the AquaShell model is also being used in the CoExist project (www.coexistproject.eu) for the analysis of the offshore culture of finfish and shellfish in integrated multitrophic aquaculture.

8.4.2 AkvaVis decision support system

Original publication reference:

Ervik, A., Agnalt, A.-L., Asplin, L., Aure, J., Bekkvik, T.C., Døskeland, I., Hageberg, A.A., Hansen, T., Karlsen, Ø., Oppedal, F. & Strand, Ø. 2008. AkvaVis – dynamisk GIS-verktøyfor lokalisering av oppdrettsanlegg for nye oppdrettsarter – Miljøkrav for nye oppdrettsarter og laks. Fisken og Havet, nr 10/2008. 90 pp.

Ervik, A., Døskeland, I., Hageberg, A.A., Strand, Ø. & Hansen, P.K. (forthcoming). *Virtual decision support tool (AkvaVis) for integrated planning and management in aquaculture.*

Publication/date:

Ervik *et al.* (forthcoming) is being prepared for submission.

Spatial tools: GIS.

Main issues addressed: Inventory and monitoring of aquaculture and the environment; environmental impacts of aquaculture; Web-based aquaculture information system.

Duration of study: Five years

Personnel involved: Eight aquaculture research experts and three GIS/virtual technology experts, all members of academic and governmental groups.

Target audience: Stakeholders in the fields of aquaculture production, aquaculture and coastal zone management and policy implementation.

Introduction and objectives: Aquaculture is a major coastal activity in the Kingdom of Norway. Total aquaculture production in 2010 was 1 008 010 tonnes at a value of US$5 020 275 000 (FAO Statistics and Information Branch of the Fisheries and Aquaculture Department, 2012). The industry contributes substantially to employment and rural economies. Fish are produced in fjord-based farms using net cages for Atlantic salmon (*Salmo salar*) and rainbow trout (*Oncorhynchus mykiss*), and they occupy more than 1 000 sites. Diversification of the industry is being encouraged by research and development, which seeks new aquaculture species, i.e. marine fish: cod (*Gadus morhua*), halibut (*Hippoglossus hippoglossus*); shellfish: mussels (*Mytilus edulis*), scallops (*Pecten maximus*), flat oyster (*Ostrea edulis*); and lobster (*Homarus gammarus*). Aquaculture production of seafood continues to grow; however, this continued growth has also brought concerns about environmental impacts.

As in other parts of the world, the exploitation of the Norwegian coastal zone is increasing, with new activities, stakeholders and interests facing a complexity of environmental and social interactions. New, comprehensive and more holistic approaches for coastal zone management are being applied such as the ecosystem approach and long-term maintenance of biodiversity. This is a challenge for the developing aquaculture industry. The development of new decision-support systems that can handle the variety of interests and that can transfer scientific-based knowledge to the targeted user is urgent. There is also an increasing mismatch between the rather static coastal area development plans prepared by local municipalities and the rapidly changing and dynamic nature of the aquaculture industry. This further emphasizes the need to provide planners and managers with up-to-date data, knowledge and advice.

AkvaVis is a Web-based interactive site selection, coastal zone area planning, carrying capacity, management and monitoring, decision-support system. Although the system is currently under development (Ervik *et al.*, forthcoming), it is aiming to provide a Web-based interface that will be transparent to public users and dynamic, in the sense that it is adaptable to new knowledge and new regulatory frameworks, and that it addresses the demands from the industry, including public and private stakeholders. AkvaVis aims to cover all main aquaculture species in the Kingdom of Norway and also to integrate other activities as part of marine spatial planning so as to make informed and coordinated decisions about how to use marine resources sustainably. The challenges for integrated planning and management for aquaculture in the Norwegian coastal zone have prompted the launching of a new cohesive management system called MOLO (Environmental adaption and efficient area usage for the aquaculture industry)[201] (Anonymous, 2009), under which AkvaVis is intended to be developed as the virtual decision support tool.

Methods and equipment: AkvaVis makes use of "intelligent objects"[202] and integrated data models. The system creates a virtual reality[203] for aquaculture site selection and carrying capacity.
AkvaVis consists of three modules:

1. The management module compiles the best available information needed by the authorities for aquaculture management. It provides thematic maps, i.e. 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.
2. The siting module identifies and evaluates the suitability of areas for specified aquaculture activities and provides simulations of their carrying capacities.
3. The application module aids in an efficient application procedure for aquaculture licences and ensures that all relevant information is provided.

The AkvaVis siting module divides the study area into grid cells containing quantitative information on several relevant location factors (e.g. depth, current velocity, etc.). The user can insert on the map of the study area an intelligent object (e.g. a virtual mussel farm) to communicate dynamically with information provided by databases and mathematical models simulating aspects of the physical, production and ecological carrying capacities, as well as with information on other conflicting objects such as sewage outlets, fisheries, conservation areas, etc. Once a virtual farm is inserted in a given site (or grid cell) on the map, AkvaVis will immediately report back on how suitable the site would be for the cultured species by giving a suitability score for each parameter (depth, wave exposure, carrying capacity, etc.) and a calculated total score on how all requirements are met. Databases and information are both shared between national data providers and internally between the three system modules.

Results: As part of the ongoing development of the AkvaVis tool, demonstration versions are available at www.akvavis.no for the blue mussel (*Mytilus edulis*) and Atlantic salmon (*Salmo salar*) in the Hardangerfjord. This area was chosen for testing AkvaVis owing to the availability of environmental data, such as current velocity conditions (Figure 8.12), the availability of an already tested hydrodynamic model and a very active aquaculture scene.

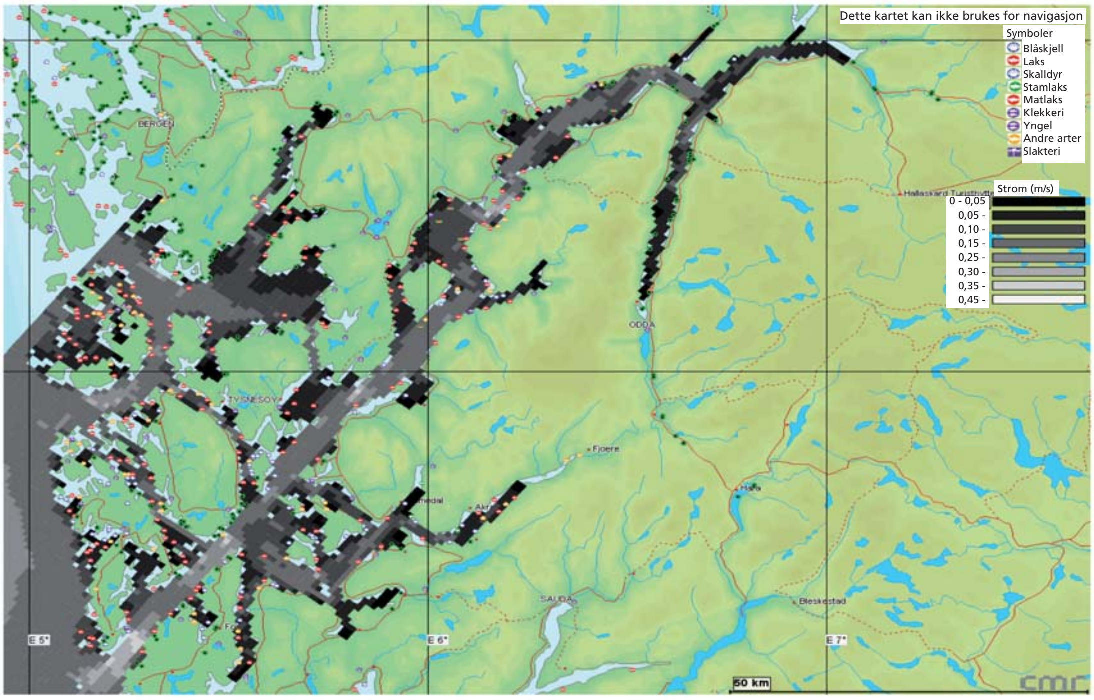
The simulation of a specific siting of a salmon farm will interact with an industry compliant and/or adopted version of the Modelling-Ongrowing fish farms-Monitoring (MOM) model (Ervik *et al.*, 1997; Hansen *et al.*, 2001; Stigebrandt *et al.*, 2004), assessing the potential effects on the bottom and on benthic fauna, and reporting a suitability score according to accepted environmental impact standards. Figure 8.13 shows a part of the Hardangerfjord with contour depth information displayed and

[201] Environmental effects and access to areas will be crucial factors in the Norwegian aquaculture industry's development and growth. The Minister of Fisheries and Coastal Affairs has asked the Institute of Marine Research to prioritize the work on developing a total system for the regulation of environmental effects and adaption of areas for aquaculture. The system is called MOLO and the development work will take place in cooperation with other institutions. It will cover both the planning and operation phases for aquaculture and combines the use of geographic information systems with calculations of the carrying capacity and the monitoring of environmental effects (Institute of Marine Research: http://www.imr.no/english/__data/page/6540/Coast_and_Aquaculture_2007.pdf).

[202] Intelligent objects are virtual representations of a spatial or non-spatial entity (object).

[203] Virtual reality is a technology that allows a user to interact with a computer simulated environment.

FIGURE 8.12
The AkvaVis – Hardangerfjord grid for simulating current velocity



Source: Ervik *et al*. (forthcoming).

Map legends:
Top-right symbols (from top to bottom): Mussels, salmon, shellfish, broodstock of salmon, cage farming, hatchery, fry, other species, processing.
Mid-right symbols: Current (m/s).

the locations of different types of existing aquaculture. The red-squared location (ID 14144) at the centre of the figure is the virtual fish farm presented with suitability indicators in the form of coded results (traffic lights) at the bottom left corner. In this case, all indicators (i.e. carrying capacity to benthic impact, carrying capacity to cage environment, current velocity, depth, distance to sewage outlet) are acceptable (green code) except for the distance to the nearest existing aquaculture location (red code), for which minimum distance is indicated by the red circles on the map.[204]

For the current development of the demonstration version, models such as MOM that are already adopted as guidelines and are regarded as partially implemented in the management of aquaculture in the Kingdom of Norway are proposed for implementation. Examples are exposure to currents and waves, risk of eutrophication on regional scale, and risk of oxygen depletion in fjord basins.

The AkvaVis demonstration tool integrates: (i) data on a range of parameters (e.g. currents, aquaculture sites and waste outlets); (ii) data based on expertise (e.g. growth models, rules for weighting selection factors and boundary values); (iii) legislation, regulations and directives (e.g. distance to other aquaculture sites); (iv) calculations, visualizations and interactivity between the tool and the user; and (v) basic topographic and thematic maps. The interactive feature allows the users to immediately see the consequences of their choices. A user survey (Hageberg, 2008) has been conducted as part of the current development of the system.

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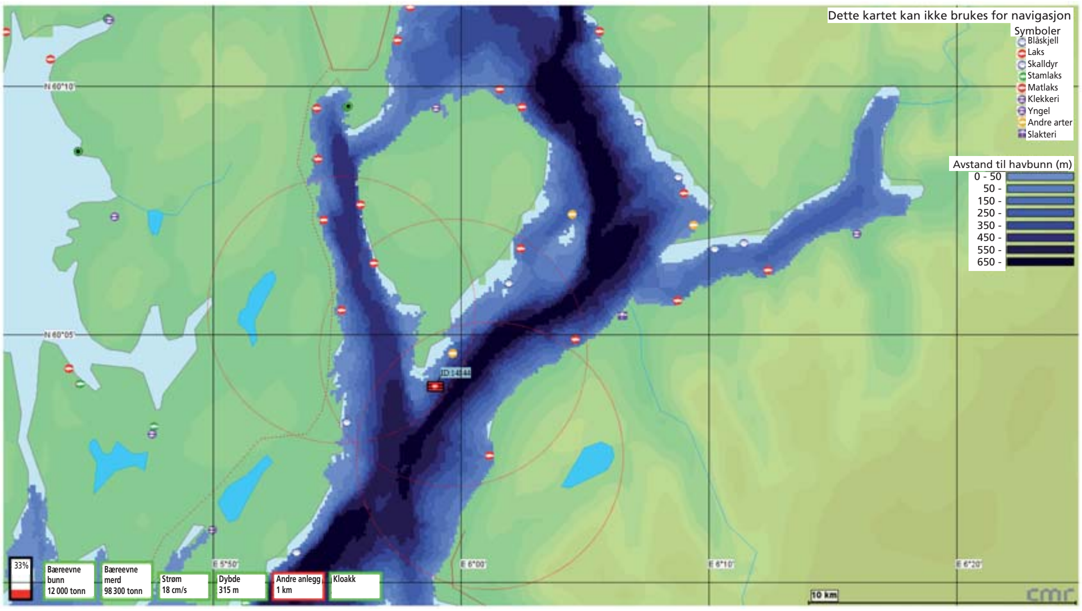
[204] Farm sites fallow on a rotational basis to prevent disease transmission to the stock. Compliance to minimum distance between farms may also vary over time. The minimum distance used is adopted as the standard. At present, AkvaVis is still under development; therefore, suitability indicators are not fully developed.

FIGURE 8.13
The AkvaVis site selection expert system



Source: Ervik *et al*. (forthcoming).

Map legends:
Top-right symbols (from top to bottom): Mussels, salmon, shellfish, broodstock of salmon, cage farming, hatchery, fry, other species, processing.
Mid-right symbols: Depth (m).
Bottom-left symbols (from left to right):Carrying capacity benthic, carrying capacity cage, current, depth, other farms, sewage.

Discussion, conclusions and recommendations: The AkvaVis decision-support system will provide a hands-on Web-based aquaculture simulator and data management tool that will give the user immediate feedback on site selection choices. The management, siting and application modules are purpose-designed to meet some of the prime needs in aquaculture management by authorities and industry. The transparency to public users and dynamism to accept new knowledge, new regulatory frameworks and the demands from industry and public and private stakeholders are regarded as important for development of an efficient and trustworthy tool.

Challenges and lessons from the case study: Several challenges have characterized the development work and demonstration presentations of the AkvaVis system. Some of the challenges and lessons learned are summarized as follows:

- In order to be totally effective, AkvaVis will probably need long-term experience in practical management to be realized, even for the most important species (e.g. Atlantic salmon). However, some of the subcomponents suggested for the siting module, such as the MOM-model, environmental quality standards and others, are regarded as already being partially implemented for the management of aquaculture in the Kingdom of Norway. This inclusion of established subcomponents will ease the process of developing AkvaVis towards a full operational application.
- Factors important to site suitability when represented in a spatial domain require high-quality data, both from measurements and models, and these are currently only available for a few areas.
- Current velocity data are crucial for estimating most of the factors affecting site suitability. The hydrodynamic models, from which the currents were obtained,

are also used in other simulation models, and these will need to be implemented for the whole Norwegian coastal system. (i.e. the models will need to use average current conditions, derived from model simulations, and not only average values, for example, variability is needed for some indicators and this process of producing a catalogue of extracted data is ongoing).

- Involvement of stakeholders is complicated because the target audience consists of industry, management and policy-makers. The process of integrating user-friendly aspects as part of the decision-making procedure is ambitious.
- The simplification of information that is used and presented as indicators and simple codes causes a risk of both loss of information and misinterpretation of it.
- The dynamic nature of the aquaculture industry and the expected challenges to meet environmental and socio-economic issues related to sustainable production sets specific requirements on how regulatory frameworks can adapt and the types of decision-support tools that are needed. The need for adaptation to these changes requires a transparent system, but there are limitations that need to be resolved to make it fully transparent and operational, such as access to some of the functions of the system, databases, models and Web tools.

8.4.3 Environmentally sustainable offshore aquaculture: an eco-physical perspective

Original publication reference:

Longdill, P.C., Healy, T.R., Black, K.P. & Mead, S.T. 2007. Integrated sediment habitat mapping for aquaculture zoning. Journal of Coastal Research, Special Issue 50, 173–179.

Longdill, P.C. 2008. Environmentally sustainable aquaculture: an eco-physical perspective. Waikato University. 280 pp. (PhD dissertation)

Longdill, P.C., Healy, T.R. & Black, K.P. 2008a. GIS-based models for sustainable open-coast shellfish aquaculture management area site selection. *Ocean and Coastal Management* (51), 612–624.

Longdill, P.C., Healy, T.R. & Black, K.P. 2008b. Transient wind-driven coastal upwelling on a shelf with varying width and orientation. *New Zealand Journal of Marine and Freshwater Research* (42), 181–196.

Spatial tools: GIS.

Main issues addressed: Strategic planning for development; anticipating the consequences of aquaculture.

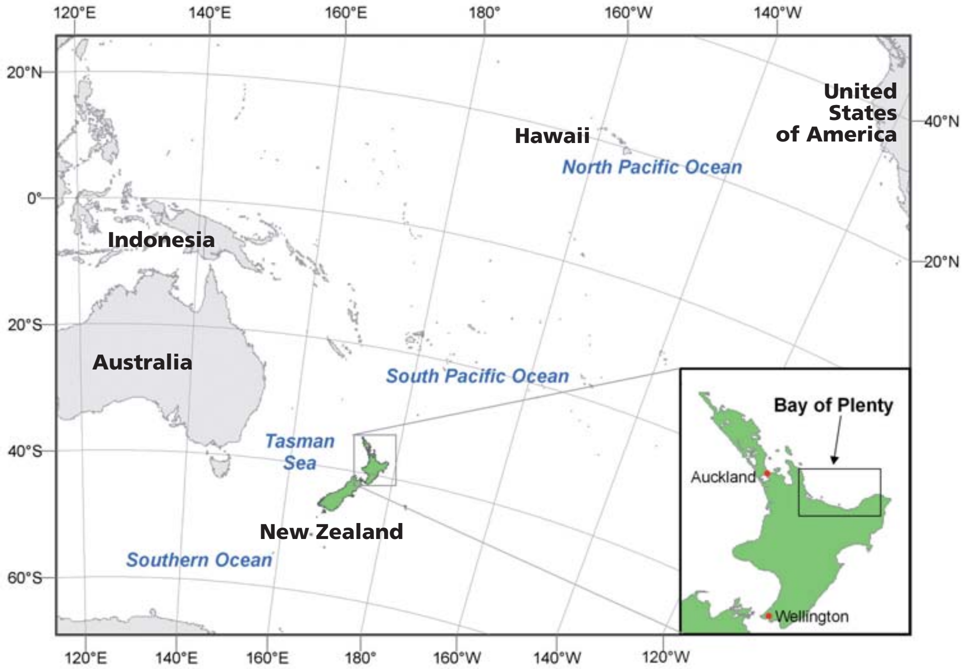
Duration of study: Four years: 2004–2008.

Personnel involved: 1 full time Ph.D. student. Advice and assistance as required during the study.

Target audience: Local government, aquaculture industry groups, aquaculture researchers, marine scientists, local interest groups and the general public interested in marine resources.

Introduction and objectives: The study stemmed from the growth of the New Zealand Greenshell mussel (*Perna canaliculus*) industry during the 1990s and early 2000s. Traditional methods of mussel aquaculture within New Zealand have been longline techniques located in sheltered enclosed embayments. A near saturation of the predominant culturing locations led to interest in offshore, open coast locations. This case study summarizes the results of investigations to determine the suitability of offshore open coast locations (from the coast to 100 m water depth) for commercial bivalve aquaculture within the Bay of Plenty, New Zealand (Figure 8.14). The study was funded both by local government (Environment Bay of Plenty Council, EBOP) and the New Zealand Tertiary Education Commission.

FIGURE 8.14
The Bay of Plenty, located on the north-east coast of New Zealand's North Island in the South Pacific Ocean



Source: Longdill (2008).

The study implemented a framework to collect and analyse data sets relating to the environmental effects of bivalve culture, competing uses of the marine environment, and also the productive capacity for aquaculture. To achieve this framework, a network of factors that aid the development of a sustainable and viable industry were identified and examined (Figure 8.15).

Methods and equipment: Key existing spatial data sets were obtained from government agencies and research institutions, e.g. bathymetry, fishing density, existing ocean zoning areas, shipping areas, climatology, remotely sensed data that includes sea surface temperature and ocean colour time series. Other essential data sets were collected specifically for this study, e.g. benthic habitats, sediment character, water quality, water current data, calibration data for remotely sensed data sets, calibration data for numerical physical and ecological models. Fieldwork was performed in a cooperative engagement between the local environment agency (EBOP), a local university specializing in marine and coastal studies (University of Waikato), and a marine consulting firm (ASR Ltd).

The analysis was divided into three separate steps:

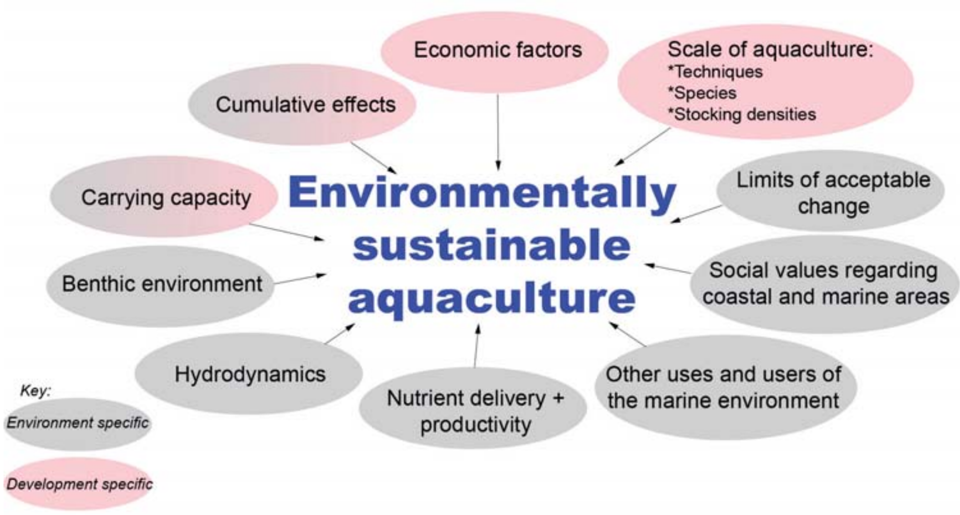
(i) GIS analysis of benthic environments and their ability to assimilate the inputs from aquaculture;
(ii) GIS analysis of other factors influencing the potential zoning of open coast aquaculture farms (environmental, institutional[205] and productive capacity);
(iii) Numerical analysis of physical marine processes (tides, currents, temperatures etc.), along with ecological processes (nutrient and plankton dynamics) and analysis of the model output within a GIS to assess the impact of aquaculture development on water quality and phytoplankton dynamics.

All GIS work was performed using ESRIs ArcGIS v9.2.

[205] Institutional factors relate to other users and uses (e.g. access ways, protected areas, existing shipping routes and anchorage areas) of the coastal marine environment (See Fridley, 1995).

FIGURE 8.15

Development specific and environment specific factors influencing the potential for environmentally sustainable aquaculture within the marine environment



Note: Cumulative effects and carrying capacity are tightly linked to both environment and development specific factors (e.g. species being cultured, size/extent of the farm).

Source: Longdill (2008).

The collected benthic data (bathymetry, habitat type, sediment grain size, sediment organic content and benthic fauna assemblages) were classified into discrete categories depending upon its suitability for culturing infrastructure (bathymetry) and for its ability to assimilate the inputs resulting from a mussel culture operation, e.g. increased deposition of organic material on the seabed. This classification then allowed for these data sets to be included within the raster-based GIS analysis.

The determining factors that were included in order to identify suitable or optimal locations for open coast aquaculture were the growth and quality of the cultured shellfish, the magnitudes of potential environmental impacts, and existing uses and users of the marine area (including societal values). These factors were considered in a spatial framework using raster-based GIS analysis.

Data layers employed included:

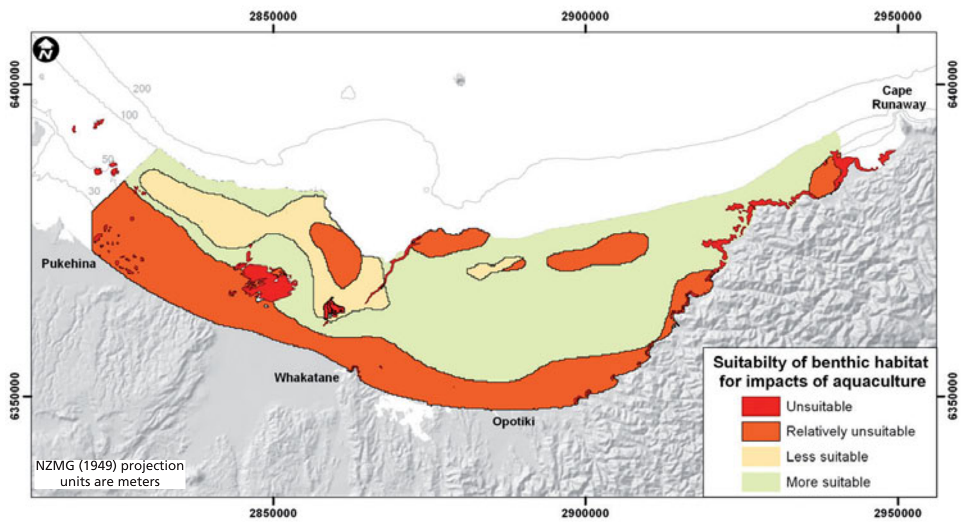
- the visibility of farm-related infrastructure, e.g. buoys and barges, from the coastline;
- access ways;
- culturally significant areas, e.g. traditional fishing zones;
- protected areas;
- legally constrained areas;
- recreational use;
- commercial fishing;
- shipping zones;
- residual current directions;
- mean current speeds;
- benthic habitats;
- relative productivity (chlorophyll-*a* and sea surface temperature climatology);[206]
- water depth.

[206] In this case study, monthly means over a ten-year period were utilized for both remotely sensed chlorophyll-*a* and sea surface temperature to define the climatology.

Combining these selected data sets requires that each parameter be transformed to comparable and consistent units. For this purpose, parameter-specific suitability functions (PSSFs – e.g. see Vincenzi *et al.*, 2006) were defined to assess the suitability of a given site with respect to biogeochemical and physical parameters. These PSSFs convert the raw data set to bivalve aquaculture suitability scores, e.g. a score of 1 for a highly productive area ranging to close to 0 (i.e. 0.001) for a very low productivity area.[207] Individual data sets were converted to either continuous suitability scores (e.g. productivity) or to discrete groups, e.g. culturally significant areas – score of 0 if present, or 1 if not present, as applicable. The subsequent raster layers were then subjected to the multi-criteria evaluation technique (see, for example, Nath *et al.*, 2000) whereby they were combined using an unweighted geometric mean type approach. The use of the geometric mean type formulation allows a "0"score in any of the layers to be reflected in the final result (i.e. a score of 0). This provides an advantage over more simplistic summation or arithmetic mean type techniques where the final result for any raster cell could still be greater than 0, despite constraints (i.e. scores of 0) being present at that cell in one or more of the data layers[208].

Physical process modelling utilized the 3DD modelling suite and entailed calibrating and applying a 3-dimensional numerical model simulating tidal dynamics, wind driven influences, and regional current systems. A dedicated 3-dimensional numerical ecological model (3DD Life) was developed in both MATLAB and FORTRAN environments and superimposed on the physical process model to simulate nutrient-phytoplankton-zooplankton-detritus interactions. This ecological model also comprised an aquaculture submodel to simulate the effects of bivalve aquaculture.

FIGURE 8.16
Assessed capacity for benthic habitats to assimilate the inputs from suspended bivalve aquaculture



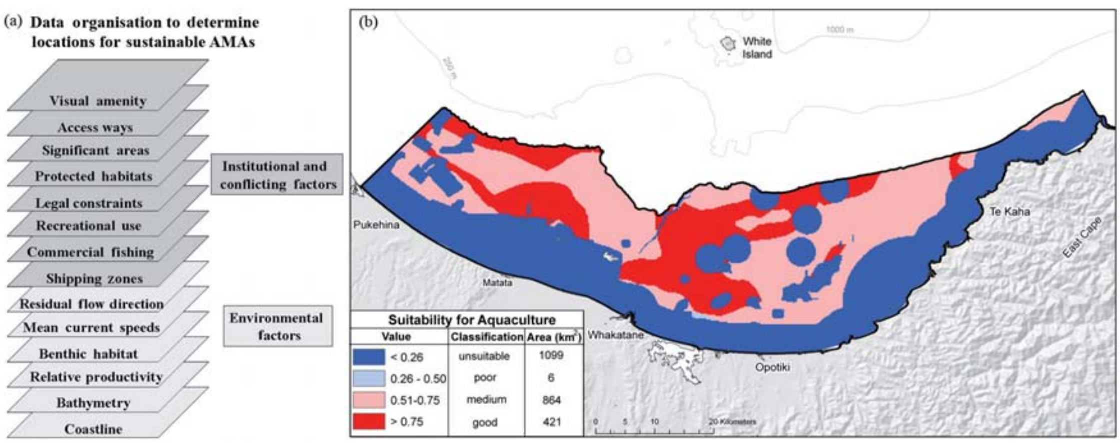
Source: Longdill *et al*. (2007).

[207] A value of "0"would represent a "zero productive area". In implementing the model, it was ensured that there were no "0" values in specific relevant data sets, such as productivity potential. This was performed as it would be incorrect to categorize areas as of "zero productivity potential", i.e. there would always be some level of productivity (or this productivity could be obtained at a high cost).

[208] If data layers have values of 0.5, 0.5, 1,0, the geometric mean is 0 and the arithmetic mean is 0.5. As one of the layers is a constraint (score of 0), then with the geometric approach the final result is 0.

Results: Benthic habitats have varying abilities to assimilate inputs from intensive aquaculture. The discrete benthic data sets (habitat type, sediment size, sediment organic content and potential for aquaculture-induced change) were combined to create a benthic suitability index[209] (Figure 8.16), which was subsequently used for further GIS assessments (Figure 8.17). The analysis of benthic data indicated that soft-sediment habitats, comprised of fine silty and muddy sediments with low organic contents, as the most suitable benthic environment (within the Bay of Plenty continental shelf) above which to site bivalve aquaculture. An integrated GIS assessment of selected factors influencing environmental, institutional and productivity aspects of aquaculture zoning resulted in 18 percent (or 421 km^2) of the 2 390 km^2 Bay of Plenty continental shelf being classified as "good" or "most suitable"(Figure 8.17).

FIGURE 8.17
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 *et al*. (2008a)

Taking the analysis further, 3-dimensional numerical modelling of both physical processes (tide and wind currents, etc.) and ecological processes (nutrients and phytoplankton, etc.) was calibrated against measured data to ensure replication accuracy. Figure 8.18 shows a comparison of observed (SeaWiFS) and model-predicted surface layer[210] (0–15 m) chlorophyll-a concentrations on 19 November 2003.[211] Chlorophyll-*a* concentrations in deeper layers within the 3-dimensional model were calibrated against field data collected from alongshore normal transects made during four separate seasonal survey campaigns (Longdill, Healy and Black, 2008a). With the model predicting accurately, a mussel feeding submodel could be implemented to predict the influence of substantial offshore bivalve mussel culture (two farms were proposed by the industry of 4 000–4 500 hectares each located from 5–15 m below the sea surface) on the modelled ecological parameters.

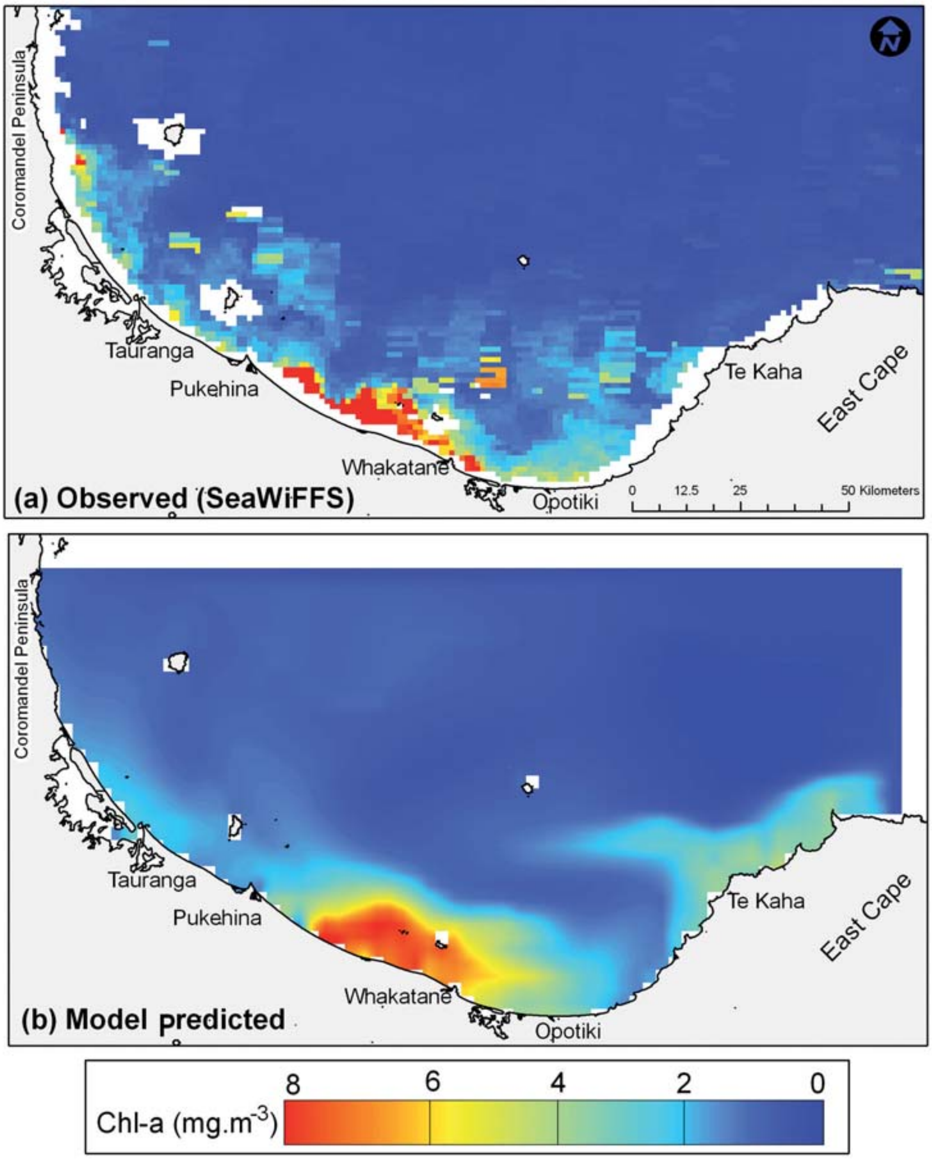
[209] This index comprised a classification of benthic environments into four broad categories. The basis for the suitability categories is described in detail in Longdill *et al.* (2007).

[210] The 3-dimensional model attempted to replicate both the horizontal and vertical distributions of chlorophyll-a. Remote sensing provided surface layer calibration data while the results of field survey campaigns (four surveys spaced throughout the year) provided calibration data for deeper model layers (to 80 m depth), as described in Longdill (2008a).

[211] The date of 19 November 2003 was selected for display in Figure 8.19 because of the relative cloud-free remote sensing data available at this time, along with the date corresponding to 110 days into the model run, thereby indicating model stability.

FIGURE 8.18
Observed (a) and model predicted (b) surface chlorophyll-*a* concentrations on 19 November 2003, 110 days after model initialization

19-Nov-2003, 110 days since model start
Sea surface chlorophyll-*a* observations and model predictions



Source: Longdill (2008).

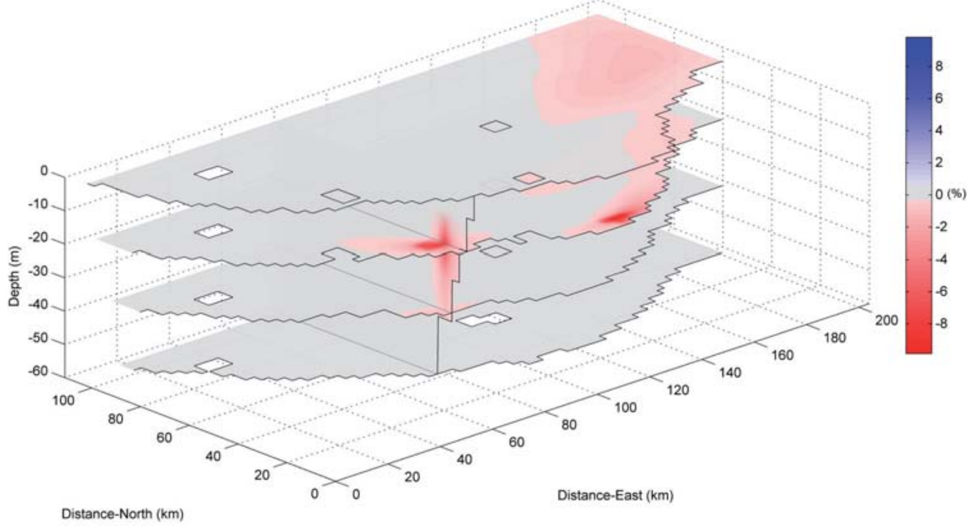
Results from this testing were valuable and indicated that maximal depletions of chlorophyll-*a* (≥ 5 percent of background) were restricted in spatial extent to scales similar to those of the farms themselves (Figure 8.19). At lesser chlorophyll-*a* depletion magnitudes (< 5 percent of background), the modelled depletion halos of the two farms are largely influenced by local hydrodynamics. In particular, the westernmost farm shows a depletion zone extending both horizontally and vertically while the easternmost farm shows a more vertically restricted (and horizontally extensive) depletion halo (Figure 8.19).[212] The greater vertical extent of the westernmost farm's depletion halo is related to the vertical mixing caused by upwelling and downwelling processes occurring at this location (and not at the location of the easternmost farm),

212 It is important to note the large-scale variation shown in this figure between the vertical and the horizontal axes.

Longdill, Healy and Black (2008b). Magnitudes and extents of these depletion halos were summarized within the GIS. Simulated interactions between the mussel farm and the surrounding waters (such as mussel-farm-related chlorophyll-*a* and ammonium concentration changes) varied substantially throughout the year owing to seasonal environmental stressors.

FIGURE 8.19
Modelled changes in chlorophyll-*a* concentration resulting from two mussel farms (% change from no mussel farm scenario).

Predicted mussel-farm induced *Chlorophyll-a* Changes (% of no mussel farm simulation) - Yearlong



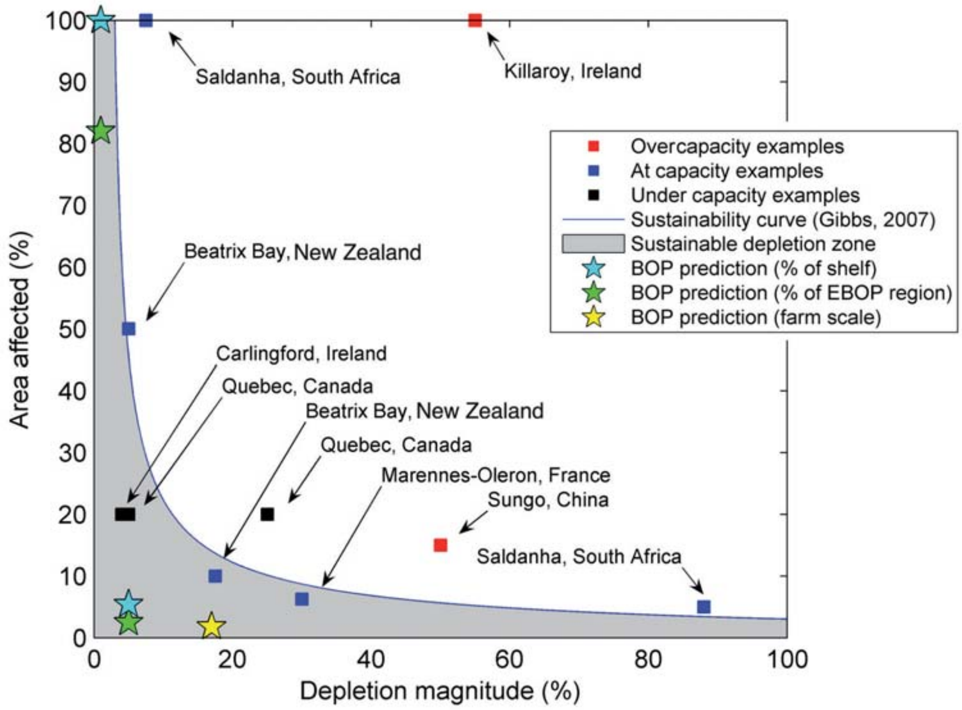
Note: The mussel farms are located where the highest depletion in chlorophyll-*a* are observed in the different shades of red. The rectangles represent the locations of islands (compare with Figure 8.17), i.e. the four white rectangles shown in Figure 8.17.
Horizontal surfaces of model results are shown at -2.5, -20, -40, and -60 m depths.

Source: Source: Longdill (2008).

Discussion, conclusions and recommendations: The applied method can effectively identify the most suitable areas (based on the predefined input criteria), and indicate the potential level of impact (on basic ecological variables and based on a predefined farm size/type). However, difficulty arises when attempting to answer the final question of "What level of aquaculture is acceptable or sustainable?"i.e. What is the ecological carrying capacity? The study attempted to provide some response to this question by placing the magnitude and spatial extent of chlorophyll-*a* change (used as a proxy for phytoplankton) into a global context. A promising methodology for assessing the limits of "acceptable"depletion magnitudes and spatial extents is that of depletion limits. This methodology requires that consideration be given to both the magnitude of depletion and the spatial scale over which it occurs. Specific definitions and the application of "acceptable depletion limits" or "trigger values"are currently only in the initial stages of implementation with respect to aquaculture (e.g. Gibbs, 2007). Through a review of other studies and their authors' assessments of carrying capacities, an "acceptable depletion curve"was generated and results from the Bay of Plenty model included (Figure 8.20).

For the simulated farms within the Bay of Plenty, the predicted extent of the 5 percent chlorophyll-*a* depletion halo reached a maximal value of 243 km^2 (during autumn), while the 1 percent depletion halo reached a maximal value of 7 821 km^2 (during winter). Converting the extent of these depletion halos to a percentage-based value (required for depletion magnitude-extent values) presents a problem on open

FIGURE 8.20
Bivalve aquaculture induced chlorophyll-*a* depletion values



Source: Longdill (2008).
Sustainability curve concept from: Gibbs, (2007).

coast sites because a "total area"must be defined in a location where boundaries can be difficult to define. Suitable boundaries within the Bay of Plenty might be the continental shelf (extending to 200 m water depth) and the marine administrative area of the regional council (EBOP). The use of both these areas results in multiple potential depletion magnitude-extent combinations, i.e. blue and green stars respectively in Figure 8.20, rather than single point estimates. Predicted depletion magnitude-extent combinations using both of these boundaries, along with the maximal extents of the 1 and 5 percent depletion halos and the maximal depletion at farm scales (17 percent over ~85 km^2 and the yellow star in Figure 8.20) all result in combinations well within the "sustainable zone"of the inferred "sustainable depletion curve"(Figure 8.20).

Challenges and benefits from the case study: The application of the GIS to identify the most suitable sites for aquaculture in an open coast location appears to be beneficial. However, several challenges were met during the study and they must be either overcome or acknowledged for the study to be useful. These include the costs of data collection and a focus on a predefined aquaculture system and species. By using such a predefined system and species, however, the analysis can be taken further to include preliminary productivity estimates and economic aspects for a future aquaculture lease as demonstrated by some of the data layers employed in this study. There should be no doubt that the identified areas cannot, on the sole outcome of such a GIS analysis, be assigned as aquaculture areas. The analysis can be used to indicate suitable (and unsuitable) locations, though much more consultation and many agreements would of course be required prior to implementation.

This study and others of its type also fail to allow for the future changes in existing uses and/or users, legal settings and culturing techniques. Such changes could of course lead to fundamentally different outcomes. If these are real and key concerns for the study, the application of the described approach should be kept in perspective. Additionally, the technique favours existing uses of the marine area as it does not consider that aquaculture may have as much of a “right”to an area as a pre-existing use. The use of an ecological model to simulate potential farms and the corresponding GIS analysis represent a valuable and exciting future direction for the use of GIS and aquaculture.

8.4.4 Development of potential and financial viability of fish farming in the Republic of Ghana

Original publication reference: Asmah, R. 2008. *Development of potential and financial viability of fish farming in Ghana*. Institute of Aquaculture. University of Stirling. 289 pp. (PhD dissertation)
Spatial tools: The primary software tools used were IDRISI Andes and Cartalinx.
Main issues addressed: Strategic planning for development.
Duration of study: 1 year.
Personnel involved: Ruby Asmah (PhD student), James Muir (principal supervisor) and Lindsay G. Ross (additional supervisor).
Target audience: Water Research Institute of the Council for Scientific and Industrial Research, Accra, Ghana. Fisheries Commission of the Ministry of Food and Agriculture, Ghana, and aquaculturists.

Introduction and objectives: The Republic of Ghana is located in West Africa, a few degrees north of the equator. It has a total land area of 238 540 km^2 and a coastline length of 550 km. Aquaculture has been practised in Ghana since the 1950s, but until about a decade ago fish culture was largely undertaken in earthen ponds, primarily at the small-scale level and where rudimentary tools were employed. From about 1998, the sector has transformed with the introduction of commercial cage fish farming in Lake Volta. Vigorous campaigns and promotions of the sector by government agencies over the years have further enhanced commercial interests of both foreign and local investors. A number of farms, with targeted production capacities ranging from 700 to 5 000 tonnes per annum, have been established within the last five years and are operating at various levels of their full capacities. Several other small-scale production facilities or farms, mainly operated by locals, have also sprung up and their numbers continue to grow. The main cultured species is Nile tilapia (*Oreochromis niloticus*). Other cultured species are African catfish (*Clarias gariepinus*), African Arowana (*Heterobranchus spp.*), striped snakehead (*Channa striata*), grey mullet and Heterotis sp. (Asmah, 2008).

Decreased fish production from wild capture coupled with increasing human population in the Republic of Ghana has led to a shortfall in domestic fish supply with current annual supplies being about 40 percent less than the required 735 000 tonnes. With aquaculture being a more reliable way of increasing fish production than management of wild stocks, the Government of the Republic of Ghana has enhanced its focus on aquaculture with a goal of increasing production from 1 150 tonnes per annum (2006 annual production figure) to 15 000 tonnes in about five years. A key issue in aquaculture development is that of defining its potential location and scale. This conventionally involves site selection, and requires definition of conditions and strategic locations where appropriate farming systems can be developed, although this can be complicated by conflicting economic, social and environmental interests and the requirement for the activity to be commercially viable (McLeod, Pantus and Preston, 2002). With an adequate database, however, GIS can be used to organize and present spatial data to allow effective environmental management planning, and GIS can thus serve as a powerful analytic and decision-making tool (Nath *et al.*, 2000).

The first assessment of the country's fish farming opportunities using GIS was undertaken by Kapetsky *et al.* (1990) to identify the districts with the best prospects for farming Nile tilapia (*Oreochromis niloticus*) and African catfish (*Clarias gariepinus*) in ponds with manure and rice bran as the main inputs. Other assessments involving the Republic of Ghana and other countries in the African region were those by Kapetsky (1994) and Aguilar-Manjarrez and Nath (1998).

The objective of this study was to use a GIS approach to reassess the potential for small-scale and commercial aquaculture development in the Republic of Ghana in the light of the expected expansion in the sector, using data of higher resolution compared with previous studies and incorporating recommendations for improved assessment methods mentioned in the previous studies. The study focused on freshwater aquaculture, considered to be the primary area of sectoral development at this stage, with particular but not exclusive focus on tilapia. It incorporates primary definers[213] of water, climate, soils and feed/fertilizer sources, together with more specific issues such as market access and other social and economic factors. This case study is a summary of Chapter 5 from Asmah (2008).

Methods and equipment: Data were obtained from secondary sources, primarily from the Ghana Country At a Glance (G-CAG) database, which was developed in 1999 as an additional resource to the Environmental Information System Development component of the Ghana Environmental Resource Management Project (GERMP). Fifty-one geographical, referenced and harmonized data sets covering 12 geographical themes are presented in the database. The themes are: national and international boundaries, conservation areas, climate information (temperature, rainfall and evapotranspiration), geology, hydrology, land cover, land ownership, soils, topography, infrastructure, transportation and population information.

Digital elevation models used in the slope submodel were obtained from the Shuttle Radar Topography Mission (SRTM) Web site (http://srtm.usgs.gov/index.php). Updated information on district populations and growth rates used in the market submodel were obtained from the Ghana Statistical Services 2000 population and housing census report (Ghana Statistical Service, 2002) and the Ghana Districts Web pages (www.ghanadistrict.com). Information on road density for each of the districts was obtained from online reports at the Ministry of Roads and Highways (www.mrt.gov.gh).

The suitability of areas for aquaculture development in the Republic of Ghana was assessed by identifying important factors and constraints. A factor (or production function) is defined as a criterion that adds to the suitability of the specific alternative area under consideration, while a constraint serves to limit alternatives under consideration (Eastman, 2001), such as forest and game reserves, road networks, river courses and large waterbodies (in relation to pond construction). Factors considered basic for aquaculture development in the study were: water availability and quality, terrain and soil suitability, infrastructure in the form of roads, support in the form of extension services and supply of fingerlings, availability of inputs (manure, agriculture by-products and other feed types) and markets.

[213] "Primary definers" are the basic physical and biological factors that control the possibility of (in this case) fish production taking place.

The factors were classified in four suitability rankings i.e. very suitable (VS), suitable (S) fairly suitable (FS) and unsuitable (US). The VS level provides a situation in which minimum time or investment is likely to be required in order to develop fish farming, an S classification implies that modest time and investment are required, FS level implies that significant interventions may be required before fish farming operations can be conducted, while US implies that the time or cost, or both, are too great to be worthwhile for fish farming (Aguilar-Manjarrez and Nath, 1998). Criteria classifications for the various factors are summarized in Table 8.4. Classification was primarily based on the literature and on prevailing practices in the Republic of Ghana (referred to as local practices).

To develop a decision-making model, the selected and classified criteria were developed into a series of submodels that can logically group certain factors together within a general model. For example, some factors were grouped to form submodels naturally, e.g. in a soil classification, soil texture, soil pH and slope were grouped into a submodel called soils and terrain, while some others factors were grouped into submodels to enable a better understanding, e.g. research centres and fisheries offices were grouped to form a support submodel. Aguilar-Manjarrez (1992, 1996) and Aguilar-Manjarrez and Ross (1995b) noted that the creation of submodels may be divided into stages within the general model, i.e. primary, secondary, tertiary, etc. The number of stages will vary according to the application, but the overall approach is the same and contains the following steps:

(i) The primary stage of the models constitutes its foundation and is represented by the collection of original data, i.e. thematic maps, statistical data and data available in computer format.

(ii) In the second stage, factors are grouped naturally, i.e. river density, effective rainfall and annual rainfall were associated to a water sources group, and as nonspecifically as possible (Table 8.4).

(iii) As the model develops, more submodels are created in a more specifically orientated way so as to develop specific responses required by the user, e.g. construction constraints for pond construction.

(iv) Only at the very end of the modelling process do the groupings become application-specific in order to solve a particular problem/issue, e.g. suitability for commercial farming of Nile tilapia.

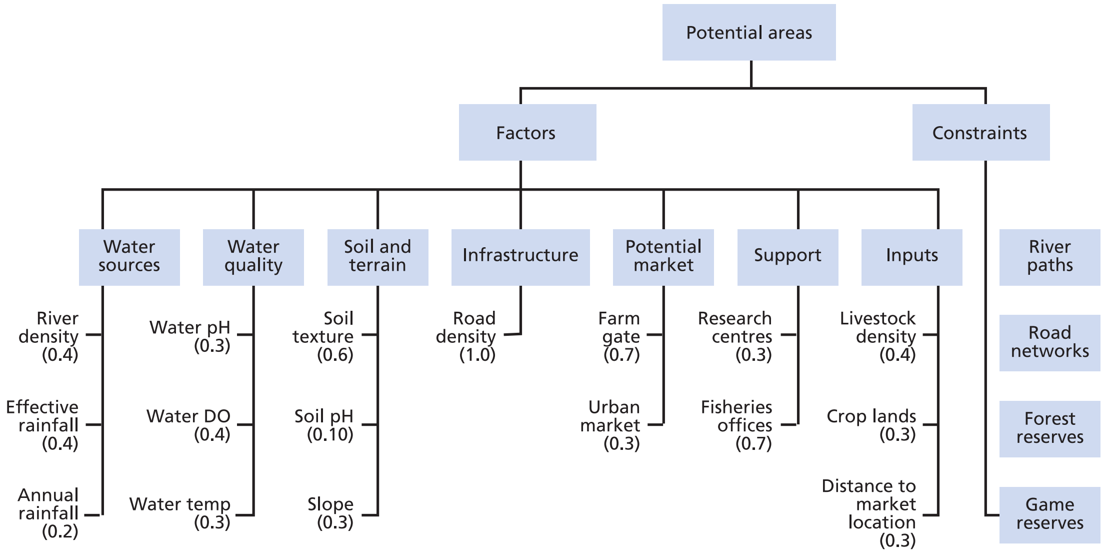
To illustrate the approach used, Figure 8.21 is a schematic diagram of the integration of the submodels showing the weights applied to each submodel.

TABLE 8.4
Criteria classification

Land characteristics	Classification criteria				References
	Very suitable	Suitable	Fairly suitable	Unsuitable	
Water sources submodel					
Annual rainfall (mm)	> 1 200	1 000–1 200	700–1 000	> 700	Kapetsky, 1994
Effective rainfall (mm)	≥ 0	1 to -2000	-2000 to 3499	< -3500	Aguilar-Manjarrez and Nath, 1998
Perennial river density (km/km²)	≥ 0.36	0.2–0.35	0.04–0.20	< 0.04	Kapetsky, 1994
Water quality submodel					
pH	6.0–8.0	5.0–6.0	4.0–6.0	< 4.0	Salam, 2000
Dissolved oxygen (mg/l)	5.0–10.0	4.0–5.0	3.0–4.0	< 3.0	Salam, 2000
Water temperature (°C)	25–32	22–25	18–22	0–18	Salam, 2000
Soil quality and terrain submodel					
Soil texture (%)	> 80	50–80	20–50	0–20	Coche and Laughlin, 1985
Soil pH	6.5–8.5	5.5–6.5	4–5.5	1.0–4.0	Coche and Laughlin, 1985
Soil slope (%)	0.2	2 – 5	5–8	> 8	Coche and Laughlin, 1985
Infrastructure submodel					
Road density (km/km²)	≥ 0.36	0.20 – 0.36	0.04 – 0.19	< 0.04	Kapetsky, 1994
Market submodel					
Farmgate (inhabitants/km²)	150–310	25–150	1–25	< 1 and > 31	Kapetsky and Nath, 1997; Aguilar-Manjarrez and Nath, 1998
Urban market (inhabitants/km²)	> 1 000 000	250 000 – 1 000 000	50 000 – 250 000	< 50 000	Aguilar-Manjarrez and Nath, 1998
Proximity to urban market (km)	0–165	165–330	330–499	> 500	Based on local practices
Inputs submodel					
Crop lands (suitability index)	80– 00	50–79	20–49	< 20	Boateng *et al.*, 2001
Proximity to urban market locations (km)	0–166	167–333	334–499	> 499	Based on local practices
Support submodel					
Proximity to institutions and commercial farms (km)	100	200	300	> 300	Based on local practices

Note: The suitability index refers to the suitability of an area for growing particular crops whose by-products (e.g. rice bran, waste crops etc) were used as fish feed by farmers. Soil type and other environmental factors were considered for this index.

FIGURE 8.21
Schematic diagram of submodels showing the weights applied to each factor



Results: Results of the submodels showing the size (km²) and percentage of total land area identified as very suitable, suitable, fairly suitable and unsuitable are summarized in Table 8.5, and are presented pictorially in Figure 8.22. Included in Table 8.5 are the results of the integrated models in which size and percentage suitabilities of land for small-scale and commercial farming are indicated.

Integrated models

The submodels were integrated using the weights shown in Table 8.6. Maps of the integrated submodels are presented in Figure 8.23 a and b. About 80 percent (191 854 km²) of the country's land area, excluding forest and game reserves (47 017 km² in size), were found to be suitable for small-scale fish farming. Of this, close to 2 percent (3 692 km²) was very suitable, 97.4 percent was suitable, and less than 1 percent was fairly suitable (Figure 8.23a). The very suitable areas for small-scale farming were largely in the Ashanti and eastern regions, and these were areas where a number of the relevant variables overlapped each other favourably.

The area of land found to be very suitable for commercial farming (Figure 8.23b) was about ten times smaller (314 km²) than that for small-scale farming, and this may be attributed to the greater emphasis placed on market and infrastructure. These areas were again in the Ashanti and eastern regions. A much larger area (161 943 km²) of the country was, however, found to be suitable for commercial farming, which based on the definition of suitability given in the methodology overview, implies that modest time and investment may be required to implement such projects. Similar to that for small-scale aquaculture, the fairly suitable sites were largely in the northern-most part of the country, more precisely in the upper east and upper west regions (Figure 8.23b).

The weights derived for each culture system submodel were based on feedback from aquaculture and development specialists in the Republic of Ghana and the United Kingdom of Great Britain and Northern Ireland between 2004 and 2008. Weights assigned for each submodel ranged from 0–1.

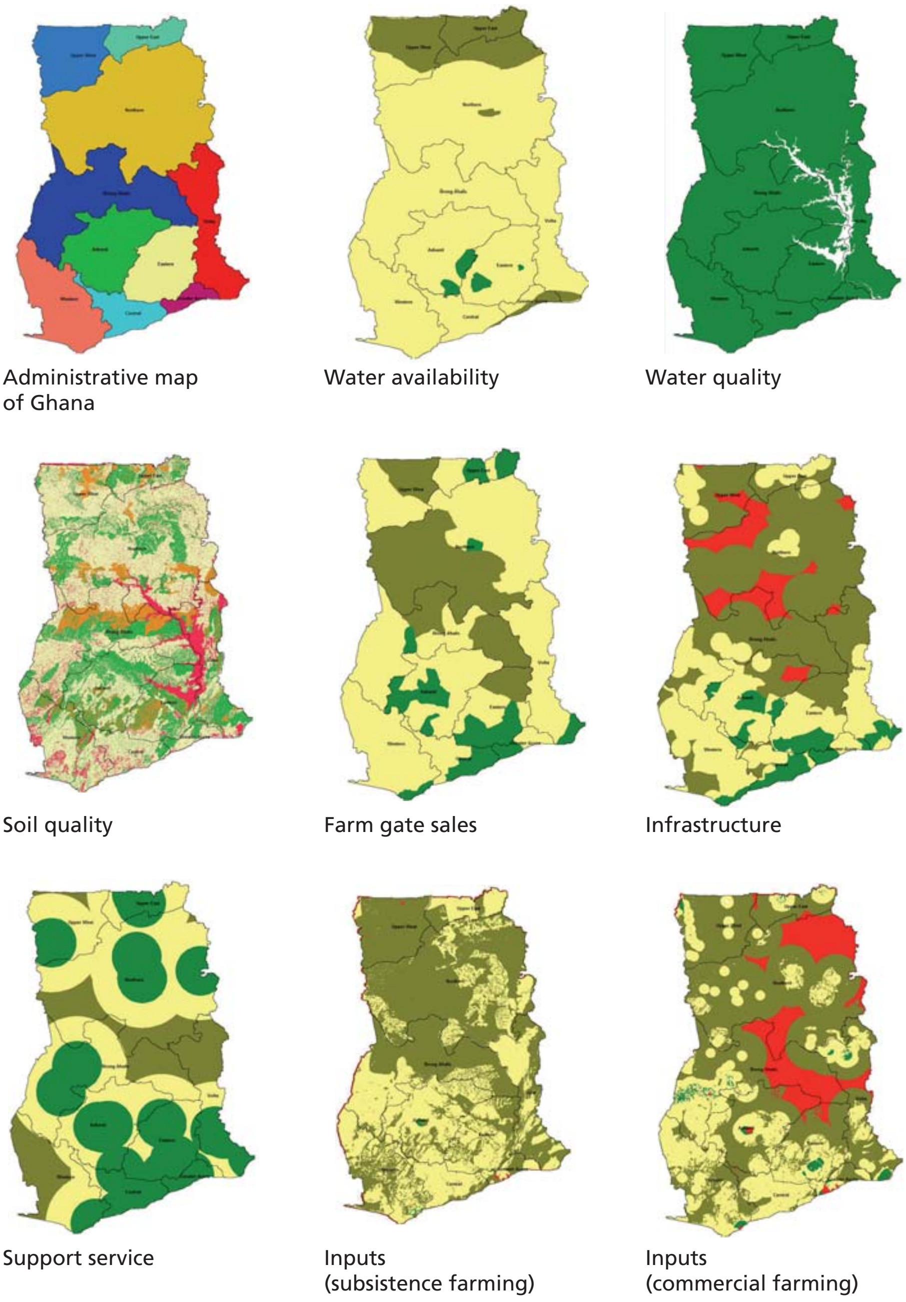
TABLE 8.5
Areas (km²) and percent suitabilities of lands for the factors, submodels and integrated models for small-scale and commercial farming

Land characteristics	Very suitable		Suitable		Fairly suitable		Unsuitable	
	Km^2	%	Km^2	%	Km^2	%	Km^2	%
Inputs submodel								
Effective rainfall	-*	-	184 102	77.1	54 769	22.9	-	-
Perennial river density	4 661	2.0	126 916	53.1	91 357	38.2	15 936	6.7
Annual rainfall	128 257	53.7	70 770	29.6	39 842	16.7	-	-
Overall	4 113	1.7	194 856	81.6	39 901	16.7	0.36	0.0
Water quality submodel								
Water temperature	238 872	100	-	-	-	-	-	-
pH	238 872	100	-	-	-	-	-	-
Dissolved oxygen	194 101	81.3	44 770	18.7	-	-	-	-
Overall	238 872	100	-	-	-	-	-	-
Soil quality and terrain submodel								
Soil texture	34 546	14.4	41 790	17.5	52 610	22.0	110 305	46.1
Soil pH	42 555	17.8	156 122	65.3	25 140	10.5	15 436	6.5
Slope	62 042	27.9	99 634	44.8	29 924	13.4	30 901	13.9
Overall	21 709	9.1	62 516	26.1	130 468	54.4	24 876	10.4
Infrastructure submodel								
Road density	28 106	11.8	70 883	29.7	131 712	55.1	8 170	3.4
Market submodels								
Farmgate	16 482	6.9	146 426	61.3	65 185	27.3	10 777	4.5
Urban market and proximity	480	0.2	35 927	15.0	202 463	84.8	-	0.0
Inputs submodel								
Crop lands	2 790	1.2	47 707	20.0	67 887	28.4	120 489	50.4
Animal density	2 015	0.8	13 266	5.5	141 267	59.0	82 904	34.6
Proximity to urban market locations**								
Over all	260	0.1	41 458	17.2	158 858	66.0	40 103	16.7
Support submodel								
Proximity to institutions	96 760	40.5	98 009	41.0	44 101	18.5	-	0.0
Integrated models								
Final model – small-scale	3 692	1.9	186 880	97.4	1 278	0.7	-	-
Final model – commercial	314	0.2	161 943	84.4	29 597	15.4	-	-

* The area is less than 1 km2 . ** Physical locations.

Note: The data in Table 8.5, represented by Figure 8.22 include the reserved areas. These areas were only taken out in the final integrated models in Figure 8.23 a and b, as they show areas where one can supposedly site a pond.

FIGURE 8.22
Results of the submodels used in overall model building



Note: In Figure 8.22, green = very suitable, beige = suitable, brown = fairly suitable and red = unsuitable. The classification of water quality as “very suitable” over the whole country is based on the three factors used in this model. However, this portion of the model should be retained in the overall structure so that any future change or addition of new factors can be easily accommodated to reflect new scenarios.:

TABLE 8.6
Weights derived for the submodels

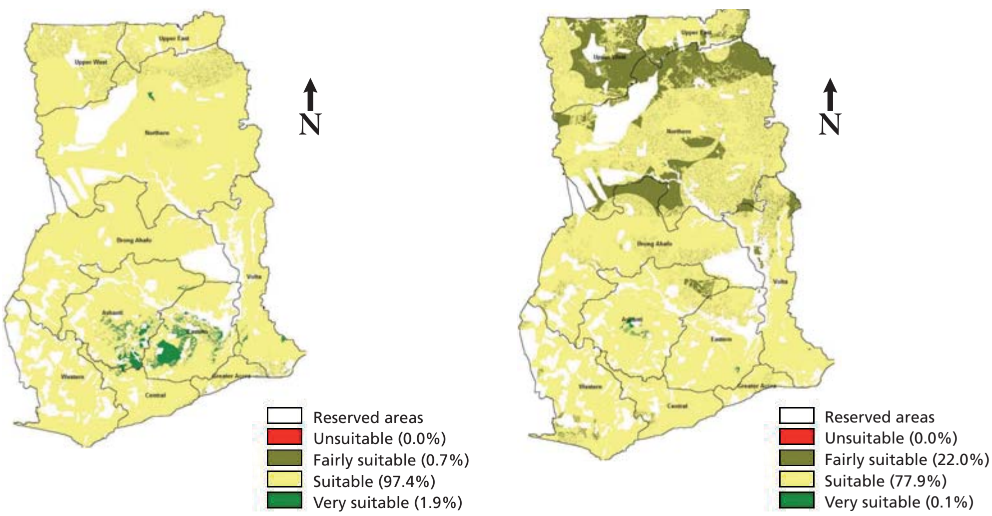
Submodels/ models	Water resources	Water quality	Soil quality and terrain	Infrastructure	Markets	Inputs	Support	Total weight
Small scale	0.41	0.18	0.21	0.06	0.01	0.07	0.06	1.0
Commercial	0.27	0.15	0.12	0.08	0.25	0.08	0.05	1.0

The inputs submodel was given a low rating for both small-scale and commercial farming because most fish farmers obtained ingredients from the market and produced their own feed on the farm so availability was not an issue. On-farm feed production was only abandoned in recent times as people have realized that imported extruded feed gave better growth rates and that the quality of inputs is very important. Markets had a high rating for commercial farming as it served two purposes: (i) selling of product; and (ii) buying of feed components. Farmed fish did not have the market that it has now and there were times when farmers could not sell their produce, so identifying a good market in the early to mid-2000s was very important. The commercial farmers also produced their own fingerlings on-farm from broodstock that were sometimes obtained from the wild.

FIGURE 8.23
Suitability classification for fish farming

a. Suitability classification for small-scale farming

b. Suitability classification for commercial farming

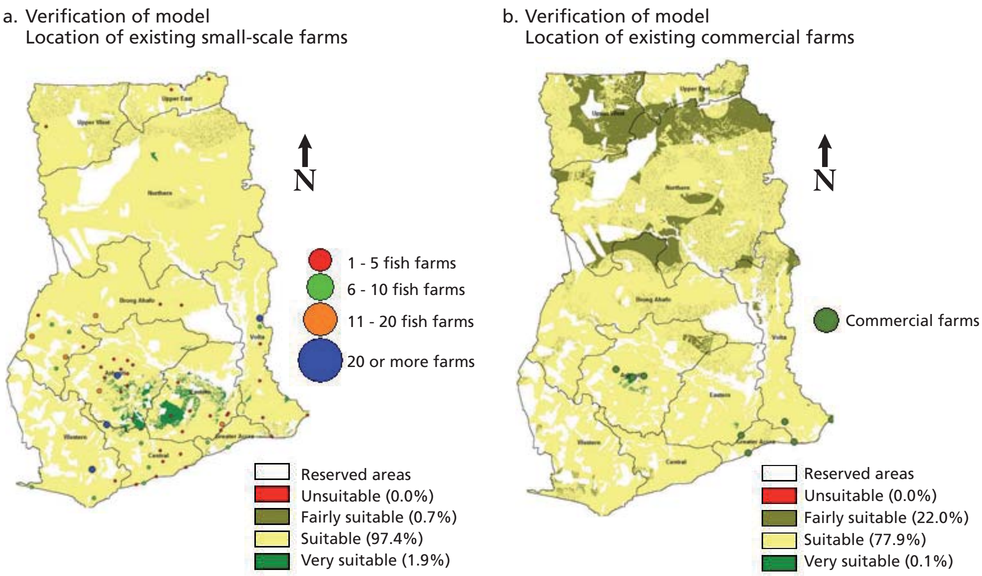


The key differences in factor rankings for small-scale compared with commercial farming were in the relative importance placed on urban markets and infrastructure with respect to likely commercial farming success. Harvests from commercial farming will be expected to sell beyond the farmgate where proximity to urban markets and infrastructure becomes very important, whereas in small-scale farming farmers consume part of the harvest, use some as compensation for labour and sell the surplus locally. Water availability, water and soil quality, and terrain models were given the highest importance in small-scale farming, as farmers in this category may not be in a position to incorporate expensive technologies.

Verification of integrated models

The verification process simply compares the extent to which current fish farms are located in the optimum areas predicted by the models. Outcomes of the verifications are presented in Figure 8.24 a and b for small-scale and commercial farming, respectively. Most of the fish farms in both cases were located in areas classified as either very suitable or suitable and largely concentrated in the southern and middle belts of the country. The concentration of pond farms within particular areas is depicted on the map by the colours red, green, orange and blue for areas with 5 farms or less, 6 to 10 farms, 11 to 20 farms, and more than 20 farms, respectively.

FIGURE 8.24
Verification of models



Discussion, conclusions and recommendations: In general, the very suitable areas for both levels of production were all in the southern parts of the country, specifically the Ashanti and eastern regions. Kapetsky *et al.* (1990) also identified the southern part of the country as having the best opportunities for fish farming.

Based on an overview of fish farming in the Republic of Ghana undertaken by Asmah (2008), mean fish yield/ha by small-scale farming was found to be 2.3 tonnes/annum. Yields by commercial farmers were varied ranging from 4.4 tonnes/ha per annum to 45 tonnes/ha per annum depending on scale and intensity of production. Commercial farming currently accounts for about 60 percent of the country's annual aquaculture production. Meeting the government's target of 200 000 tonnes of fish production from aquaculture per annum in five years, based primarily on pond culture and current production practices and trends, may require developing about 13 978 ha (14 km^2) of land for commercial farming and 34 783 ha (347.8 km^2) of land for small-scale fish farming, which, based primarily on the availability of land, is certainly feasible. Aquaculture production of 1 150 tonnes in 2006 and an annual mean farm development growth rate of 16 percent (Asmah, 2008), however, makes the target unachievable in the time scale given. Achieving this target, in addition to considering the availability of land, may require a growth rate of both commercial and small-scale farming of not less than 60 percent per annum over five years.

Challenges and lessons from the case study: This study uses data available from public sources to generate a holistic overview of aquaculture opportunities in the Republic of Ghana in order to support broad-scale strategic planning decisions. A multi-criteria evaluation (MCE) technique was used to generate logical submodels and MCE was used again in order to combine submodels to achieve the overall project objectives. The model structure and the assignment of weights used were based on expert opinion from United Kingdom and Ghanaian aquaculture and development specialists. Model structure and weight assignment are an important stage and is what distinguishes simple cartography from more advanced use of such systems to form expert models. While further data refinement and model adjustment could be achieved, the outcome is nevertheless a powerful illustration of the integrative use of GISs and their ability to work with and model from widely disparate data sets.

This study is based on a relatively simple model structure and, consequently, is easily replicated for other countries (assuming that the data are available), for example, to support the preparation of national aquaculture strategies and national development plans. Having identified potential areas within the Republic of Ghana, more detailed studies would follow using data sets at a greater resolution to allocate zones for aquaculture and to conduct site selection and carrying capacity assessments and to establish monitoring programmes.

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

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9.1 INTRODUCTION

Applications of GIS and remote sensing technologies have increased dramatically since the mid-1980s (Meaden, 2001; Fisher, 2007). Although GIS and remote sensing have been widely applied to marine fisheries, there have been fewer applications of these technologies in inland fisheries management and planning. Like many marine fisheries GIS applications, inland fisheries applications of GIS have largely dealt with mapping the distribution and abundance of fish species, and mapping and modelling habitat in rivers, reservoirs and lakes, and relating the two (Meaden and Kapetsky, 1991; Nishida, Kailola and Hollingworth, 2001; Fisher, 2007; Nishida, Kailola and Hollingworth, 2004; Nishida, Kailola and Caton, 2007). Unlike marine fisheries, which occur widely in oceans and where data on catch and the environment may be dense from landings and remote sensors, freshwater data are sparse and are much more limited in space and time. Geostatistical and distributional modelling of fishes, spatially explicit fish population modelling, predicted species distributions, and the use of remote sensing and sensor networks are some of the challenges and opportunities for freshwater fisheries managers and researchers using GIS.

Meaden and Kapetsky (1991) reviewed GIS and remote sensing applications in inland fisheries and aquaculture, particularly as they relate to spatial decision-making. They describe an approach to decision-making using spatial data that begins with aims and objectives, identifies spatially variable production functions (i.e. factors that control economic activities) and the necessary data to describe them, converts these data into thematic and derived maps in a GIS, and concludes with decisions about locations for fishery production. This approach emphasizes the importance of spatial data, whether it is physical, biological, social or economic, in guiding decisions about fisheries management and planning. Recent summaries of the use of GIS and remote sensing in inland fisheries management and planning provide much of the information used in this technical paper (Nishida, Kailola and Hollingworth, 2001; Fisher and Rahel, 2004a; Nishida, Kailola and Hollingworth, 2004; Nishida, Kailola and Caton, 2007).

The aim of this chapter is to describe the present use of GIS and remote sensing in inland fisheries management and planning. Some detail is given on five main thematic areas in which GIS is applied with respect to inland fisheries. The current status of this GIS work is also examined as it pertains to the main geographic areas where inland fisheries related GIS work is being applied, and the main inland fisheries themes are discussed, i.e. as derived from FAO's Aquatic Sciences and Fisheries Abstracts (ASFA) database on fisheries and aquaculture. The chapter concludes with three case studies on the use of GIS and remote sensing in management and planning for inland fisheries.

9.2 INLAND FISHERIES THEMES AND GIS APPLICATIONS

In Table 1.1 (Section 1.4), the major GIS and fishery themes were identified for marine fisheries, inland fisheries and aquaculture. In Box 9.1, the focus is on themes that are specific to GIS applications in inland fisheries. These themes are an update of those identified by Fisher (2007) for freshwater environments and they focus on GIS processes (operations and analyses).

BOX 9.1
Main themes relating to GIS applications in inland fisheries

Among the variety of GIS applications in inland fisheries, the following themes and operations identify those that are commonly used in freshwater.

- **Visualization and species distribution modelling** – Mapping and visualizing fish distribution and abundance and aquatic habitat remains the most common use of GIS in inland fisheries.
- **Fish movements** – Mapping fish locations and measuring rates of fish movements provide information for managing populations and their habitat.
- **Habitat modelling** – Combining data on fish locations with instream habitat features, such as spawning, feeding and refuge areas, informs stream habitat management and restoration efforts.
- **Watershed management** – Identifying land use and land cover types, topography and elevation, and hydrography and waterbody types and relating these features to fish populations and communities allows for integrated fisheries management.
- **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.

Source: Modified from Fisher (2007).

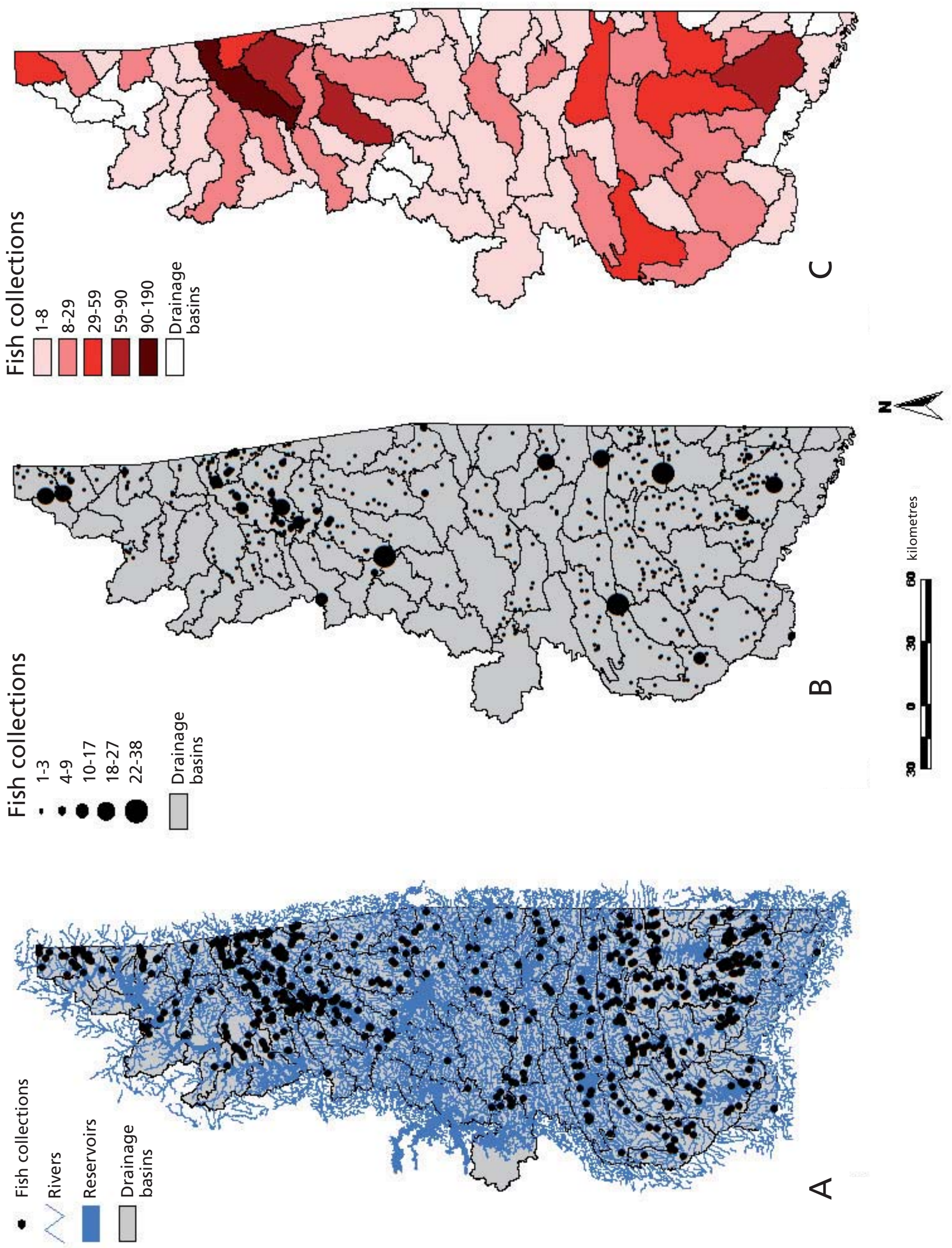
9.2.1 Visualization and species distribution modelling

Nearly all GIS applications in inland fisheries (and all other fisheries for that matter) involve the visualization of fish locations in their environment. This visualization is most often in the form of maps of fish occurrence and/or the habitats they occupy. This fundamental use of GIS provides a geographic frame of reference that can be used to effectively communicate information about the fish population or community. Because of the scalability of GIS, maps can be created at nearly any geographic or spatial scale from a single stream reach to a drainage basin or to an entire continent. These maps can be depicted as point locations in streams or lakes or as drainage basins in a region. For example, Fisher and Rahel (2004b) illustrated the distribution and density of collections of a minnow, the central stoneroller (*Campostoma anomalum*), in streams and drainage basins in eastern Oklahoma, the United States of America (Figure 9.1).

Data on fish species locations is one of the primary components used to model species distributions. This locational data is combined with habitat data about the inland environments, including physical features such as bottom type, vegetation type or woody debris, land use types, and physico-chemical conditions such as water temperature, dissolved oxygen, water depth and water flow. Species-habitat models in GIS are used to model occurrences and suitable areas for fish populations in streams and rivers (Fausch *et al.*, 2002; Fisher and Rahel 2004b) and reservoirs (Amarasinghe, De Silva and Nissanka, 2002; Paukert and Long, 2004) and lakes (Bakelaar *et al.*, 2004; Vander Zanden *et al.*, 2004). Species distribution modelling is a valuable tool for managing and conserving inland fisheries resources.

FIGURE 9.1

Maps of the central stoneroller collections in eastern Oklahoma, United States of America, depicted as occurrence (A) and density by symbol size (B) and drainage basin (C)



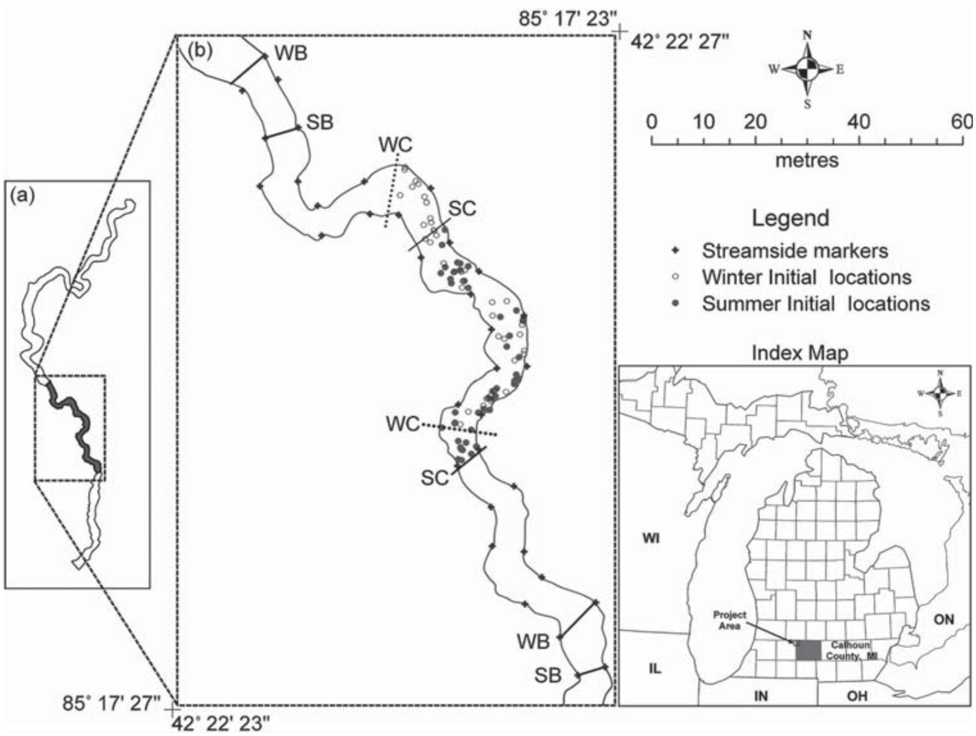
Source: Fisher and Rahel (2004b).

9.2.2 Fish movements

Understanding when and where fish move provides important information for managing fish populations and for location decisions made by anglers. Tracking fish movements in freshwater environments involves using some type of tags (passive integrated transponder, PIT) or tracking (radio or ultrasonic telemetry) device. These devices are inserted (tags) or implanted (transmitters) in fish and tracked either by collecting the fish or detecting the fish with an external sensor or receiver. Fish movements in inland streams, rivers, reservoirs and lakes have been studied extensively, particularly with underwater telemetry (Winter, 1996). Figure 9.2 illustrates summer and winter locations of mottled sculpins (*Cottus bairdii*) that were tagged with PIT tags in a stream in Michigan, the United States of America (Breen *et al.*, 2009)[214]. Fish locations were recorded with a GPS and these data files were exported to a GIS for visualization, error correction and distance measurements. This approach of recording locations of fish tagged with transmitters using GPS and exporting those data to GIS for analysis of movements and home range is increasingly being used in freshwater environments to understand individual and population-level movement patterns.

FIGURE 9.2

Map of PIT-tagged mottled sculpin locations during summer and winter in a 700-m reach of Seven Mile Creek, Michigan, United States of America



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

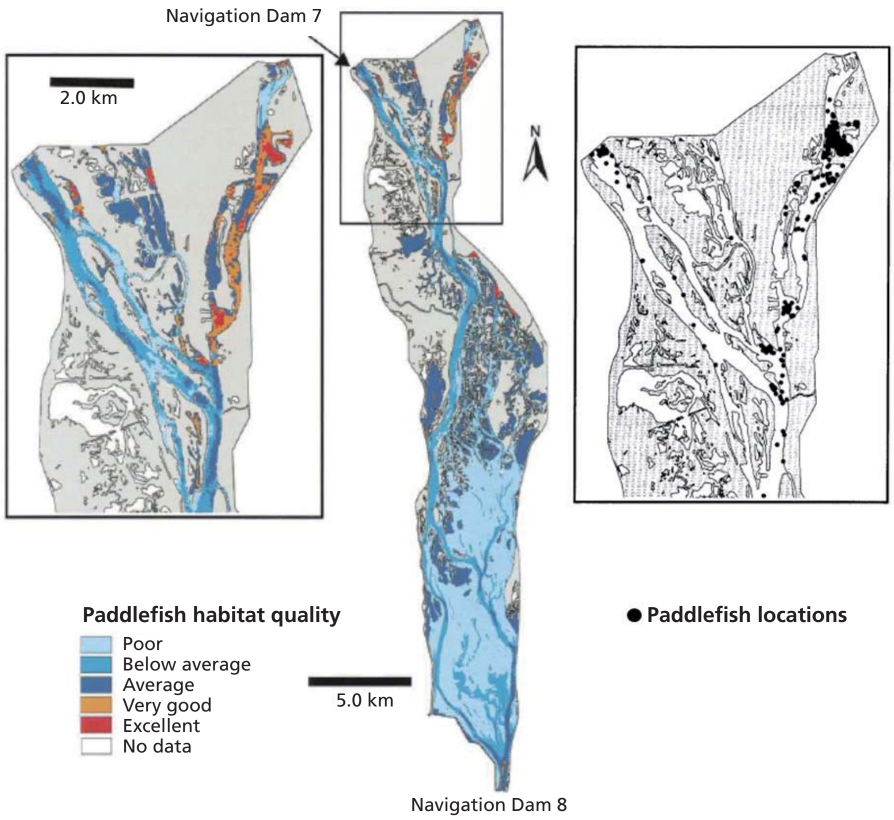
9.2.3 Habitat modelling

GIS has been widely used 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

[214] Figure 9.2 (a) represents the complete 700-m stretch and (b) represents a central 170-m stretch of the Seven Mile Creek.

them according to their importance based on statistical analyses or expert opinion. The results from the modelling are usually depicted in a GIS map of the freshwater environment. These suitability models can be validated with independent data of fish locations. In Figure 9.3, suitable habitat for paddlefish (*Polyodon spathula*) was modelled for an area (Navigation Pool 8) of the upper Mississippi River, the United States of America (Zigler *et al.*, 2003). A cartographic model was created using GIS layers for bathymetry and current velocity. Areas of the river with deep water (≥ 6 m) and slow flow (< 5 cm/s) were classified as excellent habitat. Areas with "excellent" and "very good" habitat collectively encompassed 74 percent of all paddlefish observations in Navigation Pool 8; however, these areas accounted for only 2.6 percent of the total area of the watercourse between Navigation Dams 7 and 8 (Figure 9.3 – the whole of the middle map). The authors concluded that suitable habitat is relatively limited in the upper Mississippi River system and connections between suitable areas are impeded by the navigation dams.

FIGURE 9.3
Map of suitable habitat for paddlefish in the upper Mississippi River, the United States of America and locations of paddlefish obtained from radio telemetry tracking

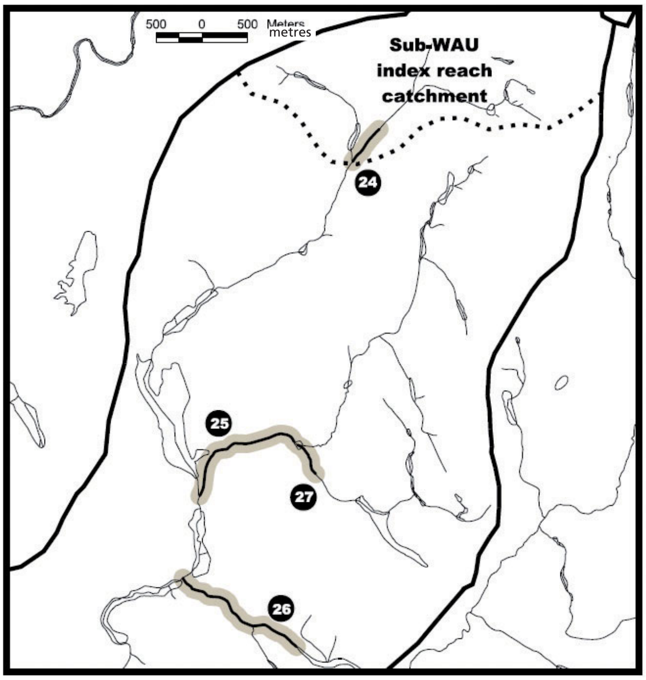


Source: Zigler *et al*. (2003).

9.2.4 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 the stream or lake and thereby affecting fish populations and communities (Wang *et al.*, 1997). Pess *et al.* (2002) explored relationships between adult coho salmon (*Oncorhynchus kisutch*) abundance and landscape characteristics (wetlands, surficial geology, stream gradient, potential for landslides), and land use-land cover types (forest, rural residential, agriculture, urban, roads). Figure 9.4 shows the study area, the four sampling reaches (numbers 24–27) and the 100-m buffers (grey areas) around them from which watershed landform and land use data layers were obtained. Data for these landscape and land use characteristics were obtained using GIS, which is common among studies of this type. The authors found that wetland occurrence, local geology, stream gradient and land use type were significantly correlated with adult coho salmon abundance, and that fish densities were 1.5 to 3.5 times greater in forested areas than in rural, urban and agricultural areas. Understanding the relationship between these watershed factors and fish population and communities enables resource managers to prioritize areas for restoration and protection.

FIGURE 9.4
Stream reach and watershed areas in the Snohomish River, Washington, United States of America

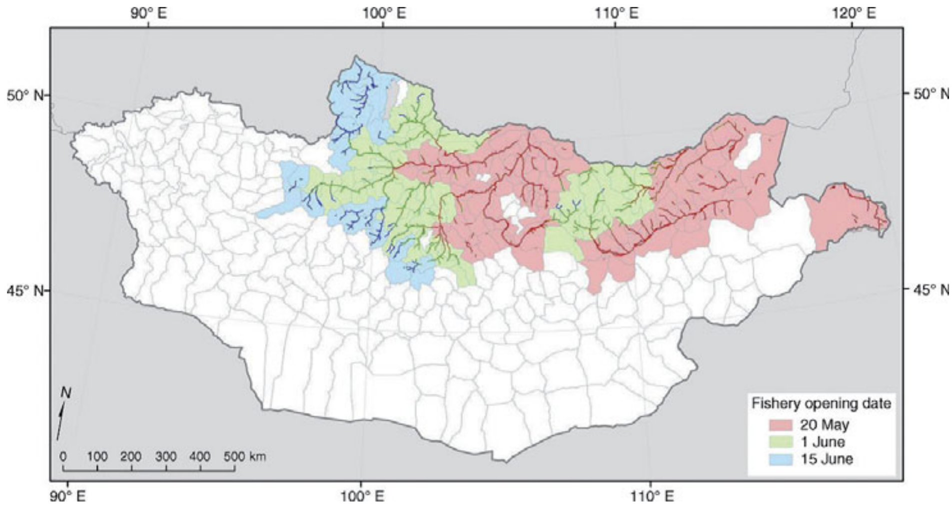


Source: Pess *et al*. (2002).

9.2.5 Spatial design and conservation planning

Designing fisheries surveys and sampling plans in inland freshwater environments can be greatly facilitated by using GIS. For example, Toepfer, Fisher and Warde (2000) developed a multistage approach for estimating the abundance of stream fishes using GIS. The authors mapped stream channel units (riffles, runs, pools) and used information on fish habitat preferences to assign each channel unit to a habitat suitability class. They then determined the abundance of fish in each suitability class and estimated the total abundance of fish throughout the stream using GIS. Designating regional fisheries management areas using GIS and watershed and environmental data provides information that is valuable to fisheries managers (Fisher, Tejan and Balkenbush, 2004). Figure 9.5 shows a map of recommended management zones that were developed for the giant Eurasian trout (*Hucho taimen*) in Mongolia based on spawning dates and potential habitat. Using statistical models, climate data, knowledge of the biology of the Eurasian trout and GIS, Vander Zanden *et al.* (2007) recommended three fisheries management zones that corresponded with opening recreational fish dates that improve on existing fishing regulations and still provide benefits for local economies and conservation efforts.

FIGURE 9.5
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).

9.3 THE CURRENT STATUS OF GIS APPLICATIONS TO INLAND FISHERIES

Any attempt to evaluate the current status of GIS applications to inland fisheries is a serious challenge given the rapid changes in technology and the expanding availability and use of GIS across many disciplines. The previous section (9.2) provided several examples of how GIS has been applied across various inland fisheries themes.

Beginning in 2007, FAO compiled a database showing the main uses of GIS for inland fisheries as part of the GISFish Web portal. A search of the 224 records in this GISFish database (Table 9.1) reveals overlaps of many of the themes presented in Section 9.2, plus some additional themes that were not covered. The three most common fishery resource issues and themes were habitat based (linking habitat quality/quantity to plant and animal abundance and distribution; classifying and inventorying habitats; rehabilitating and restoring habitats) and accounted for over half (51 percent) of the records in GISFish. In fact, 8 of the 12 themes under fishery resources refer to habitat, whereas the other themes relate to management, assessing fish diversity, abundance or movements. This is not surprising given the availability of existing GIS data for rivers and lakes, the relative ease of using GIS to classify and inventory habitat, particularly in streams and rivers, and the use of these data to aid in restoring or rehabilitating fish habitat that has been modified by human activities such as agriculture, silviculture and urban development. The environment issues and themes most closely relate to the use of GIS to evaluate the effects of land use practices in watersheds on stream water quality and quantity and the habitats and health of aquatic organisms. Clearly, GIS has played an important role in helping fisheries managers understand how activities on the land (farming, timber harvest, industry) facilitate sediment and pollutant movements over land and into streams, thereby affecting stream and lake habitat and fish populations. GIS training and promotion was not covered in Section 9.2. During the advent of GIS applications in fisheries in the 1990s, there was a greater emphasis on promoting the uses of GIS and in providing training (Nishida, Kailola and Hollingworth, 2001). Although there are now more opportunities for GIS training through university programmes and private companies, fewer articles are being written about it. In fact, GIS is becoming so widespread and ubiquitous that the term is essentially disappearing from titles (Fisher, 2010) and blending into the methods sections of many scientific articles.

TABLE 9.1

Main issues in inland fisheries GIS as derived from the GISFish database (1985–2009)

Main inland fisheries issues from the GISFish database	Number of literature records
GIS training and promotion of GIS	
Promotion	10
Training	7
Fishery resources	
Habitat quality/quantity linked to plant and animal abundance and distribution	67
Classification and inventory of habitats	29
Rehabilitation and restoration of habitats	18
Planning and potential	18
Fisheries management	11
Direct assessments and inventories	10
Habitat approaches to aquatic biodiversity	7
Movements and migrations of aquatic animals	5
Essential fish habitat	3
Artificial habitats	2
Natural habitats	1
Modification of habitats	1
Environment	
Effects of terrestrial activities on habitats and aquatic organisms	18
Water quality and quantity	15
Environmental health	2
Total	**224**

Source: FAO (2012d).

Another way to track the current status of GIS applications in inland fisheries is to assess the countries where the studies were conducted. A sample of 145 literature records from 1996–2010 retrieved from the ASFA database revealed that, of those records that included a country of origin (n = 137), 56 percent were from north America, with most of these being from the United States of America (Table 9.2). Perhaps somewhat surprising, of the remaining 44 percent of records (n=60), south and east Asia accounted for 17 of the studies, and Africa accounted for a further 14 studies. This means that the rest of the developed world (mainly Europe and Australasia) only produced about 16 percent of all GIS related studies of inland fisheries during the 14 year recent period. These percentages parallel those reported by Fisher (2007) in his review of recent trends in fisheries GIS. He reviewed 100 studies of GIS applications to freshwater and marine fisheries GIS and found that 47 percent were conducted in the United States of America. The dominance of this country is most likely due to the widespread availability of GIS data and software to government agencies and to relatively many university researchers who publish their findings in scientific journals.

TABLE 9.2
Country of application for 145 literature records on papers covering inland fisheries + GIS in FAO's ASFA database (1996–2010)

Region	Country of application	Number of applications
North America	United States of America	42
	Great Lakes area	28
	Canada	7
Latin America	Latin America (general)	3
	Argentina	1
	Brazil	1
	Chile	1
	Mexico	1
Asia	Bangladesh	5
	Thailand	3
	Asia (general)	2
	Laos	2
	Cambodia	1
	China (People's Republic)	1
	India	1
	Indonesia	1
	Japan	1
Africa	Nigeria	4
	Africa (general)	3
	Cameroon	1
	Ethiopia	1
	Kenya	1
	Morocco	1
	South Africa	1
	Uganda	1
	West Africa (general)	1
Europe	Greece	3
	France	2
	Portugal	2
	Sweden	2
	Europe (general)	1
	Lithuania	1
	Norway	1
	Spain	1
Australasia	New Zealand	7
	Australia	1
	Fiji	1
Not area specific		8
Total		**145**

Source: FAO (2012b).

A final way of analyzing the work being carried out with respect to GIS applications to inland fisheries is through recognizing the main institutions where this type of work is proceeding. Box 9.2 provides an overview of this situation. The highly technical nature of much of this work means that most of it is pursued in research institutes in the developed world. At the world scale there are relatively few institutions that specialize in GIS applications to inland fisheries, and this is mostly related to the comparative lack of commercial fisheries in these waters, plus the complexities of using GIS in the context of mapping linear freshwater systems.

BOX 9.2

Overview of major organizations carrying out inland fisheries-related GIS research and projects

This box can only be illustrative because it is impractical to list the exact range or number of institutions carrying out inland fisheries-based GIS work:

- **Australia.** The Australian Rivers Institute at Griffith University focuses on understanding catchment and river ecosystem processes, aquatic biodiversity and conservation, and rehabilitation science and environmental flows.
- **Canada.** The GIS Unit, Fisheries and Oceans Canada, provides support for the protection and conservation of fish and fish habitats in the Pacific Region.
- **The French Republic.** The Hydro-ecology of Rivers team – at the National Research Institute of Science and Technology for Environment and Agriculture, Hydrosystems and Bioprocesses Research Unit – investigates the contemporary evolution of fish populations and the impact of fish habitats on their distribution.
- **The Republic of Italy.** The Asia-Pacific Fishery Commission (APFIC), working through the Food and Agriculture Organization, recognizes the contribution of often overlooked and ignored inland fisheries to the livelihoods and well-being of significant populations. Documents are available through GISFish and describe inland fisheries by country.
- **New Zealand.** The National Centre for Water Resources at the National Institute of Water and Atmospheric Research provides public information and monitors and researches freshwater rivers, lakes and groundwater conditions across New Zealand.
- **New Zealand.** The Centre for Freshwater Ecosystem Management and Modelling at Massey University applies developments in theoretical ecology and ecological modelling to new and novel ways of addressing current issues in freshwater ecosystem management, conservation and bioassessment.
- **The Republic of South Africa.** The South African Institute for Aquatic Biodiversity generates, disseminates and applies knowledge to understanding and solving problems on the conservation and wise use of African aquatic biodiversity, including developing a GIS atlas of southern African freshwater fish.
- **The United States of America.** The Great Lakes Basin Ecosystem Team at the U. S. Fish and Wildlife Service provides information on threatened endangered and invasive species, and interjurisdictional fisheries in the Great Lakes by addressing landscape-scale resource objectives using an ecosystem approach and GIS.
- **The United States of America.** The Aquatic Gap Analysis Program of the U. S. Geological Survey evaluates aquatic biological diversity and aquatic habitats using GIS-based spatial analysis and habitat suitability models to identify gaps in species distribution and works toward more effective conservation prioritization. .
- **The United States of America and Canada.** The Great Lakes Fishery Commission and Great Lakes Information Network partnership provides online facilities to find information relating to the binational Great Lakes-St. Lawrence region of North America.

9.4 SPATIAL ANALYSIS

Freshwater inland systems, including rivers, streams, lakes and reservoirs, present different challenges compared with marine systems for mapping and modelling fish distributions and habitats with GIS. Lakes, reservoirs and ponds are areal features on the landscape and, as such, they are amenable to many of the GIS techniques used for terrestrial ecosystems[215]. In contrast, rivers and streams are linear features on the landscape. Although at small scales they are considered areal features, as networks they present a greater challenge for acquiring, analysing and displaying spatial data. This challenge, however, presents an opportunity because streams and rivers are much like transportation or other linear systems (roads, highways, pipelines, etc.) for which there have been considerable advances in the application of GIS (Goodchild, 2000),

[215] Scale is important to representation because, at a small scale, lakes, ponds, etc., can be mapped as point features.

often under the heading of "network analysis" (see Section 7.6). The following sources provide detailed information on data acquisition and processing for inland fisheries in rivers and streams (Fisher and Rahel, 2004b), reservoirs (Paukert and Long, 2004), lakes (Bakelaar *et al.*, 2004) and in aquaculture (Meaden and Kapetsky, 1991).

Spatial tools (i.e. GIS, remote sensing, spatial models) provide a variety of procedures for analysing inland fisheries and freshwater ecosystems. These procedures can be used to define drainage systems, describe watershed characteristics, and characterize fish populations and communities. Streams and rivers are linear 1D features on the landscape, and depending on the scale of mapping, they are relatively stable over time. Operations on linear systems are used to classify and analyse linear features (e.g. stream segments) that possess various attributes (e.g. stream habitat types or fish abundances). Such features may be fixed (e.g. roads) or ephemeral (e.g. fish movements) and real (e.g. stream channels) or contrived (e.g. political boundaries) (Johnston, 1998). Measurements of linear features, such as stream channels, tend to be less complicated and are more accurate with vector than raster data structures in GIS. Linear operations are particularly useful in characterizing hydrological aspects of stream ecosystems, and ArcGIS by the Environmental Systems Research Institute (ESRI) contains a tool "ArcHydro" (www.crwr.utexas.edu/gis/archydrobook/ArcHydro.htm) that processes digital elevation models (DEMs), delineates watersheds and conducts flow path analysis (Jensen and Dominque, 1998). Flow path analysis can be used to construct a stream network and trace pollutants through the stream. Inland freshwater ecosystems consist of many 2D areal features, such as stream and lake habitats, riparian zones and land use types.

Common GIS procedures used in inland freshwater ecosystems include overlaying fish distributions on habitat features and generating buffer zones around objects. Narumalani, Yingchun and Jensen (1997) identified critical areas for establishing riparian vegetation by using buffers to delineate existing riparian zones around stream channels. Operations on 3D topographic features are used to analyse the change in an attribute, such as surface elevation, bathymetry or other continuous data surfaces, over space. Elevation data are usually derived from DEMs using raster GIS (see Section 7.7). Spatial interpolation has many applications in inland freshwater ecosystems. Whole area interpolation methods, such as trend surface analysis and Fourier series, use all the points in a study area to interpolate a surface, whereas local interpolation methods use only neighbouring points to estimate values (see Section 7.5.3). For example, Gardner, Sullivan and Lembo (2003) used interpolation (kriging)[216] with three different metrics (i.e. Euclidean distance, instream distance along the stream network, and instream distance along the network weighted by stream order) to model stream temperature at target locations based on data from temperature loggers placed throughout a watershed in New York, the United States of America. Isaak *et al.* (2010) provide another example of predicting stream temperature using GIS and multiple regression, spatial statistical models that included air temperature, radiation and stream flow to compare climate change scenarios for two species of salmonids in a mountain river network.

9.5 CASE STUDIES

Applications of GIS in inland fisheries have occurred throughout all types of freshwater habitats, including streams and rivers, lakes and ponds, and impoundments (reservoirs). The following three case studies illustrate how GIS has been used in river and reservoir environments in relation to fish conservation and management. All represent different

[216] Kriging is an interpolation technique in which the surrounding measured values are weighted to derive a predicted value for an unmeasured location. Kriging is unique among the interpolation methods in that it provides an easy method for characterizing the variance, or the precision, of predictions. Kriging is based on regionalized variable theory, which assumes that the spatial variation in the data being modeled is homogeneous across the surface. That is, the same pattern of variation can be observed at all locations on the surface.

approaches to applying GIS analytical tools in freshwater habitats. The three studies chosen provide examples of:

- The application of landscape concepts and the development of customized GIS tools to manage stream fishes in riverine environments (Section 9.5.1).
- The use of GIS-based land use data in the development of fisheries yield models for reservoir environments in a developing country (Section 9.5.2).
- A large-scale application of GIS in a developed country for the identification of streams with high fish diversity in need of conservation efforts (Section 9.5.3).

9.5.1 Managing stream fishes in riverscapes

Original publication reference: Le Pichon, C., Gorges, G., Boët, P., Baudry, J., Goreaud, F. & Faure, T. 2006. A spatially explicit resource-based approach for managing stream fishes in riverscapes. *Environmental Management*, 37(3): 322–335.
Spatial tool: GIS.
Main issues addressed: Habitat quality/quantity linked to plant and animal abundance and distribution; classification and inventory of habitats; rehabilitation and restoration of habitats; direct assessments and inventories; habitat approaches to aquatic biodiversity; movements and migrations of aquatic animals; natural habitats.
Duration of study: Multiple years.
Personnel involved: Six research scientists and managers based at two institutions in the French Republic.
Target audience: River ecologists, fisheries researchers, fisheries and resource managers, government management agencies.

Introduction and objectives: Managing fish in human-impacted streams and rivers requires an understanding of the spatial arrangement of habitats and the fish that occupy them. Many rivers have been impacted by human activities resulting in fragmented and homogenized habitat conditions that adversely affect the aquatic organisms living in these environments. The aim of this paper is to provide a riverscape approach in combination with spatial analysis methods to assess multiscale relationships between patterns of fish habitat and fish movements. The riverscape is defined as a continuous view of the river environment that includes the mosaic of heterogeneous and dynamic habitats, which to most observers is often hidden beneath the opaque layer of water (Fausch *et al.*, 2002; Le Pichon *et al.*, 2006). GIS tools provide a means for measuring relationships between aquatic organisms and their habitats. Fish species occupy a variety of habitats throughout their life cycle. Thus, different life stages, such as eggs, larvae, juveniles and adults, occupy spatial habitats corresponding to activities that include spawning, feeding and seeking refuge. Landscape ecology concepts such as habitat patch dynamics (i.e. accounting for the diversity of habitats within an area), habitat complementation,[217] and source and/or sink habitats (i.e. sources are high-quality habitats that allow a population to increase and sinks are low-quality habitats that provide limited support for a population) are being increasingly used to assess the spatial patterns of fish habitats in river systems. Understanding the spatial and temporal dynamics of fish habitats relative to fish movements and to management and restoration of these habitats can be improved by utilizing GIS tools, models and landscape ecology concepts.

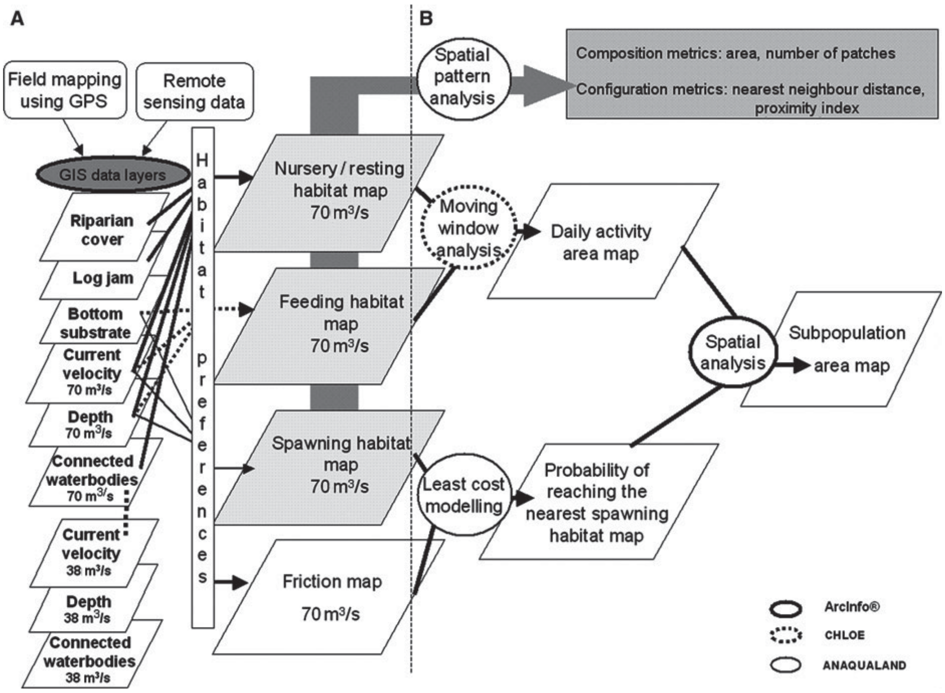
In the riverscape environment, habitats have been traditionally classified as discrete areas based on relatively homogeneous characteristics of substratum, depth and flow. This classification of channel units, each of which are more specifically referred to as pools, riffles, runs, etc., can be reclassified using GIS tools according to their suitability for a fish species. However, rather than following this more commonly used habitat classification approach, the authors classified habitat by defining resource-based (i.e. spawning, feeding and resting) habitat patches preferred by individual fish species. The

[217] Complementation is the use of different habitats by a species to complete their life cycle.

extent of these patches, their arrangement and the resolution of habitat measurements should be scaled to the activity patterns and movements of fishes among patch types.

Methods and equipment: Resource-based habitats of a minnow species, *Barbus barbus*, were evaluated in the Seine River, the French Republic. The authors mapped, at a 1-m resolution in two dimensions, a 22-km reach of the river with channel widths reaching to 50 m including lateral waterbodies such as side channels and backwaters. Channel water boundaries were delineated on digital orthophotographs and habitat variables (i.e. depth, current velocity, substrate, log jams) and riparian cover were located during field mapping at 1 m accuracy using differential global positioning system (DGPS) equipment. Raster data from the aerial imagery and vector data from the DGPS were exported into GIS (ArcInfo) and combined according to species habitat preferences to create resource habitat maps (Figure 9.6).

FIGURE 9.6
Flowchart of the processing steps, spatial analysis methods and products for creating resource habitat maps for river fish species



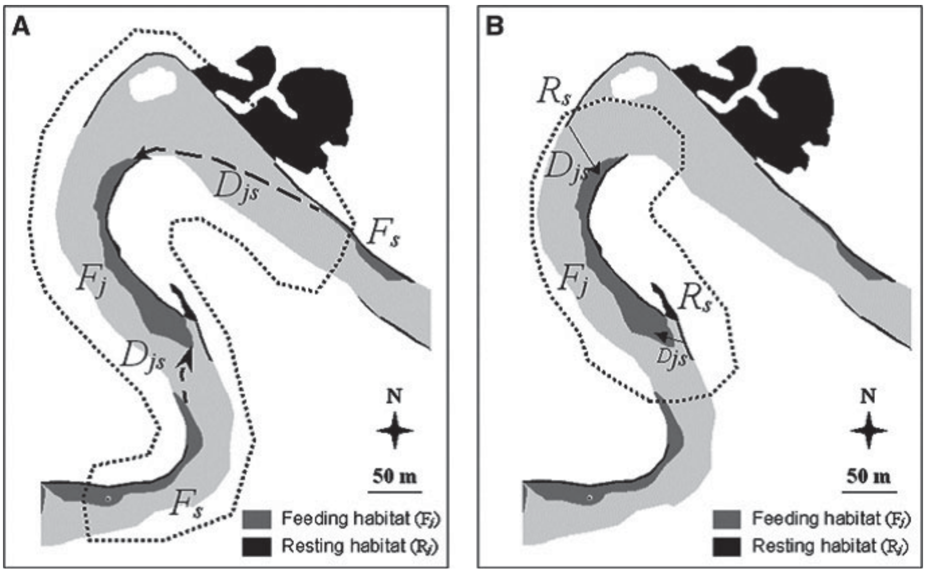
Source: Le Pichon *et al*. (2006).

In Figure 9.6, the operations illustrated in (A) to the left of the dashed line produce GIS-generated maps of resource habitat patches for *Barbus barbus* in the upper Seine River, the French Republic, where the average stream flow rate is 70 m^3/s. The friction map consists of a resistance matrix developed using least cost modelling. Least cost modelling is a modelling approach in GIS that identifies areas with the lowest relative resistance (cost) for a species moving through its environment. In the friction map, resistance for the barbel is based on its swimming capabilities and its risk of predation while swimming through different habitats. The operations in (B) to the right of the dashed line are the spatial analyses of habitat and friction maps to determine composition and configuration of habitat maps and their spatial relationships for the fish subpopulation in the mapped area.

Stream habitats and fish populations are often studied at multiple spatial scales (Fausch *et al.*, 2002), and, as such, are well suited for hierarchical-based models. Hierarchical models nest levels of habitat or populations at different spatial scales. For example, the authors describe the smallest spatial scale (ranging from 1 to 100 m) as the resource habitat patch scale where spawning, feeding and resting and nursery habitat patches are represented. The next larger spatial scale (ranging from 10 to 1 000 m) is described as the daily activities areas scale. At this scale, movements of fish for daily activities such as feeding and resting are complemented by the proximity of these habitat types. The largest spatial scale is the subpopulation area scale (ranging from 100 to 10 000 m) where subpopulations of a fish species migrate between complementary spawning habitats. These migrations could occur over tens of metres or tens of kilometres depending on the life cycle and home range of a species.

Quantifying the proximity of habitat patches requires information on the spatial arrangement, area and orientation of different patch types. To compute oriented distances between habitat types upstream and downstream, the authors developed a GIS program Anaqualand.[218] This freeware program integrates the geometry of the river channel and measures distance between two points or patches. To quantify the spatial relationship of a habitat patch with its neighbouring patch, the authors used a proximity index. Using moving window analysis in Anaqualand software, this index calculates the edge-to-edge distance between a patch and the neighbouring patch relative to their areas. Illustrations of the proximity of feeding and resting habitats are shown in Figure 9.7. Shown in these illustrations are the proximity index variables and the arrangement of feeding habitat (Fj) and resting habitat (Rs) within a delimited (dashed line) focal patch (Fj) along a river reach. The edge-to-edge distance (Djs) between habitat patches is indicated with arrows. In Figure 9.7A, the proximity of feeding patches is within a 200-m search radius, which is indicated by the dotted line. In Figure 9.7B, the complementarity of feeding and resting habitat patches (i.e. their proximity) is evaluated within a 60-m search radius, which is also indicated by the dotted line.

FIGURE 9.7
Illustration of the arrangement of feeding habitat along a river reach

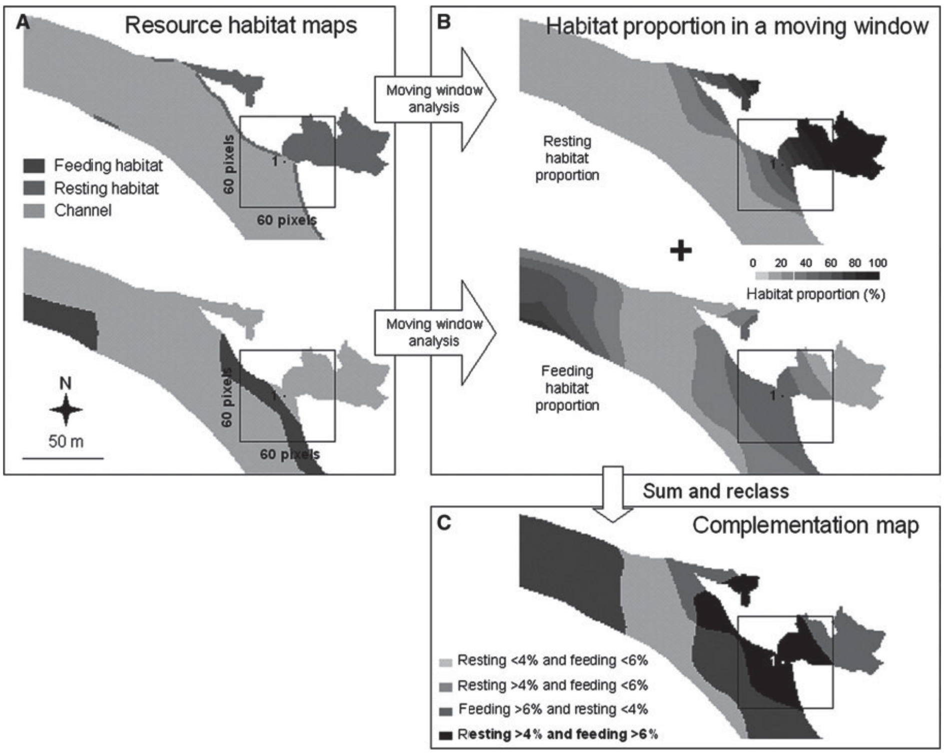


Note: Resting habitat is where fish reside when they are not feeding. Variables are described in the text.
Source: Le Pichon *et al*. (2006).

[218] See INRA: www.rennes.inra.fr/sad/outils_produits/outils_informatiques/anaqualand_2.

In addition to the proximity of different habitat patches with unique resources, the authors developed another freeware software program, Chloe (INRA SAD-Paysage, 2012), that computes multiscale spatial analysis metrics from raster data files, such as relative abundance, richness, diversity and heterogeneity. The software uses a moving window to systematically search the raster image, computes the spatial index for the squared search window and assigns the index value to the central pixel. Moving window analysis is an automated spatial (pixel by pixel) operation with raster data sets where the value of the raster cell is examined and operations are performed on it before moving on to the adjacent cell. An example of this process is illustrated in Figure 9.8. Note that GIS operations are used to summarize and reclassify the habitat proportions computed with the moving window analysis using Chloe to produce the complementation map. Figure 9.8A shows how raster maps of resource (feeding and resting) habitat patches are reclassified using moving window analysis in a 60 (m) × 60 (m) pixel window to create new maps of the proportion of each habitat that are shown in Figure 9.8B. Habitat proportions range from 1 to 100 percent. The resting and feeding maps are overlaid in GIS and reclassified to identify complementation of the two habitats within a radius of 30 pixels of potential daily activity areas, which is shown in Figure 9.8C. Complementation is defined by thresholds of 4 percent for resting and 6 percent for feeding. The number 1 is a reference point for the moving window analysis and resulting maps.

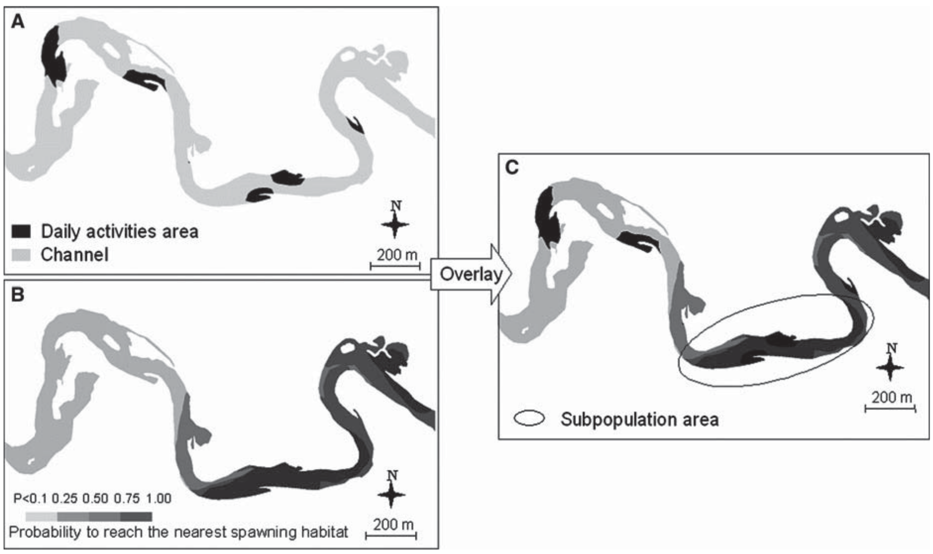
FIGURE 9.8
Illustration of the process of creating a complementation map of stream fish habitats using the moving window analysis



Source: Le Pichon *et al*. (2006).

In the fish subpopulation area (i.e. the study area of interest), the authors evaluated habitat complementation between the daily activity areas for feeding and resting and their connectivity to spawning habitats. Connectivity between areas was modelled using the minimal cumulative resistance, which is a least cost model that determines the path from a source point (e.g. feeding habitat) to a destination point (e.g. resting habitat). The model assigns a resistance or permeability value for fish movement to each habitat based on factors such as the risk of mortality, energy expenditure or movement costs, which provides a more realistic path for fish movements compared with simple straight line estimates. A resistance matrix for *Barbus barbus* was created based on swimming capacity and predation risk, which produced a friction map (shown in Figure 9.6). Using Anaqualand, the least cost model was applied to the map of spawning habitat and the friction map to produce a map of the probability of a fish reaching the nearest spawning habitat. An overlay of the probability map with a threshold probability on a daily activities area map delineated areas that could support a subpopulation (Figure 9.9). Figure 9.9A is a map of fish activity areas and Figure 9.9B is a probability map of a fish reaching the nearest spawning area. This map was also created with Anaqualand. The resulting subpopulation area map, shown in Figure 9.9C, shows low probability areas ($P < 0.25$) with potential gaps in connectivity and high probability areas ($P > 0.75$) that fish within a daily activity area will reach the nearest spawning habitat.

FIGURE 9.9
Process for delineating potential subpopuation areas using an overlay of the daily activity areas map created with Chole software



Source: Le Pichon *et al*. (2006).

Discussion, conclusions and recommendations: The approach presented in this paper provides a flexible framework for mapping habitat resources for stream fishes to help evaluate any future impacts of habitat alteration and to inform prioritization of stream restoration and species management based on the spatial proximity of habitats and at different spatial scales. The important contributions of the approach are that it includes aquatic habitats that support the entire life cycle of a species at multiple spatial scales and in the spatially continuous river environment. This differs from the more traditional reach-scale, site-based approach to representing stream habitat. The identification of high-quality, complementary habitat patches needed to sustain fish populations versus low-quality habitat areas in need of restoration provides the information needed by river managers. An important next step in the evaluation of this approach is validation of the indexes and maps using spatially continuous surveys of fish populations, which was not included in this study.

Le Pichon *et al.* (2009) validated this approach by applying their results from this natural reach of the the upper Seine River, the French Republic, to an artificial, channelized reach of the river downstream.

Challenges and lessons from case study: This case study demonstrates complex spatial analyses using specialized GIS software programs to analyse fish habitat affinities for critical life cycle activities in river environments. Replication of this study in another river system with other fish species would be challenging without a team of river ecologists and spatial data analysts. Nevertheless, this approach has great potential for applying GIS to manage and conserve fish in river environments. The authors identified two main challenges of their approach: (i) mapping habitat patches using relatively simple GIS-based methods; and (ii) calculating distance in two dimensions along a river. Additional challenges relate to the methodological difficulties of applying the approach to the shifting and dynamic nature of fish habitat in river environments. Much of habitat variability is the result of water-level fluctuations related to temporal (daily, monthly, seasonal, annual) trends in river discharge. These discharge events and those over longer time scales (decades, centuries) shape river channels and affect resource habitats of fishes. Mapping habitat under these dynamic conditions that requires measurements at different river stages (dry, average, flood) is a complex task, which is one reason why inland freshwater GIS applications are lagging behind marine GIS applications. The task of river habitat mapping can be facilitated by using remotely sensed data, including panchromatic digital aerial photography, laser telemetry (LIDAR), side-scan sonar (Kaeser and Litts, 2010), and interferometric synthetic aperture radar (i.e. the use of two or more radar images to generate elevation maps) to map channel bathymetry as well as other spectral devices, particularly in turbid rivers (Wright, Marcus and Aspinall, 2000; Vierling *et al.*, 2008). Clearly, standard GIS operations and new programs (Anaqualand, Chloe) coupled with landscape ecology indices are redefining the way conservation agencies are managing streams and rivers.

9.5.2 Predicting fish yields in tropical reservoirs

Original publication reference: Amarasinghe, U.S., De Silva, S.S. & Nissanka, C. 2004. Fish yield predictions based on catchment features, quantified using Geographical Information Systems, in lowland reservoirs of Sri Lanka. In T. Nishida, P.J. Kailola & C.E. Hollingworth, eds. *GIS/Spatial Analyses in Fishery and Aquatic Sciences, (Vol. 2)*, pp. 499–514. Saitama, Japan, Fishery-Aquatic GIS Research Group.
Spatial tools: GIS.
Main issues addressed: Habitat quality/quantity linked to plant and animal abundance and distribution; classification and inventory of habitats; planning and potential fish yields; direct assessments and inventories; effects of terrestrial activities on habitats and aquatic organisms.
Duration of study: 1997–2002.
Personnel involved: Three research scientists based at three institutions in the Democratic Socialist Republic of Sri Lanka and Australia, and two managers based at a Sri Lankan government agency.
Target audience: Reservoir and lake ecologists, fisheries researchers, fisheries and resource managers, government management agencies.

Introduction and objectives: The continental island of the Democratic Socialist Republic of Sri Lanka has one of the highest densities of reservoirs in the world. The primary purpose of these reservoirs is to provide irrigation for water-supplied agriculture; secondarily, they are the location of the island's inland fisheries, which consists mostly of exotic cichlids *Oreochromis mossambicus* and *O. niloticus*. In these artisanal fisheries, fishers use gillnets from canoes to capture fish (Amarasinghe, De Silva and Nissanka, 2002). These fisheries have received little management, in part because the reservoirs are scattered throughout the country in areas that are difficult to conduct individual assessments. The authors have been studying various aspects of selected reservoirs for over two decades, most recently focusing on developing models of fish yield. De Silva *et al.* (2001) used GIS to quantify catchment land use in nine reservoirs and related fish yield to land use patterns, to selected limnological characteristics (conductivity, chlorophyll-*a*) and to reservoir morphometry (area and capacity). The resulting single and multiple regression models produced highly significant relationships (r = 0.70–0.91) between fish yield and forest cover, shrubland and ratios of these, reservoir area and capacity, and a morphoedaphic index. In a follow-up study, Amarasinghe, De Silva and Nissanka (2002) evaluated the robustness of the predictive yield models developed by De Silva *et al.* (2001), by validating model predictions with independent data from five Sri Lankan reservoirs. The authors validated the predictive fish yield models and suggested that, with the aid of GIS-derived information, they could provide an accurate yield assessment of reservoir fisheries. The objective of the current paper was to synthesize findings from the previous studies on Sri Lankan reservoir fisheries and further support the use of GIS as a tool for developing fish yield-prediction models.

Methods and equipment: The methods provided in this paper are described in greater detail in De Silva *et al.* (2001) and Amarasinghe, De Silva and Nissanka (2002) and therefore only a brief description of the methods will be included here.

For the nine study reservoirs (Figure 9.10),[219] GIS was used to digitize land use types, rivers, roads and point features in catchment areas of each reservoir using ARC/INFO software and 1:50 000 scale topographic maps obtained from the Department of Irrigation of the Democratic Socialist Republic of Sri Lanka. The resulting GIS included the following layers: land use layer, drainage (rivers), roads, catchment boundaries and important point features (Figure 9.11). GIS was then used to determine the area of 16 land use types. The major land use types included forest cover, shrubland, chena (shifting cultivation land) and homesteads, with smaller areas of home gardens, paddy land, plantations, grasslands, waterbodies and rocks.

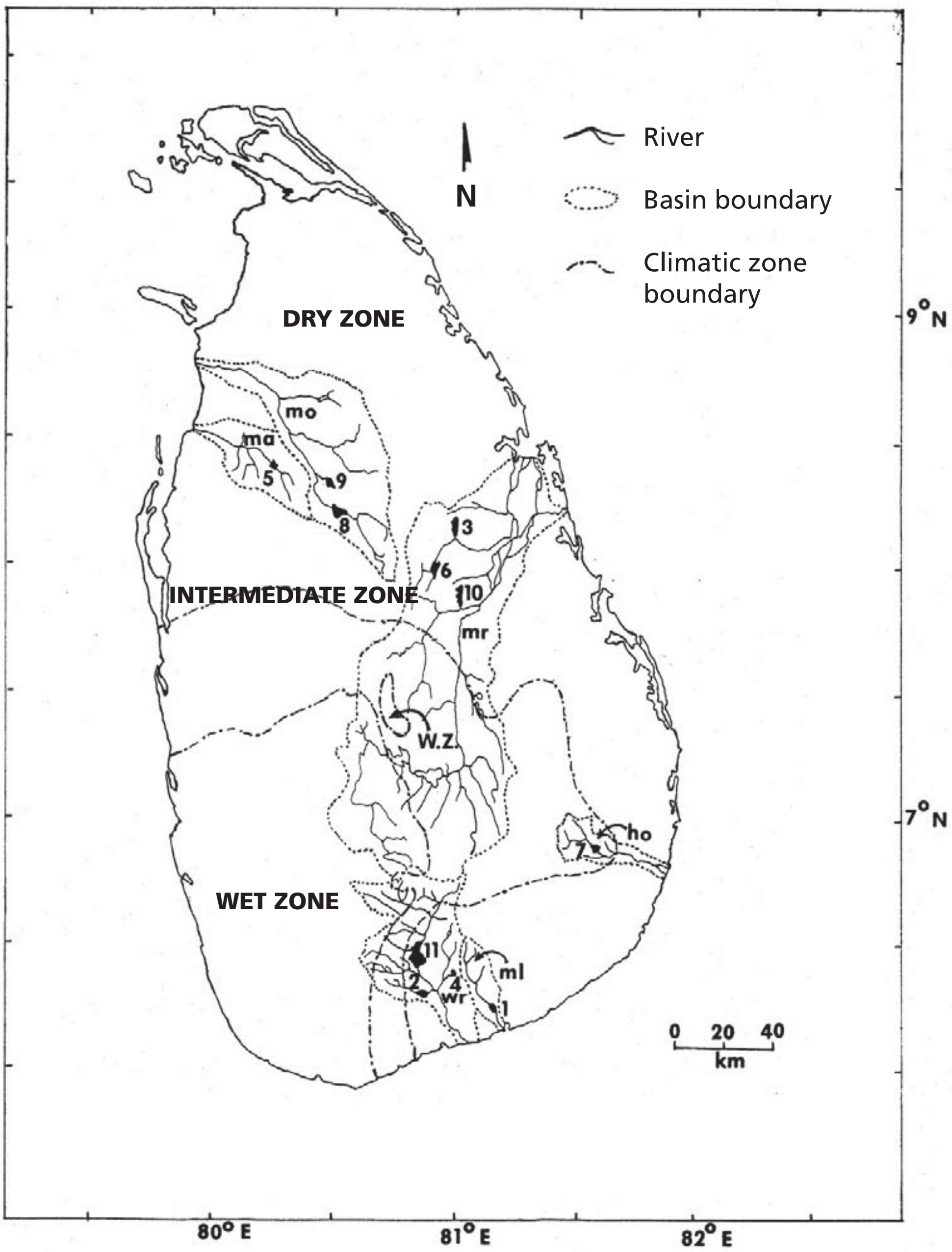
Morphological data for the study reservoirs, that is, reservoir area and capacity, and catchment area, were obtained from the Department of Irrigation of the Democratic Socialist Republic of Sri Lanka. Limnological data were collected once every two months at three stations in each reservoir. Parameters measured included conductivity, alkalinity, total nitrate, total phosphate and chlorophyll-*a* (Nissanka, Amarasinghe and De Silva, 2000). These data were used to calculate morphoedaphic indices defined as the ratio of conductivity to mean depth (MEI_C) and the ratio of alkalinity to mean depth (MEI_A), which were shown by Nissanka, Amarasinghe and De Silva (2000) to be significantly related to fish yield.

Fisheries data for the nine reservoirs were collected from 1997–1999. Fish were sampled with gillnets from canoes manned by two people. The catch from all reservoirs was dominated by two exotic cichlids: *Oreochromis niloticus* and *O. mossambicus*. These data were expressed as fisheries yield (kg/ha/yr) and fishing intensity (boat days/ha/yr). Analysis of relationships between catchment land use, reservoir physico-chemical characteristics and fisheries yield data were investigated by the authors. Statistical analyses included multiple regression of fish yield relative to reservoir morphometric and limnological characteristics (Nissanka, Amarasinghe and De Silva, 2000) and land use patterns (De Silva *et al.*, 2001), principal components analysis of limnological characteristics, catchment land use patterns and fish yield (Amarasinghe, De Silva

[219] Data from reservoirs 5 (Mahawilachchiya) and 7 (Muthukandiya) were not included in the analyses for this study.

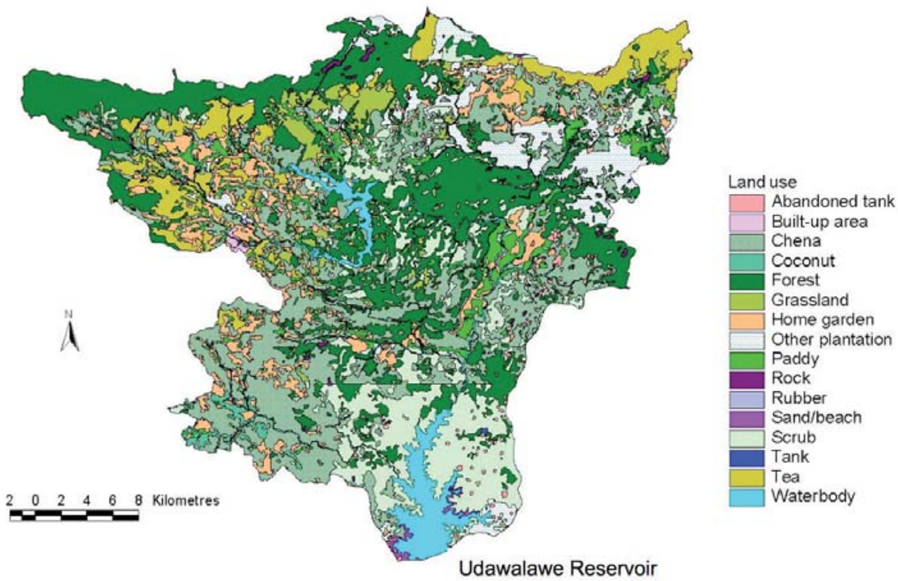
and Nissanka, 2002) and validation of the yield models using independent data (Amarasinghe, De Silva and Nissanka, 2004).

FIGURE 9.10
Map of Sri Lanka with climatic zones and the location of 11 reservoirs in six river basins: Modargum Aru (ma); Malwathu Oya (mo); Mahaweli River (mr); Walawe River (wr); Heda Oya (ho); and Malala River (ml)



Source: De Silva *et al*. (2001).

FIGURE 9.11
Map of catchment land use patterns for Udawalawe reservoir in southern Sri Lanka



Source: Upali Amarasinghe.

Discussion, conclusions and recommendations: Based on the findings of Nissanka, Amarasinghe and De Silva (2000), De Silva *et al.* (2001) and Amarasinghe, De Silva and Nissanka (2002), Amarasinghe, De Silva and Nissanka (2004) developed four models relating fish yield and catchment land use and physical and chemical characteristics of Sri Lankan reservoirs and validated them using fish yield estimates from five reservoirs sampled in an independent study. The four predictive yield models are shown in Table 9.3.

TABLE 9.3
Multiple regression models relating ratios of watershed and reservoir characteristics and fishing intensity to fish yield

Model	R^2
FY = -154.42 + 41.283 ln(FC/RC)	0.900
FY = -158.0 + 29.8 ln(FC/RC) + 10.5 FI	0.875
FY = -16.53 + 32.5 ln(FC/RA) + 12.5 FI	0.868
FY = 64.931 + 43.32 ln(FC/RA)	0.830
FY = -170.7 + 38.265 ln((FC+SC)/RC)	0.796
FY = 16.558 + 47.124 ln((FC+SC)/RA)	0.775
FY = -176 + 30.9 ln((FC+SC)/RC) + 7.86 FI	0.740
FY = 8.6 + 30.0 ln((FC+SC)/RA) + 6.85 FI	0.625

Note: R^2 is the coefficient of determination.
Source: Amarasinghe, De Silva and Nissanka (2004).

In an attempt to validate these models, Amarasinghe, De Silva and Nissanka (2004) estimated fish yield using the average of the eight models shown in Table 9.3 for five reservoirs in the Democratic Socialist Republic of Sri Lanka. These models relate ratios of forest cover (FC, in km^2), shrubland cover (SC, in km^2), reservoir surface area (RA, in km^2), reservoir capacity (RC, in km^3) and fishing intensity (FI, in boat days ha^{-1} yr^{-1}) to fish yield (FY, in kg ha^{-1} yr^{-1}) for nine reservoirs in Sri Lanka. Those estimates were compared with actual fish yield from the reservoirs. Differences between estimated and actual fish yield ranged between 1.3 kg ha^{-1} yr^{-1} to –42.8 kg ha^{-1} yr^{-1} with an absolute average value of 19.02 kg ha^{-1} yr^{-1}. The models with the greatest predictive power ($R^2 \geq 0.830$) included the ratio of forest cover (FC) to either reservoir capacity (RC) or reservoir surface area (RA) and two of those models included fishing intensity (FI).

Challenges and lessons from case study: For this series of studies, GIS allowed the researchers to determine catchment land use with a high degree of accuracy that was not attainable with traditional mapping methods over such a large area. 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 these reservoirs. Land cover influences nutrient supply, which can result in increased production from the aquatic ecosystem.

The authors noted that in the Democratic Socialist Republic of Sri Lanka reservoir water regimes are controlled by irrigation authorities depending on agricultural and domestic needs, and fisheries are rarely taken into consideration in irrigation management and development plans. They called for an integrated approach to watershed management that would optimize resource use in the reservoirs of the Democratic Socialist Republic of Sri Lanka. Clearly, this is a good opportunity for implementation of an ecosystem approach to fisheries.

9.5.3 Conservation of freshwater biodiversity

Original publication reference: Sowa, S.P., Annis, G., Morey, M.E. & Diamond, D.D. 2007. A gap analysis and comprehensive conservation strategy for riverine ecosystems of Missouri. *Ecological Monographs*, 77: 301–334.
Spatial tools: GIS
Main issues addressed: Habitat quality/quantity linked to plant and animal abundance and distribution; classification and inventory of habitats; rehabilitation and restoration of river habitats; habitat approaches to aquatic biodiversity.
Duration of study: 1997–2006.
Personnel involved: Four research scientists based at a university in the United States of America and affiliated with state and federal agencies.
Target audience: Aquatic ecologists, river conservationists, natural resource managers, government management agencies.

Introduction and objectives: Freshwater ecosystems in the United States of America are very diverse. They contain 10 percent of the world's freshwater fish species, 30 percent of freshwater mussel species and 61 percent of all freshwater crayfish species (Sowa *et al.*, 2007). Although the diversity of these freshwater ecosystems is impressive, many of these ecosystems are in peril. For example, over the past 100 years, 123 freshwater animals in North America have become extinct (Ricciardi and Rasmussen, 1999), and in the United States of America, 71percent of freshwater mussels, 51 percent of freshwater crayfish and 37 percent of freshwater fish are considered vulnerable to extinction (Sowa *et al.*, 2007). Although considerable attention has been focused on tropical ecosystems, given these stark statistics on the decline of freshwater biodiversity, more attention is needed on causes of decline and in identifying gaps in existing efforts to conserve freshwater biodiversity and prioritizing efforts to fill these gaps.

The national Gap Analysis Program (GAP) of the United States Geological Survey (USGS) was started in 1988 to provide a coarse-filter approach for identifying biodiversity conservation needs. The approach identifies species, habitats and ecosystems that are not sufficiently represented in land management areas (i.e. gaps) that may be filled by establishing new management or protected areas or by implementing changes in land management practices. This spatially oriented approach uses remote sensing and GIS technologies, and it has been applied to terrestrial ecosystems across the United States of America. This article by Sowa *et al.* (2007) is the first published application of GAP in an aquatic ecosystem, in particular to riverine ecosystems in the State of Missouri.

Biodiversity conservation using GAP proceeds through several steps, including identifying gaps and developing criteria for what constitutes effective conservation (Sowa *et al.*, 2007). The steps are as follows:

- The first step is establishing the goal of the planning effort, which in biodiversity conservation is conserving native species, habitats and ecological processes in an area of interest.
- The next step is to select an appropriate geographic framework. This framework consists of the planning region, which is the area where the conservation plan will be developed, and the assessment units, which are the geographic sub-units of the planning region.
- Next, the biodiversity conservation targets need to be identified and mapped, and this information coupled with the planning regions and assessment units is used to select priority areas within the regions. Selecting priority areas or locations, a logistical process, is facilitated by the use of GIS and expert opinion.
- The final step is to establish a monitoring programme to ensure successful conservation efforts or modification of management actions.

The objectives of this study were to provide details on complementary conservation planning efforts: the Aquatic GAP Project for Missouri and the State Wildlife Action Plan for Missouri. Much of the focus of this case study is on the methods used in the Aquatic GAP Project. Results from the State Wildlife Action Plan are presented as an application of GAP in Missouri.

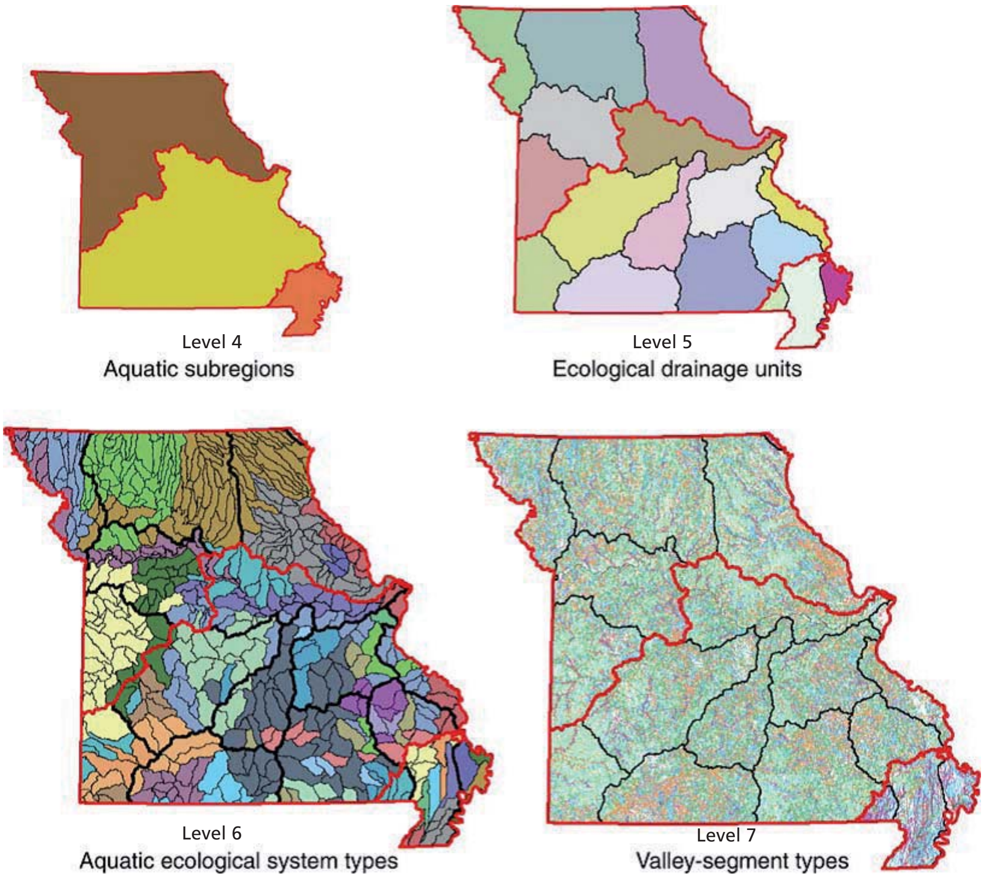
Methods and equipment: Four primary GIS data sets were used in this study: (i) hierarchical classification of river ecosystem; (ii) species distribution modellling; (iii) public land ownership and stewardship;[220] and (iv) human threats. The methodological stages are detailed as follows.

(i) Hierarchical classification of river ecosystems. This classification system consists of eight levels that were used to identify, classify and map distinct ecological units and habitats of rivers at multiple spatial levels. This system considers structural features, functional properties, and biological (ecological and taxonomic) composition of riverine ecosystems (Figure 9.12). Levels 1–3 are zoogeographic strata and include the zones, subzones and regions and follow the ecological units delineated by Maxwell *et al.* (1995). Level 4 is aquatic subregions (n = 3 for Missouri) and they are the physiographic or ecological subdivisions of regions that account for differences in the ecological composition of riverine assemblages resulting from variation in ecosystem structure and function. Level 5 is the ecological drainage units (n = 17 for Missouri) that account for differences in taxonomic composition. These units are empirically defined by the USGS eight-digit hydrologic units. Level 6 is the aquatic ecological system's types (n = 542 for Missouri). These types were derived from 22 landscape variables (geology, soils, landform, and spring/groundwater inputs) that establish the hydrologic and physico-chemical conditions of stream ecosystems. Level 7 is valley-segment types (n = 74 types for Missouri), which represent hydro-geomorphic units defined by local physical and fluvial factors and position in the stream network. These segments were mapped at the 1:100 000 scale based on the United States National Hydrography Data set. Finally, level 8 is habitat types, that is, fast-flowing (e.g. riffles) and slow-flowing (e.g. pools) habitats. These types were not mapped in this case study because the spatial area covered was too large for an appropriate resolution.

[220] Conservation practices are more easily implemented in the United States of America on public than on private lands.

FIGURE 9.12

Maps of the aquatic ecological classification hierarchy for four levels (4–7) in Missouri, United States of America



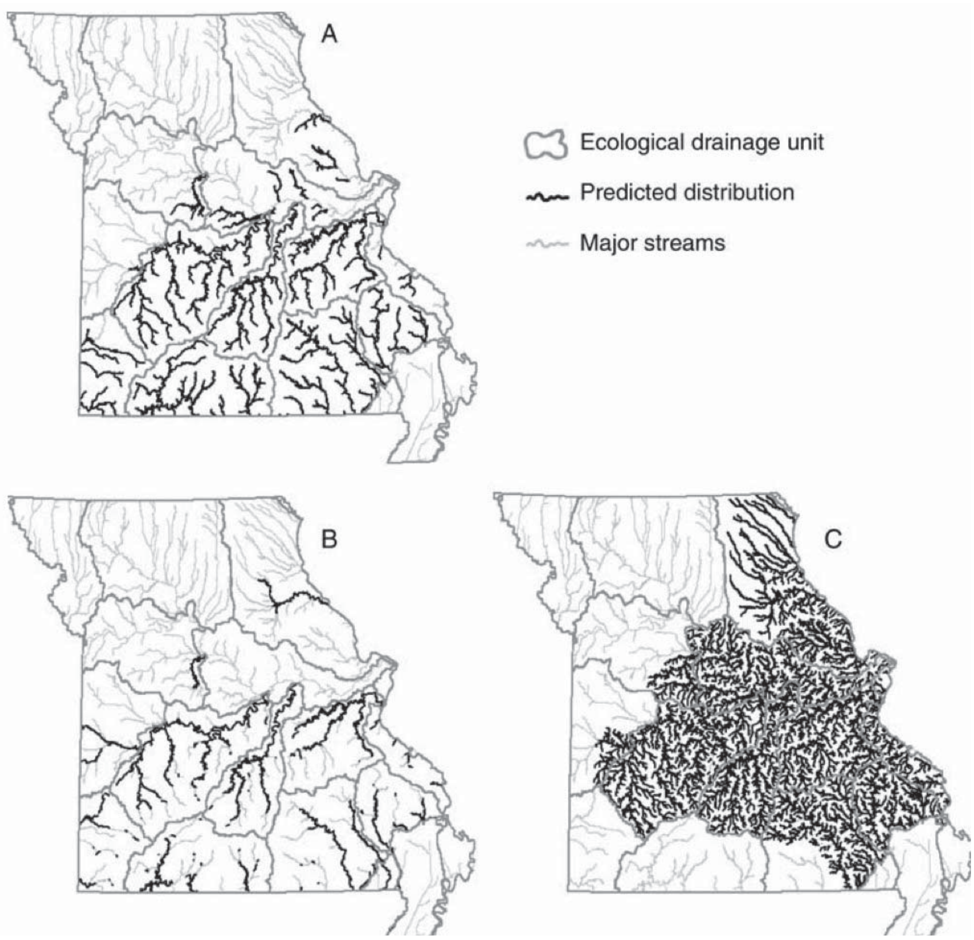
Source: Sowa *et al*. (2007).

(ii) Species distribution modelling. Predicted distributions of 315 aquatic species, including 32 crayfishes, 67 mussels and 216 fish species, were made from nearly 6 000 collection records and a suite of seven environmental predictor variables of stream size, stream gradient, stream temperature and stream flow (Figure 9.13). Range maps were created for each species at the 14-digit hydrologic unit (hierarchical classification of drainage basins used by USGS that is numerically coded) using GIS. Ranges were predicted using classification and regression tree analysis[221] using the AnswerTree 3.0 software. Because of regional variation in species distribution and habitat, regionally specific models were constructed for some species, and the number of regional models ranged from 1 - 4 for any given species, although most species required two models.[222]

221 Regression tree analysis is a form of decision tree learning often used to mine data in which the leaves of the tree represent classifications and the branches represent the conjunction of features (variables) that lead to those classifications. The goal of a regression tree analysis is to create a model that predicts the value of a variable based on several input variables.

224 Two models are required because any species can evolve to become regionally specific according to variations in physical conditions.

FIGURE 9.13
Predicted distribution maps for (A) a fish species, black redhorse (*Moxostoma duquesnei*), (B) a mussel species, round pigtoe (*Pleurobema sintoxia*), and (C) a crayfish species, golden crayfish (*Orconectes luteus*)



Source: Sowa *et al*. (2007).

(iii) Public land ownership and stewardship. To assess gaps in biodiversity conservation areas, an assessment is needed of mapped species that occur within existing public land holdings and the management status of these holdings. GAP uses a stewardship scale to denote the relative degree of biodiversity maintenance for a land area that ranges from 1 (the highest level of maintenance) to 4 (the lowest level of biodiversity management). Each stream segment flowing through public lands was attributed with a stewardship status in the valley segment layer.

(iv) Human threats. A human threat index was developed to provide a measurement of the degree of human disturbance affecting freshwater ecosystems. A suite of 65 threat metrics was compiled from state and federal environmental databases and attributed to the aquatic ecological systems. Using correlation analysis, the final set was reduced to 11 relatively uncorrelated metrics of human disturbance (Table 9.4).

TABLE 9.4
Eleven metrics for the human threat index and the criteria used to define their relative ranks for Missouri, the United States of America

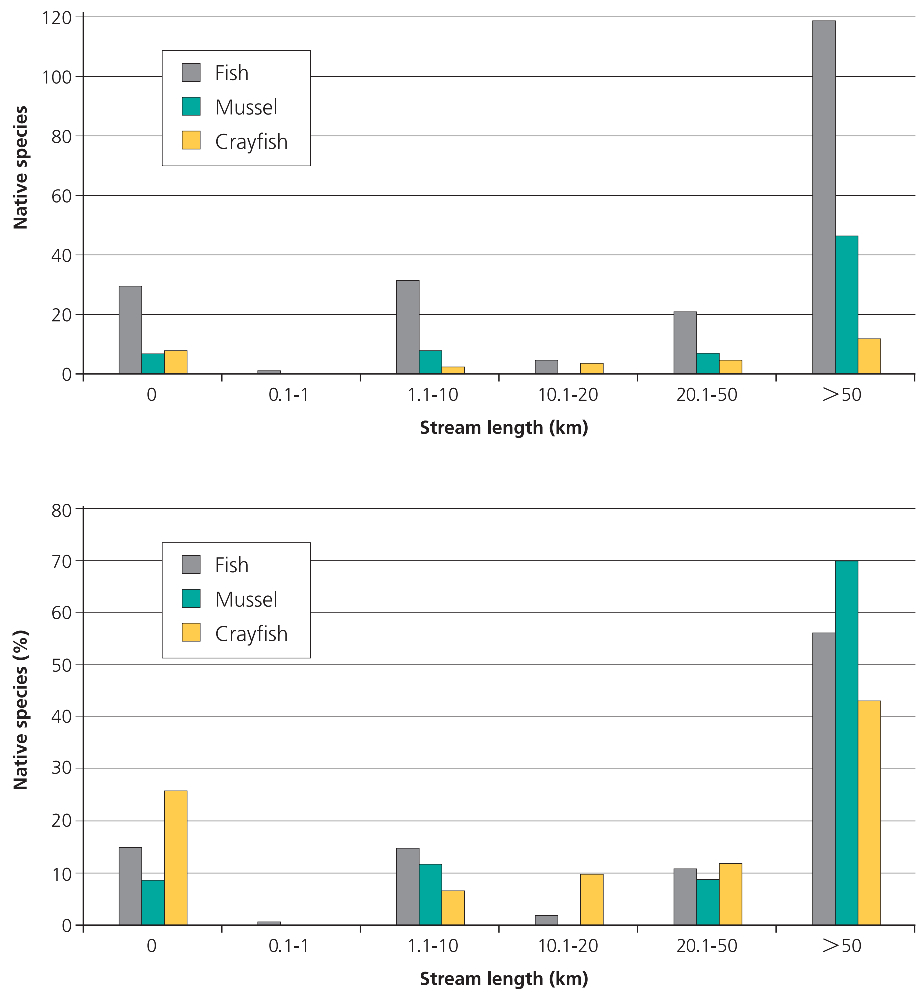
Metric	Relative rank			
	1	2	3	4
1. Number of introduced species	1	2	3	4–5
2. Percentage urban	0–5	5–10	11–20	> 20
3. Percentage agriculture	0–25	26–50	51–75	> 75
4. Density of road/stream crossings (no./km^2)	0–0.09	0.10–0.19	0.2–0.4	> 0.4
5. Population change 1990–2000 (no./km^2)	16–0	0.04–5	6–17	> 17
6. Degree of hydrologic modification and/or fragmentation by major impoundments	1	2 or 3	4 or 5	6
7. Number of federally licensed dams	0	1–9	10–20	> 20
8. Density of coal mines (no./km^2)	0	0.1–2	2.1–8	> 8
9. Density of lead mines (no./km^2)	0	0.1–2	2.1–8	> 8
10. Density of permitted discharges (no./km^2)	0	0.1–2	2.1–8	> 8
11. Density of confined animal feeding operations (no./km^2)	0	0.1–2	2.1–4	> 4

Source: Sowa *et al.* (2007).

The metrics in Table 9.4 were not weighted. The relative ranks provide an increasing measure of human threats from low (rank = 1) to high (rank = 4). For example, threats related to human habitation are measured by the percentage of an area that is urban (compared with rural) and how the population has increased in an area over the past decade. Both metrics quantify the potential threat of urbanization to streams and their aquatic organisms.

Results: Sowa *et al.* (2007) analysed both abiotic (habitat) and biotic (fish, mussels and crayfish) elements of biodiversity focusing on lands classified as management-status categories 1 and 2, which are considered to have reasonably secure conservation plans and management actions that benefit biodiversity conservation, compared with management-status categories 3 and 4, which provide limited or little protection to conserving biodiversity. At the valley-segment type (Level 7), 55 of the 74 types (74 percent) in Missouri contained status 1 and 2 lands. Habitat features associated with these 55 types included coldwater streams, streams flowing through igneous geology and large rivers. With regard to analysis of the target species, 19 of the 315 species were either non-native or cryptic (cave-dwelling) and therefore the authors limited their final analyses to the 296 native species of fish, mussels and crayfish and their association with management status 1 or 2 lands. When broken down by stream length, most of the 296 species of fish, mussels and crayfish have more than 50 km of their predicted distribution within management status 1 or 2 lands (Figure 9.14). For example, nearly 120 native fish species, or about 56 percent of all native fish species that occur in stream lengths greater than 50 km, are in management status 1 or 2 lands.

FIGURE 9.14
Graphs of (A) the number of native species and (B) percentage of native species within each taxon in management status 1 or 2 lands and their distribution by six categories of stream length



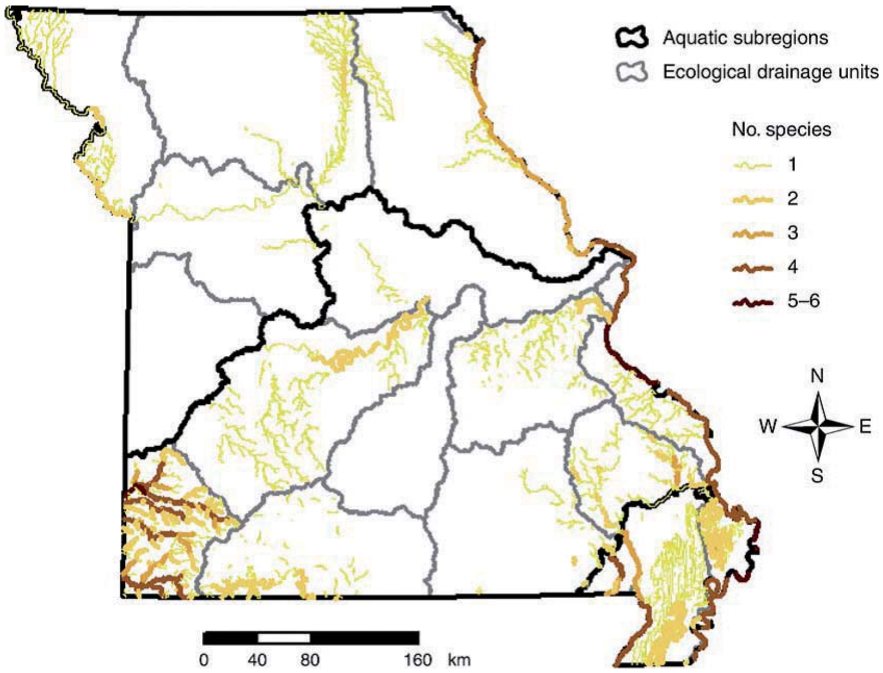
Source: redrawn from Sowa *et al.* (2007).

When broken down by aquatic subregion, the Ozark region in southern Missouri had the greatest number of native species (278) with only 52 species not represented in status 1 or 2 lands, which was followed in order by the Mississippi Alluvial Basin in southeastern Missouri (163 native species; 69 not in status 1 or 2 lands) and the Central Plains (178 native species; 90 species not in status 1 or 2 lands). These results were used to illustrate gaps for streams with species not currently represented in management status 1 or 2 conservation lands in Missouri (Figure 9.15)[223].

To help ensure the long-term persistence of native biota, Sowa *et al.* (2007) compiled a team of aquatic resource professionals from Missouri to identify and map a set of aquatic conservation-opportunity areas (COAs) that would represent the breadth of distinct riverine ecosystems and habitat in Missouri and multiple populations of species. These areas were selected as targets for the State Wildlife Action Plan. The team developed a portfolio of COAs based on quantitative and qualitative assessment criteria

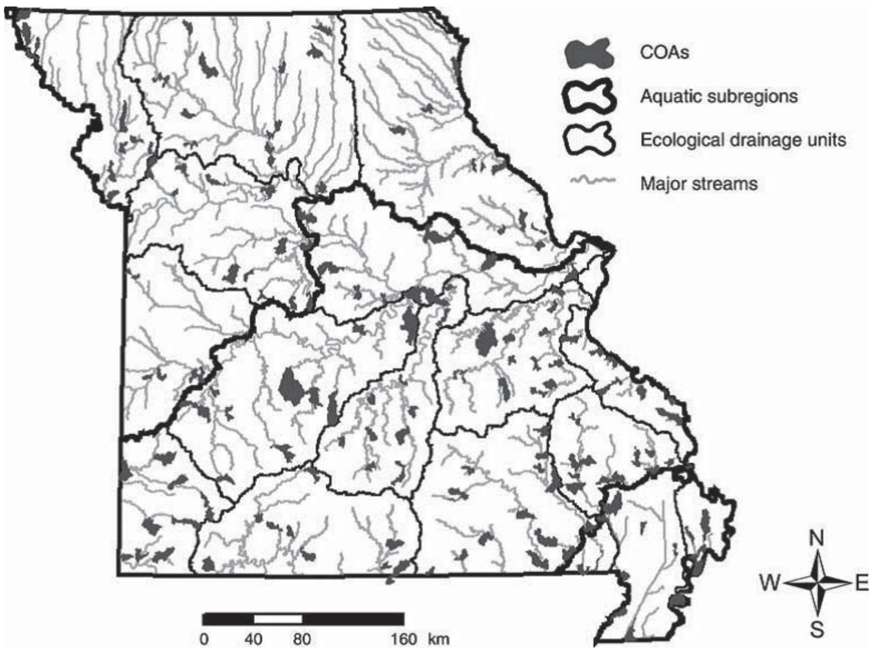
[223] Category 1 species lines are thinner than category 2 species. There is only one small segment of category 5–6 species in southwestern Missouri.

FIGURE 9.15
Map of species richness for 45 native fish, mussel and crayfish species not currently represented in GAP management status 1 or 2 conservation lands in Missouri, United States of America



Source: Redrawn from Sowa *et al*. (2007).

FIGURE 9.16
Map of 158 conservation-opportunity areas (COAs) selected by the aquatic resource professional team for Missouri, United States of America



Source: Redrawn from Sowa *et al*. (2007).

for aquatic ecological system polygons and valley-segment type complexes. The resulting assessment identified 158 COAs that include a broad diversity of stream ecosystems, riverine assemblages and populations of all 296 fish, mussel and crayfish species. These COAs contain only 6.3 percent of the total 174 059 km of streams (Figure 9.16). The small percentage of streams with COAs shown in Figure 9.16 compared with the larger number of streams with high species richness shown in Figure 9.15 is due in part to the fact that only 5 percent of the total length of streams in Missouri is in public ownership.

Discussion, conclusions and recommendations: The Aquatic GAP approach, with the aid of GIS, identified priority riverine ecosystems and was an important first step toward implementing effective biodiversity conservation planning. The analysis process was complex and involved large databases and multiple levels of analysis, including statistical techniques, database management and the judgement of technical experts. The authors concluded that establishing geographic priorities for biodiversity conservation is one of the many steps needed to achieve actual conservation on the ground. Implementation of biodiversity conservation in Missouri will entail vigilance and cooperation by government agencies and private land owners, and coordination of the logistical tasks needed to implement the conservation plan. The Aquatic GAP Program is ongoing in many regions of the United States of America and is being managed by USGS (http://gapanalysis.usgs.gov/gap-analysis/aquatic-gap/). This program provides an approach to freshwater river conservation that could, with sufficient access to requisite data, be applied to rivers systems throughout the world.

Challenges and lessons from case study: Projects covering a large geographic area with large and diverse data needs, and the complex analyses used in this study, present a challenge for countries or regions that are lacking financial resources. In the United States of America where these data are available across the country, Gap Analysis projects are currently being conducted regionally (e.g. streams in watersheds of the Great Lakes) rather than in individual states. Where data are available, Gap Analysis provides a powerful planning tool for managing and conserving fish species and other aquatic resources. Geographic information system technology, relational databases and multivariate analyses are the tools and resources needed for both large-scale and small-scale fish and aquatic biodiversity management and conservation.

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

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10.1 INTRODUCTION

It is worth recalling that in Chapter 1 the fundamental reasons for the demise of many of the world's major marine fisheries were outlined and a range of human and physical reasons were given for this. For those studying this demise it has become increasingly clear that the problems facing fisheries and fish production can best be viewed as disequilibrium[224] in the spatial domain. Thus, the capacity to provide outputs from fisheries activities at an optimum level is dependent upon the variable factors controlling this output to be in balance. This balance might be easy to achieve in fish farming situations where there are tight human controls over the production process. But when the fish feed supplies rely upon captured fish from "the wild", then keeping both fish capture rates and the condition of "the wild" at an optimum level of efficiency (or sustainable) is difficult to achieve. However, the availability of spatial tools (principally GIS and remote sensing) offers the opportunity to carefully appraise and then to manage fisheries and related activities in the marine domain.

Previous chapters have explained how GIS has developed, what it has been generally used for, and considerable detail has been given to the input needs for GIS in terms of software, data, hardware and personnel. GIS implementation considerations have also been discussed. The output achieved by the system has been hinted at in terms of the vast array of functions that GIS can perform and the subsequent decision-making information that is derived. It is now time to concentrate on how GIS can best be used for a range of marine fisheries purposes. First, the chapter examines the main thematic areas currently being addressed so as to give the reader an overview of the wide range of uses for a marine fisheries GIS. Second, it briefly looks at the current issues and status of GIS activity as applied to marine fisheries, and finally the chapter ends with three quite detailed case studies where GIS has been particularly successful. This chapter also provides information as to where further details might be obtained and various recommendations are made with respect to optimizing the use of GIS technology. By the end of the chapter, although readers might not know exactly what is possible with respect to the use of GIS in the marine fishery domain, they should feel fairly confident about the range of spatial problems that GIS can (or might) currently address.

10.2 MARINE FISHERY THEMATIC AREAS CURRENTLY BEING ADDRESSED VIA THE USE OF GIS

In Section 1.4 the scene was set relating to the early developments in the use of GIS for fisheries purposes (since the mid-1980s), and Table 1.1 set out the major GIS and/or fishery themes (issues) that were being followed as of a decade ago[225]. Here, the opportunity is taken to update the situation. The updating is done by reviewing two "levels of issues classification", i.e. first by looking at the broad thematic areas

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224 Disequilibrium here means that the fisheries environment is out of balance and thus must be unsustainable.

225 Note that Table 1.1 included aquaculture themes as well as those pertaining to marine and inland fisheries.

(Box 10.1)[226] and by giving some examples of each of the thematic areas, and second by examining a more detailed list of specific themes and issues (Table 10.1). The categorization used in Box 10.1 is generalized and there would be an almost infinite way of drawing up thematic categories. In addition, most GIS analyses might be described as interdisciplinary and some of the entries in Box 10.1 could be considered as "processes"while others might best be thought of as "topics". With the exception of ecosystem-related matters and the need for protected areas, the thematic areas in which GIS are now being used have not expanded much from those that were used ten years ago (Table 1.1), but the detail contained within the work is likely to be far more comprehensive (see Table 10.1), as is the use of methods incorporating more complex modelling, geostatistics, animations, 3D and 4D analyses and other processes.

BOX 10.1

The main thematic areas in marine fisheries to which GIS is currently being applied

There are a large number of ways in which GIS is presently being utilized to assist in fisheries management or research. Some of these include:

Distribution displays – this is simply the drawing of maps to show the distribution of any feature or combination of marine and/or fisheries features.
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 – to quantify and display the disposition and dynamics of any marine resource or combination of resources.
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.
Monitoring management policies – i.e. to best sustain fish yields, fishing effort needs to be optimally deployed, perhaps with the help of electronic logbooks or vessel monitoring system tracking data.
Ecosystems relationships – e.g. predator/prey relationships, or relationships between fish distributions and any environmental parameter.
Marine protected areas – i.e. identifying suitable areas for species protection, or for exclusion of fishing and analysing the results achieved by these areas.
Marine spatial planning – i.e. determining marine allocations, such that competing users of the marine space can all best function sustainably. This is complex given the number of often conflicting parties involved plus the variety of spatial considerations.
The creation of economic surfaces – i.e. 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 disequilibrium and to predict and depict scenarios for improved management practices.

Source: Modified from Fisher (2007) and updated from Meaden (2009).

In order that readers can further appreciate the types of thematic areas of investigation that are currently being undertaken, the authors exemplify a selection of studies that might appear under most of the thematic areas shown in Box 10.1. A large number of additional fisheries and/or GIS studies, papers and articles can be obtained from much of the literature quoted in Section 4.8.3, plus the conference proceedings listed in Section 4.8.4.

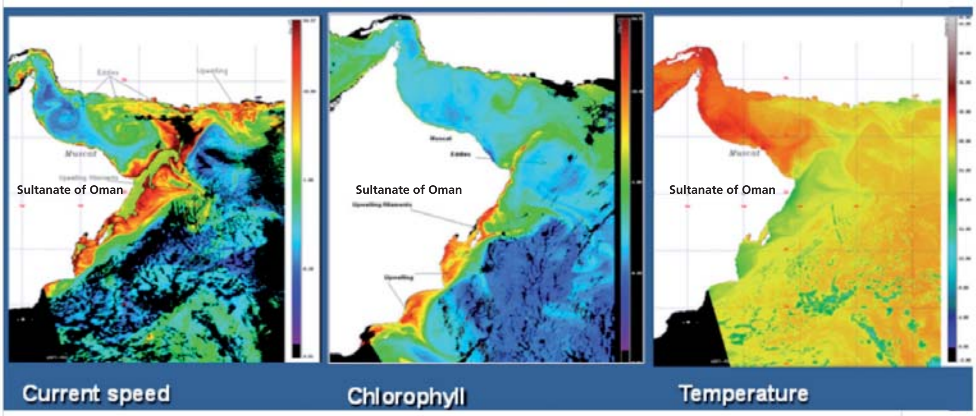
10.2.1 Distribution displays

Whatever GIS analysis work is being undertaken, it will require digital mapping showing the distribution of factors that are relevant to the analysis, i.e. to the production of the resource. These are the so-called "production functions"mentioned in Section 3.2, and they can be maps showing an almost infinite number of factors. Sometimes these maps

[226] Box 10.1 is based upon work by Meaden (2009) and it essentially updates Table 1.1.

can be quickly produced for any analyses through acquiring or otherwise downloading the relevant data and then mapping this data, e.g. it is easy for users to acquire the political outlines for most countries in order to obtain a boundary map. At other times, maps may need to be compiled by the GIS user. For instance, Figure 3.6 showed mapped data on commercial fishers' perceptions as to where they were likely to fish in the eastern English Channel. This distribution map could then be used in further analyses, such as querying the relationship between fishing locations and water depth or bottom sediment types. Similarly, Figure 6.6 showing the distribution of"ocean colour"(derived from remote sensing data) and Figure 7.15, showing the distribution of an invasive pond weed, can both be used as a basis for further analyses with respect to mariculture or to inland aquaculture, respectively. Figure 10.1 shows a small range of typical mapped distributions that will be influential in controlling fish and fishery ecosystems in the Gulf of Oman and the Arabian Sea areas. These are enhanced images from remotely sensed data, where for each distribution the colour spectrum ranges from high values in red through yellows, greens and blues to low values in violet (black is unrecorded data). A perusal of the images shows that there seems to be a relationship along the Oman coast between low water temperatures and high chlorophyll values, and this is caused by cold upwelling waters bringing nutrients to the surface that in turn stimulate chlorophyll production. The GIS could provide further and more detailed information on the strength of this and other possible relationships.

FIGURE 10.1
Some typical distributions of marine parameters in the Gulf of Oman and the Arabian Sea



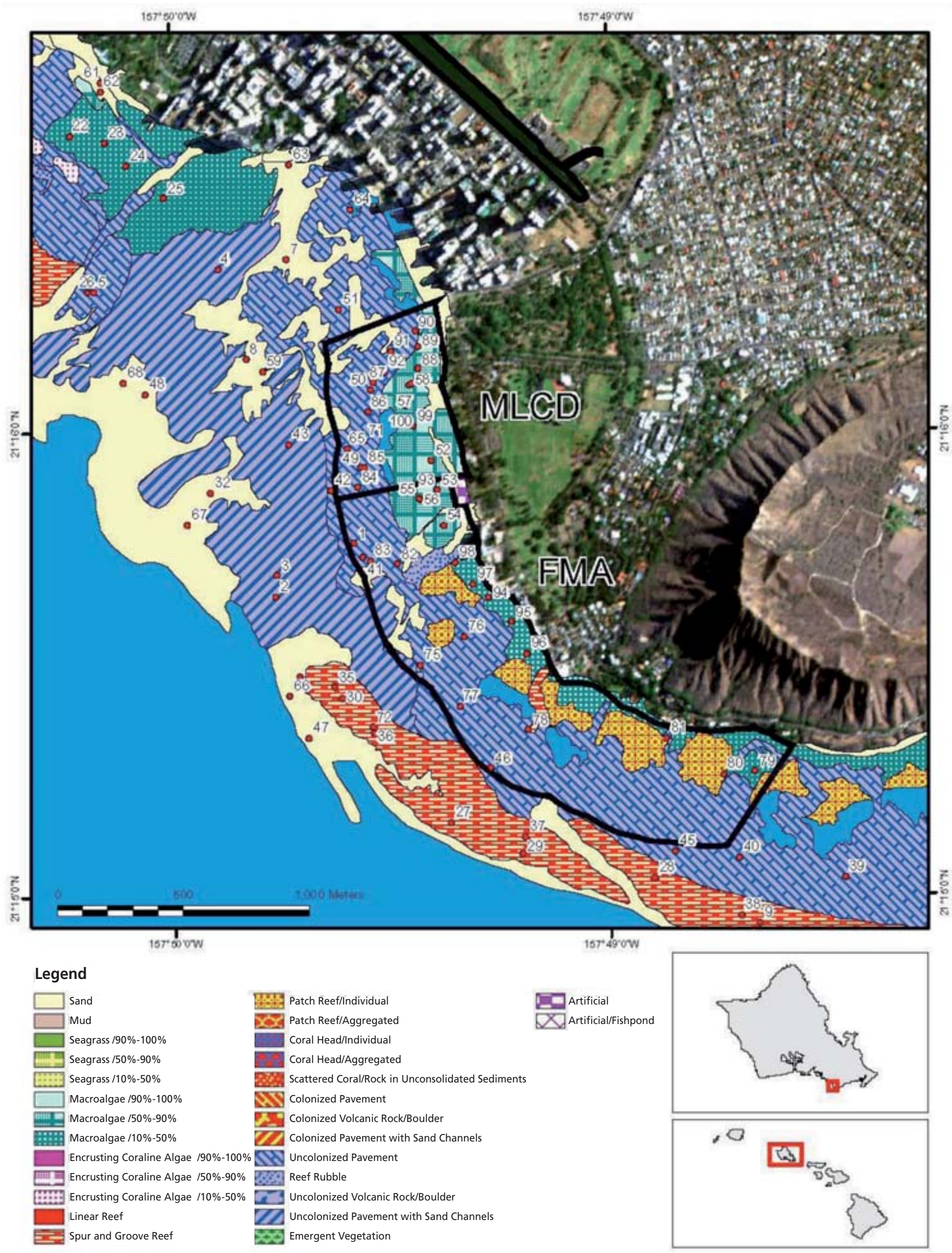
10.2.2 Marine habitat mapping and analysis and/or ecosystem relationships

These two thematic areas can be examined together because they have many similarities, especially concerning any GIS methodologies employed. If the demise of fish stocks is to be reversed, not only will it be important to better manage fisheries but it will also be essential to ensure that existing habitats are conserved and enhanced. This will require that a detailed knowledge of the range of habitats is understood and recorded and that there is a sound knowledge of the part played by various habitat types in the sustenance of marine life. Figure 10.2 provides a detailed recording of the range of benthic habitats found in a small area adjacent to the town of Waikiki Beach on O'ahu Island in Hawaii, the United States of America, in the central Pacific Ocean[227]. Data for this map (and others in a series) came from the visual interpretation of aerial photography, which was possible down to water depths of 25 m (Friedlander *et al.*, 2006). The visual interpretation of the photographs was guided by

[227] A summary of this work can be found at Center for Coastal Monitoring and Assessment, NOAA, United States of America (http://ccma nos.noaa.gov/ecosystems/coralreef/main8hi_mapping/ – accessed 10 December 2012).

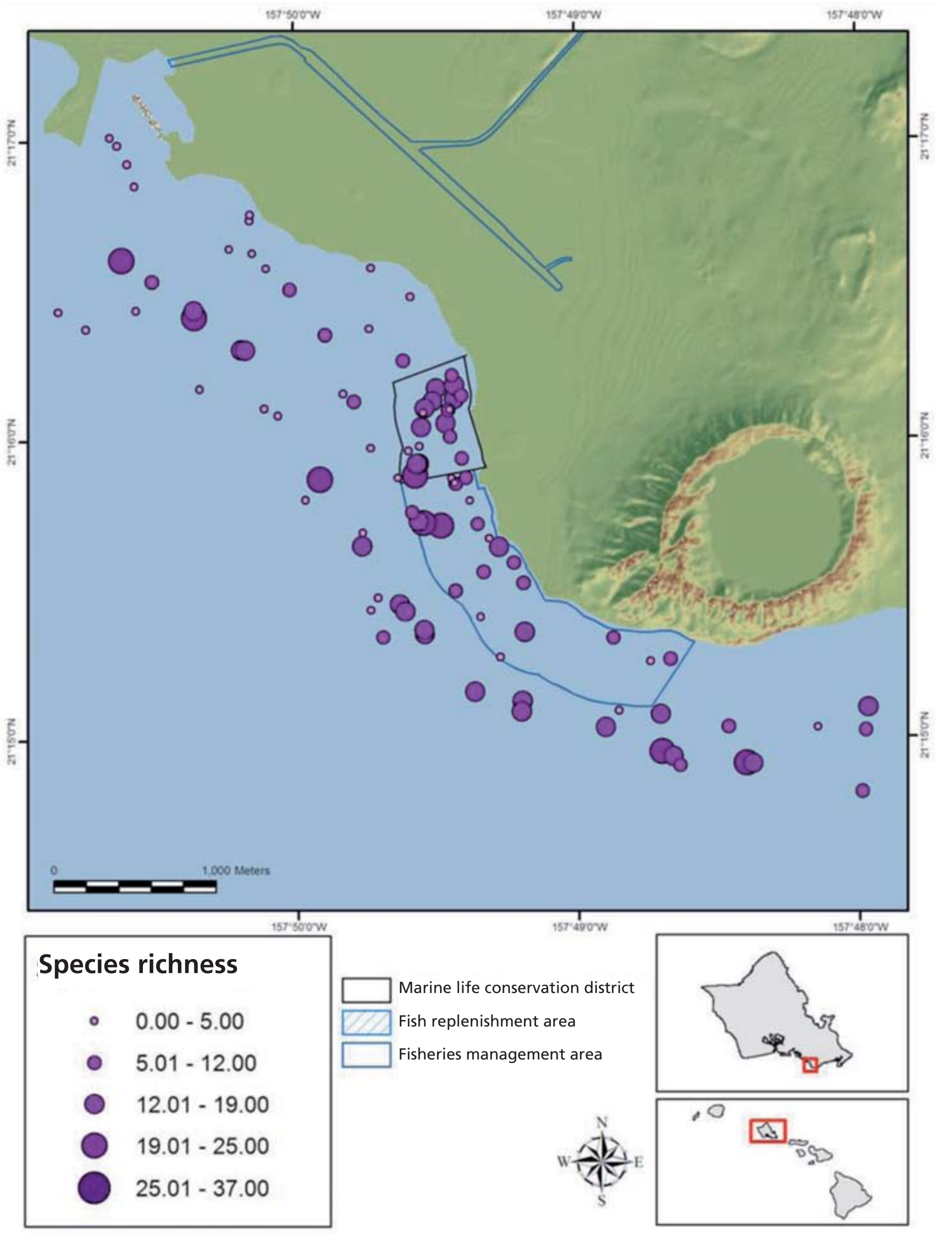
a hierarchical classification scheme that defined and delineated benthic polygon types based on insular-shelf zones and habitat structures of the benthic community. As in many other areas in the world, this popular holiday destination has suffered from fish stock depletions caused by development, sedimentation, loss of coral and other habitats, spear fishing, power boating and intrusions by invasive species. In an attempt to reverse this trend, many marine life conservation districts (MLCDs) have been established. Once mapping has been done, then a range of analyses can be undertaken to show various relationships within each MLCD. For instance, for approximately the same spatial area as shown in Figure 10.2, Figure 10.3 illustrates the species richness, and other analyses carried out by the authors showing, for example, fish densities and fish diversity. This information, in combination, can provide a secure platform on which to set further conservation goals and strategies and, more generally, to allow informed decisions to be taken.

FIGURE 10.2
Main benthic habitats off Waikiki Beach, O'ahu, Hawaiian Islands , United States of America



Source: Friedlander *et al.* (2006).

FIGURE 10.3
Fish species richness in the same area as depicted in Figure 10.2

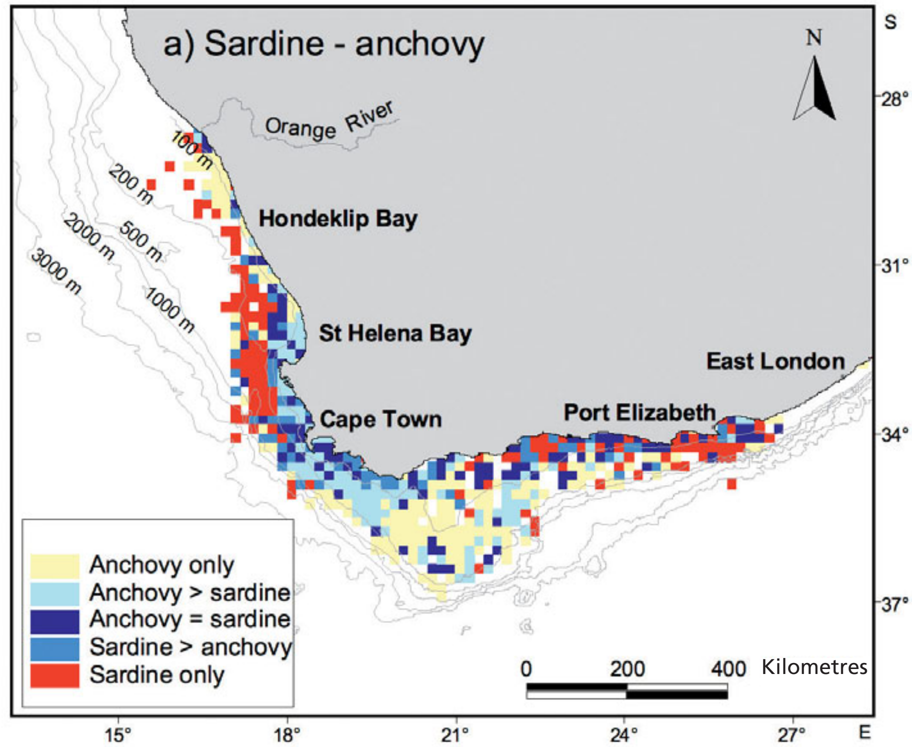


Source: Friedlander *et al.* (2006).

10.2.3 Resource analyses

Under this heading, "resources" can be thought of as consisting of a wide variety of biological or physical features that, in this case, are associated with and contribute to the marine fishing industry. Through the use of GIS, it is possible to map and to analyse the distribution of any of these resources for the purposes of research, modelling or management. Resources might include fish species, other biological species, facets of water quality, various bottom sediment or ecological types. Figure 10.4 shows the potential interactions between anchovy and sardine stocks in South African coastal waters. These waters have been divided into 10' × 10' cells (18 km × 18 km), and for each cell the relative biomass of each species was mapped using five abundance classifications. Although the authors produced data for mapping 13 key commercial species, they chose these two species to map because they are competing for the same planktonic resources and thus there is no predator/prey relationship. Interestingly, there are very similar numbers of cells for each classification category, yet they show quite different distributions. GIS is the optimum tool to further explore reasons why the distributions are as they appear, and it is probably clear to the reader that this type of mapping output could form the basis of a whole range of further spatial queries.

FIGURE 10.4
The interaction between anchovy and sardine stocks in South African coastal waters



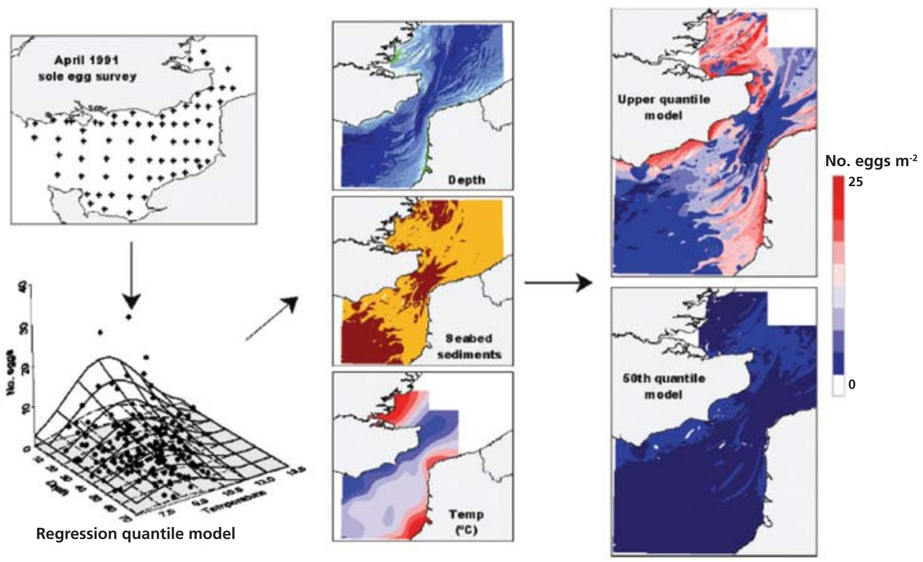
Source: Drapeau *et al.* (2004).

10.2.4 Modelling

As discussed in Section 5.4, modelling is concerned with working out a set of rules that can be established and then used for pursuing further GIS mapping or analytical procedures. It might take much experimentation to establish these rules, but once they are established they should be transferable so as to perform similar modelling procedures under a wide range of different situations. For instance, it can be appreciated that once the working methodology for portraying the information in Figure 10.4 has been worked out, the same methods could be used to compare the distribution of any two fish species in the area shown or, indeed, the relative abundance of fish species in any area. There are an almost infinite set of models that could be devised. Figure 10.5 gives a simple illustration of the basis of GIS modelling that could be used with either raster or vector data. The figure first shows the distribution of randomly selected sampling points in the English Channel where quantitative data for various parameters have been gathered. Based on this data, raster-based maps have been sampled (or values from raster-based maps have been extracted) showing the distributions of three main parameters of depth, seabed sediments and water temperature, which in this case are thought to contribute to the abundance of sole (*Solea solea*) eggs in this marine area. It was also necessary to have data on the abundance of sole eggs in the area so that the model could be developed. Eastwood and Meaden (2004) describe how the contribution of each parameter to sole egg abundance was established using regression techniques. This allowed each map layer to be"weighted"(or recoded) according to its relative contribution to the production of sole eggs. The map layers were overlaid within a GIS, and various final maps could be achieved depending on the exact regression technique being applied (in this case, the regression quantile method, which is fully described in Eastwood, Meaden and Grioche, 2001). The principles being described here show that modelling can be a particularly powerful function that GIS tools are capable of delivering.

FIGURE 10.5

Some modelling procedures for determining spawning habitats in the English Channel

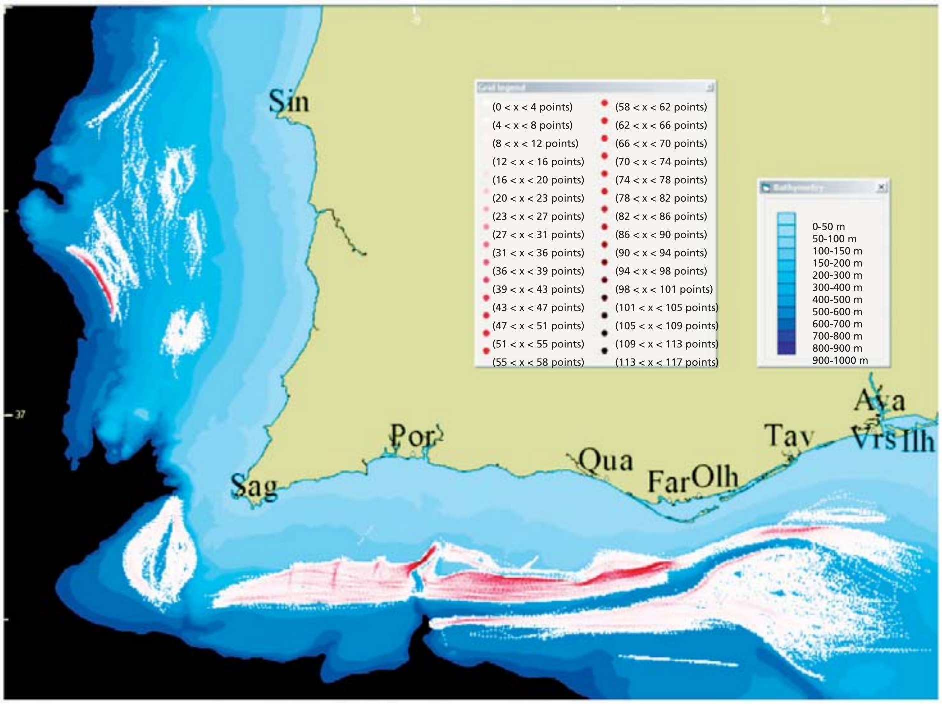


Source: Eastwood and Meaden (2004).

10.2.5 Monitoring management policies

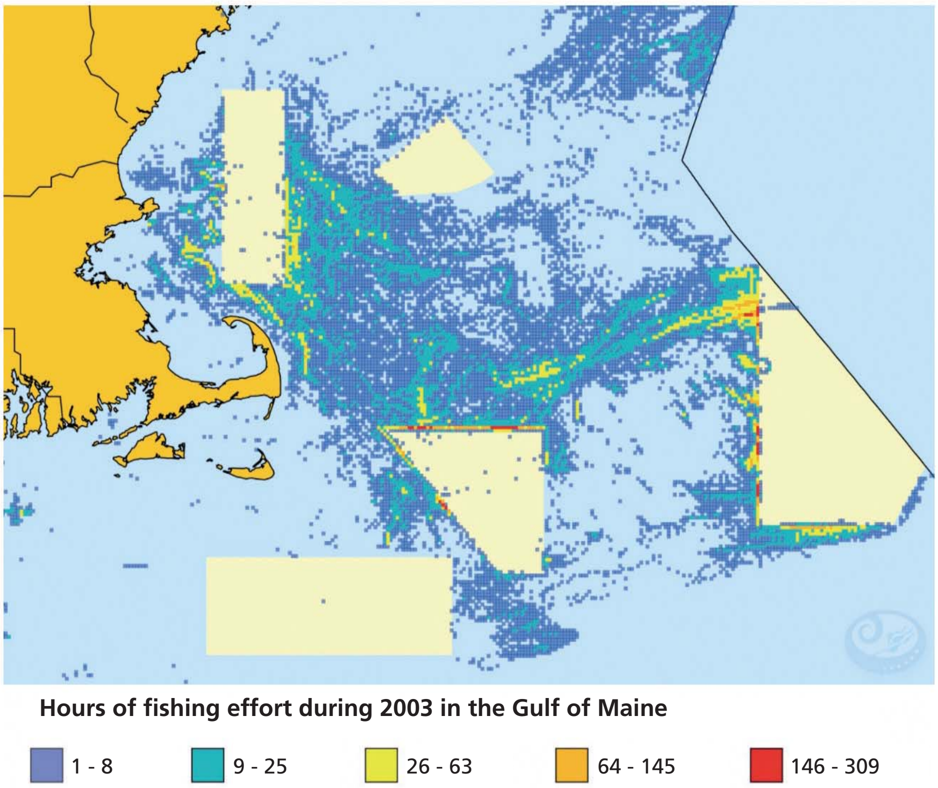
There are a large number of management policies that can be mapped or analysed using GIS. For instance, Figure 10.6 shows the disposition of the crustacean trawl fishery fleet off south-west Portugal. Here, all the individual trawl tracks (in pink) captured by the vessel monitoring system (VMS) for the 2003 season, can be seen and they show a pattern that conforms markedly with ocean depth. Thus, the trawlers are deploying their nets along contours, usually at depths of between 300 and 500 m. This is because the target species are adapted to living at specific depths – certainly at either certain times of the season or of the diurnal cycle. Clearly, stocks may become depleted in specific areas and fleet dispositions and their behaviour may need to change over time. Longer-term GIS-based analyses are likely to identify species location preferences by time, and once these are established then specific fishing strategies can be refined and economic savings can be made. Changes in fleet deployment may also be required when new regulations are introduced or when some form of marine protected areas (MPAs) are established (see Section 10.2.6). These changes can have severe consequences because they may either concentrate fishing activities into smaller areas or fisher groups can find that they are receiving unwanted additional fishing effort in their traditional locations. Figure 10.7 clearly illustrates the effects that MPAs can have on the distribution of fishing effort. Here, the areas having low effort inputs (dark blue) are widely distributed across the Gulf of Maine, the United States of America, whereas areas having medium to high effort inputs (yellow to red) are highly concentrated, almost exclusively around the edge of the MPAs. Because these MPAs have been in place for a number of years, their

FIGURE 10.6
Fishing effort in the south-west Portuguese crustacean trawl fishery as registered by VMS location data (2003)



Source: Afonso-Diaz, M, Simoes, J. and C. Pinto (2006).

FIGURE 10.7
Hours of fishing effort in 2003 in the Gulf of Maine, United States of America, and the location of marine reserves



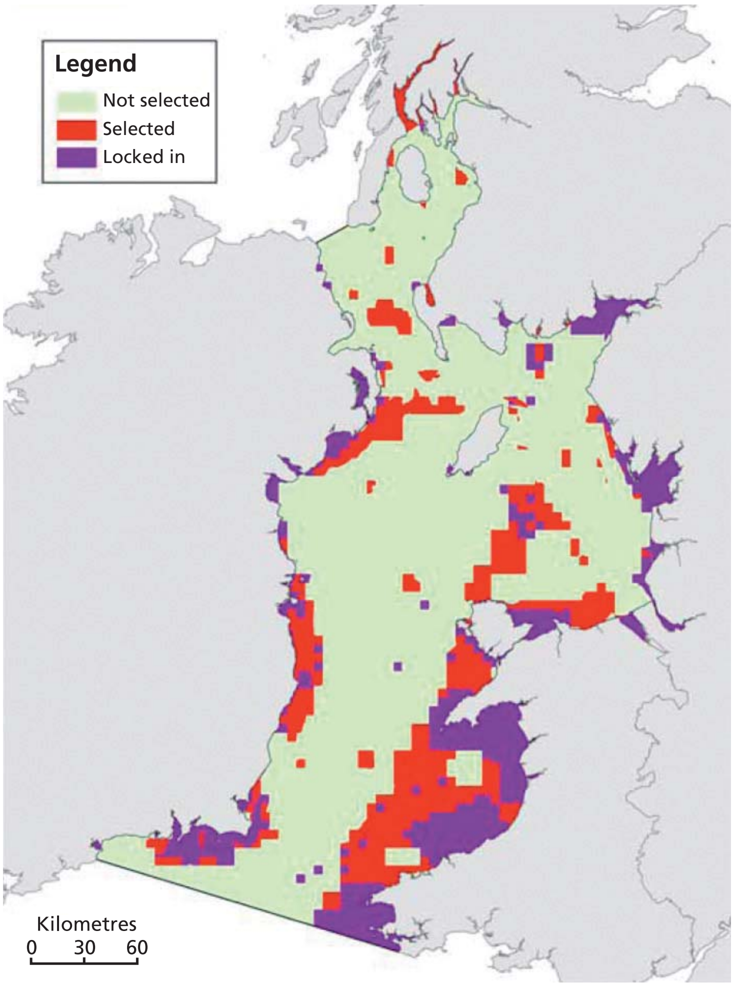
Note: Areas in beige colour represent the marine protected areas.
Source: Murawski *et al.* (2005).

fish populations are high and there is an overspill effect whereby excess fish are leaving the areas. These locations present good fishing opportunities. For management purposes, most fleet disposition mapping relies upon the use of some sort of VMS-based location capture equipment. Without this equipment only very generalized data can be gathered on fishing activity locations, though the deployment of some types of fishing activity can be monitored by other means, for example, at small scales the georeferenced location of fixed nets or the position of crab traps and lobster pots can be collected by means of handheld GPS equipment.

10.2.6 Marine protected areas

Throughout many parts of the world, it is now recognized that there is an imperative to identify marine areas that offer some degree of protection from specific marine-based activities. These marine protected areas (MPAs) might be called conservation zones, marine parks, no-take zones, vulnerable marine ecosystems (VME), etc. To this end, a large number of countries have recently issued guidance on their objectives for MPAs, how much area should be protected and on the procedures for designating MPAs in their territorial waters, and almost all the practical work in making these spatial allocations has involved the use of GIS. For example, Figure 10.7 shows the areas

FIGURE 10.8
Suggested marine protected areas (MPAs) in the Irish Sea



Note: Purple (Locked in) areas are selected as definite MPAs; red (Selected) areas are potential MPAs.

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

identified for MPA placement in the Gulf of Maine, the United States of America, as well as the impact of MPAs on fish production and on fishing effort in this area. As another example, Figure 10.8 shows selected and potential MPAs in the Irish Sea. To produce this type of output, the GIS software is being increasingly linked to software called Marxan, which has been specially developed as a conservation planning tool (see Ball and Possingham, 2000). Marxan is able to suggest optimum areas for conservation depending on the objectives for conservation, the percent of a marine area that users require to be conserved, and the degree of consolidation required among the individual designated conservation areas, e.g. from a highly fragmented to a very consolidated suite of conservation areas. Therefore, a range of conservation scenarios can be explored and visualized such that all stakeholders can consider a variety of options. Marxan is explained in greater detail in Section 10.4.1 and details on the application of Marxan for MPAs can be found in Smith *et al.* (2009).

10.2.7 Marine spatial planning

A Marine Spatial Plan (MSP) is a national or international plan devised in order to make certain that the marine space is equitably partitioned such that competing activities for the space can best be sustained. GIS has recently begun to play a major role in the delineation of these planning areas[228], in which the Marine Management Organisation of the United Kingdom of Great Britain and Northern Ireland has developed a GIS-based interactive mapping system for the display of most of their MSP data layers. MSP is urgently needed in areas where the marine space is congested and/or in areas where there are potential or actual resource conflicts, or, similarly, in areas where one marine activity is likely to have a major impact on another[229]. Figure 10.9 illustrates a portion of an MSP for a small nearshore area of southern California, the United States of America. Here, there are heavily congested activities along the coastal zone, and some of these activities are potential sources of conflict generation, e.g. sewage discharge points, ports, oil and gas facilities, and other activities are those that might be easy recipients of disturbance or conflict such as hatcheries, aquaculture, marine sanctuaries and conservation areas. Clearly, MSPs need to be instigated by neutral authorities and their implementation and future management may involve a considerable number of interested stakeholders. As with the ecosystem approach to fisheries (EAF) (see Section 10.2.9), a range of spatial tools can be linked to GIS for purposes of integrating physical and socio-economic factors for MSP, e.g. a detailed example is given by Snickars and Pitkänen (2007). The fisheries and aquaculture authorities in Newfoundland, Canada, have recently issued a clear and comprehensible analysis of the background considerations for MSP (see Department of Fisheries and Aquaculture, Government of Newfoundland and Labrador, 2011) and Douvere *et al.* (2007) provide an interesting case study of the actual inception of MSP in the case of Belgium. The United Nations Educational, Scientific and Cultural Organization (UNESCO) has also provided a useful publication combining EAF and MSP (Ehler and Douvere, 2009).

10.2.8 The creation of economic surfaces

Fishing vessels will almost certainly wish to deploy to locations where catches can be optimized in terms of maximizing economic returns. Figure 7.21 showed the central part of the New York Bight, the United States of America, in terms of where economic returns could best be maximized based on the known values of groundfish that are

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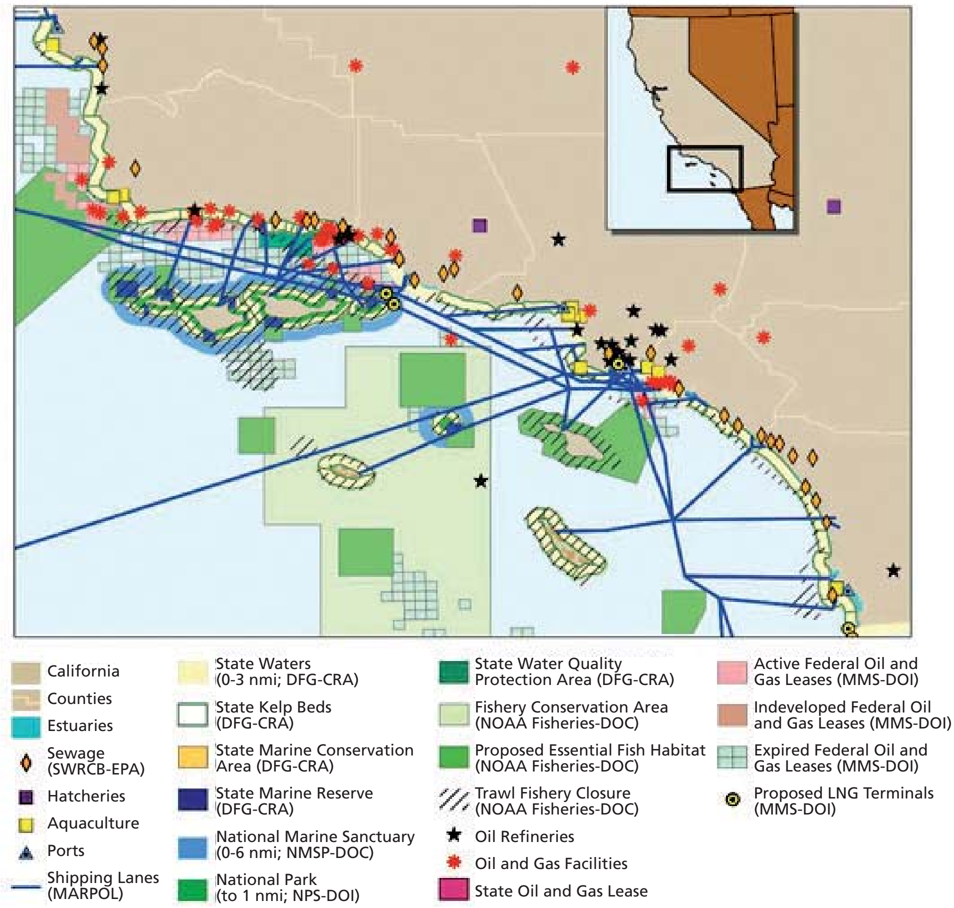
[228] For example, see http://planningportal.marinemanagement.org.uk/

[229] The potential benefits of MSP include more coordinated decision-making among government agencies and with stakeholders; improved efficiencies in granting permits; leveraging of limited resources for ocean and coastal management; better stakeholder engagement; improved data collection, coordination and management leading to more informed decision-making; reduced conflicts among users; and greater regulatory predictability leading to enhanced economic opportunities and private-sector investment, particularly with regard to emerging ocean uses (National Ocean Council, 2011).

FIGURE 10.9
Extracts from the Marine Spatial Plan for California's Channel Islands, United States of America, marine area

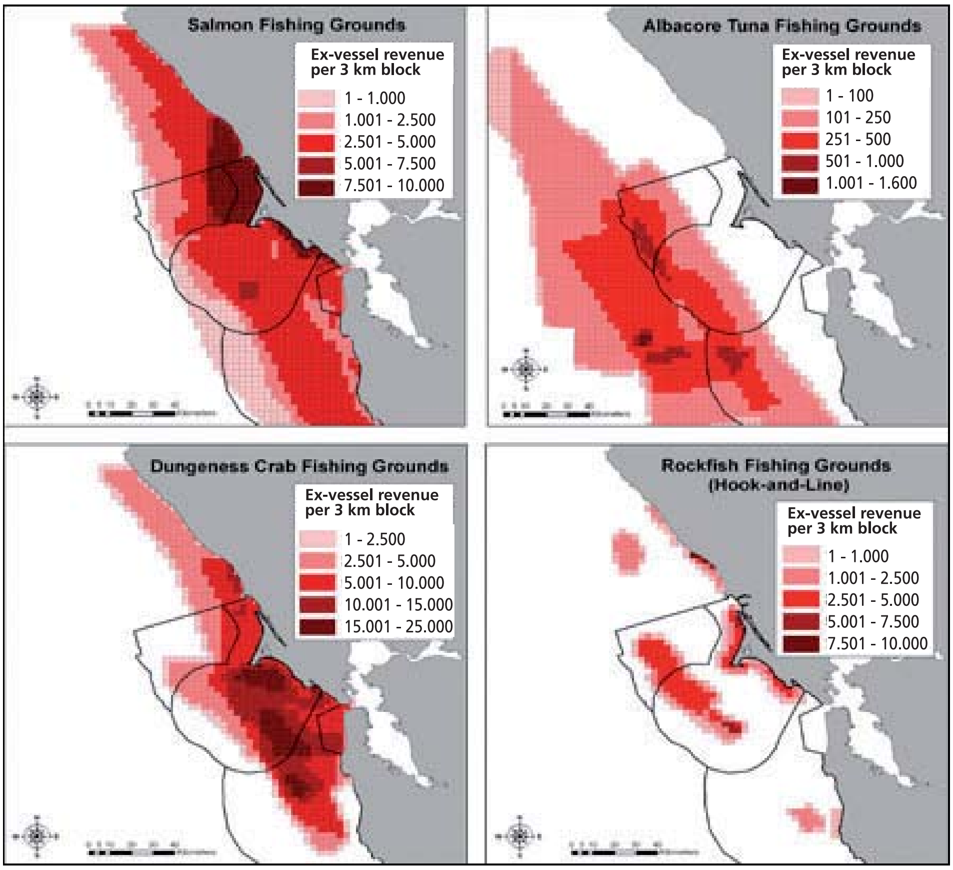


Source: Crowder *et al.* (2006).

likely to be caught by trawlers. In this figure, it can be seen that the fleet is likely to be well distributed over this broad continental shelf area, i.e. where bottom conditions are relatively homogenous and where the sea depth is only 100 m even at some 130 km from the coast. The legend reveals the considerable variations in ex-vessel value of groundfish from one area to another. Reasons for such wide variations include distance from ports, variable food availability, number of competing fishing vessels and micro-habitat variations, though it is clear that there are benefits accruing to those who can successfully fish as close inshore as possible. For a smaller area off the central coast of California, the United States of America, Figure 10.10 shows the ex-vessel value per 3 km^2 block (cells) for catches of four main commercial species caught in this area. Also shown are the boundaries of three contiguous national marine sanctuaries (NMS)[230]. Being so close to large areas of population, these species have suffered from excessive exploitation and other recruitment and oceanographic pressures over the last few decades. Fish landings have consequently declined dramatically with some species appearing to have become locally extinct. A result of stock declines was a rise in fish catch values and it is these values (averaged for the years 1997 to 2003) that are shown in Figure 10.10. Mapped economic surfaces can represent a vast number of different aspects of a fishery, including not only fish catch values by species or aggregated, but also seasonal values, changes in values over time, fuel costs for fishing in different areas and values of the differences between species.

[230] From north to south, these are the Cordell Bank National Marine Sanctuary, Gulf of the Farallones National Marine Sanctuary and Monterey Bay National Marine Sanctuary.

FIGURE 10.10
Ex-vessel values of four fisheries off the central California coast, United States of America



Source: Office of National Marine Sanctuaries (2009).

10.2.9 Ecosystem approach to fisheries

As mentioned above, this is a main new area within marine fisheries to which GIS is now being applied, one that has evolved mainly during the last decade. Although the ecosystem approach to fisheries (EAF) is a new thematic framework for fisheries management, effectively it is a process and as such it is not a theme within fisheries that needs to be illustrated by GIS-based examples. Thus, any of the figures shown in this section might well have been constructed as part of the EAF, and the whole of Section 10.4.1 is based on the EAF. Having stated this, it is important to remind readers that an EAF encapsulates much more than traditional fisheries management. Therefore, it is likely that the range of mapping output from GIS analyses will greatly increase and those using GIS or EAF-based tools will have to become familiar with a far wider range of parameters than they might have been used to handling (such as social and economic factors) as well as factors from other economic sectors. It can also be foreseen that a range of challenges will arise with respect to data gathering and mapping, and classification systems might become more difficult as it is likely that there will be a greater reliance on a range of subjectively based data. This is in contrast to most of the traditional fisheries data inputs that, although complex to handle in temporal terms, are at least fairly objective (precise) in terms of their classification boundaries. For further details on the applications of GIS to EAF, see Carocci *et al.* (2009) or Nelson, Haverland and Finnen (2009).

10.3 THE CURRENT STATUS OF GIS APPLICATIONS TO MARINE FISHERIES WORK

There are several ways in which the "status"of GIS as applied to marine fisheries might be examined. Looking generally at the main thematic areas currently being addressed (as has been done in the previous section) is one way. But it is also useful to look at other indicators concerning the status of GIS work. Here, the current thematic areas are tabulated in some detail and this is discussed. Four indicators of status have been selected: (i) main issues being addressed by fisheries GIS work; (ii) the geographic area in which the GIS work is being undertaken; (iii) the main institutions that are carrying out fisheries GIS work; and (iv) observations made by the Chair at the final session of the Symposium on GIS/Spatial Analyses in Fisheries and Aquatic Sciences held in Rio de Janeiro, Brazil, in August 2008 (Nishida and Caton, 2010).

Looking first at detailed issues and themes, in 2009 FAO compiled a database showing the main uses of GIS for marine fisheries purposes (Table 10.1) and this has been updated to 2012. This database comprises of 360 records covering 22 years, and it was compiled as part of FAO's work in developing the GISFish Web portal.[231] Table 10.1 shows that, relative to what was happening a decade ago, there has been a proliferation of GIS work, and it is now being applied over substantial areas of interest. The table also clearly highlights that marine ecosystems have become a particular area for attention, with 61 records of GIS having been directly or specifically used to help with an ecosystem approach to fisheries, plus 23 records of where GIS has been used to help address ecosystems more generally and 35 records for ecosystem modelling.[232] In many ways, this attention to ecosystems is hardly surprising. Thus, not only is EAF now seen as the only valuable approach to the comprehensive management of fisheries, but GIS offers an ideal platform and tool whereby the complex array of spatio-temporal considerations inherent in an ecosystem approach can be realistically examined. This GIS-based examination can encapsulate an array of data integration, functional manipulations and process modelling all on the same platform, and the output obtained can be viewed with a high degree of confidence, i.e. such that the visualized output is of major benefit to decision-making. Other prominent issues addressed include factors relating to both conservation and to fisheries management, which are clearly subjects of escalating importance in a world suffering from rapid species populations decline.

[231] See www.fao.org/fishery/gisfish/index.jsp.

[232] The zeros shown in Table 10.1 indicate areas where it was suspected that GIS issues would have been covered but where in fact no publications were found.

TABLE 10.1
Marine fisheries – main issues and themes from the GISFish database (1990–2012)

Main marine fishery issues and themes	Number of literature records
Ecosystems/ecoregions	23
Impacts of climate change	0
Multispecies analysis	9
Migration and individual movements	1
Catch and effort estimation	5
Habitats	27
Species distribution	20
Biodiversity	9
Human activities	6
Impact caused by fisheries	9
Management regulations	6
Spatial stock assessment	10
Ecosystem modelling	35
Marine protected area (design, implementation, monitoring)	30
Fishing vessel movements and behaviour	4
Social/economic impact studies	6
Ecosystem approach to fisheries management (EAFM) and indicators	21
Integrated marine management and planning	41
Fisheries development	1
Food security	0
Fisheries management systems	20
Monitoring and enforcement	0
Training	3
Promotion	13
Foundations for an ecosystem approach to fisheries (EAF)	61
Total	**360**

Source: FAO (2012d).

Table 10.2 addresses the 207 papers compiled from the FAO Aquatic Sciences and Fisheries Abstracts (ASFA) literature database under the keywords of "marine fisheries"and "GIS"for the period 1996 to 2010. The table is ranked according to the geographic area that the papers are covering.[233] Twenty-seven percent of the papers cover no geographic area because they are mainly methodological in content. Of the remaining 150 records, it is clear that there is an overwhelming dominance of work directed towards the developed world, i.e. especially in the United States of America, but also in the Caribbean, Australia, Canada, New Zealand, the North Pacific and the Bering Sea. These seven areas alone contain 55 percent of all records, and developed countries as a whole have the vast majority of all records. These facts are hardly surprising given the potential complexities and costs associated with undertaking GIS work that relies on data collected from a widespread and often hostile physical environment. Nevertheless, these records show a decade of what is often pioneering work, and in this current technical paper a wealth of demonstrable material has been

[235] Where a designation is made to a country, it signifies that the work was carried out by an institution or group from that country and that the work was within the exclusive economic zone of that country.

illustrated that can form the basis of new GIS and/or marine fisheries work. This is work that can be relatively easily duplicated by fisheries researchers and managers in less developed countries. Indeed, it is encouraging to note the work that is now being done by emerging economies such as the Federative Republic of Brazil, the People's Republic of China, the Republic of India, the Republic of Indonesia, the United Mexican States and the Philippines. This research is especially important because all of these countries have: (i) large populations; (ii) rapidly developing fisheries; (iii) large marine jurisdictions; and (iv) areas where fisheries production is extremely depleted.

TABLE 10.2
Country or marine area of application for 207 literature records on papers covering marine fisheries + GIS in the FAO ASFA database (1996–2010)

Country of application	Marine area of application	Number of applications
United States of America		80
	Caribbean Sea + Gulf of Mexico	16
Mexico		5
	North Pacific	5
Australia		3
New Zealand		3
Canada		3
	Bering Sea	3
	Indian Ocean	3
	English Channel	3
China		2
Africa		2
Italy		2
France		2
	North Sea	2
	South Atlantic	2
	Baltic Sea	1
	Barents Sea	1
	South Pacific	1
Brazil		1
Thailand		1
Philippines		1
Portugal		1
Spain		1
Japan		1
Indonesia		1
South Africa		1
India		1
Greece		1
Argentina		1
No specific area		57
Total		**207**

Source: FAO (2012b).

An additional background area indicating the status of GIS applications to marine fisheries is that of where much of the major and innovative work on marine fisheries GIS (in terms of the institutions) is being conducted. Box 10.2 gives an overview of some of the major organizations that are pursuing work in fisheries GIS. Given the highly technical nature of much of the work, nearly all of these institutions are in North America, Europe or Japan. However, there are now institutions in the People's Republic of China,

BOX 10.2

Overview of major organizations carrying out fisheries-related GIS research and projects

Clearly, this box can only be illustrative and it is impossible to give the exact range or number of institutions carrying out fisheries-based GIS work.

- **Australia.** The Marine and Atmospheric Research section of the Commonwealth Scientific and Industrial Research Organisation (CSIRO) undertakes a wide range of fisheries-related GIS work at several of its research laboratories.
- **Canada.** The Fisheries Centre at the University of British Columbia. Arguably the premier academic institution for fisheries research, GIS is integrated into much of their output. Many projects integrate Ecopath and Ecosim modelling.
- **France.** French Research Institute for Exploitation of the Sea (IFREMER). This institute has a large number of GIS initiatives, many of them being highly innovative including complete marine GIS systems.
- **Greece.** Hellenic Centre for Marine Research. Among many fishery-related activities, the Centre has made significant advances in GIS, mainly from their marine GIS laboratory in Heraklion, Crete.
- **Italy.** The Food and Agricultural Organization of the United Nations (FAO). Supportive work is undertaken at its Rome headquarters and a number of international projects incorporate GIS as a means of better developing fisheries in less-developed areas. GISFish and COPEMED are examples of its supportive work.
- **Japan.** Environmental Simulation Laboratory. This private company has worked with government fisheries research institutes to produce an advanced marine fisheries GIS.
- **Japan.** Hokkaido University. The Graduate School of Fisheries Science has a thriving programme that includes many GIS-based projects, with much emphasis also being placed on the use of remote sensing imagery.
- **South Africa.** The large-scale VIBES (Viability of exploited pelagics in the Benguela Ecosystem) project uses GIS to research and manage this extremely productive marine area off the southwest African coast. It is largely a combined French government and South African universities integrated project.
- **United Kingdom.** University of Aberdeen, Scotland. In the university's Zoology Department, there is a small but thriving fisheries research team that has made innovative uses of GIS on a range of projects.
- **United Kingdom.** University of Stirling, Scotland. A wide range of GIS-based projects are being worked on. It was the premier United Kingdom university to cover fisheries and aquaculture GIS, and some of its Master's modules incorporate fisheries-related GIS.
- **United Kingdom.** Centre for Environment, Fisheries and Aquaculture Science (CEFAS). This is the government fisheries research agency in the United Kingdom having a specialist GIS office at its Lowestoft headquarters.
- **United States of America.** National Marine Fisheries Service of the National Oceanic and Atmospheric Administration (NOAA). Through NOAA, the United States government sponsors a large number of research initiatives that utilize GIS, e.g. the mandate to develop essential fish habitats.
- **United States of America.** University of Miami. Here, the Fisheries Ecosystems Modelling and Assessment Research Group is doing very advanced GIS-based fishery and ecosystem-related research work.
- **United States of America.** Woods Hole Institute of Oceanography. This world renowned institute carries out many fisheries research studies that frequently exploit its GIS prowess.

Source: Updated from Meaden (2009).

the Republic of India and in some Middle East countries where applications of GIS to fisheries research projects and to management are innovative. There is also advanced work being done in Australia (chiefly by the CSIRO[234]) and in New Zealand[235]. Valavanis (2002) provides more detail on the range of work being undertaken at various institutions.

Finally, with respect to the current status of GIS applications to marine fisheries work, Box 10.3 describes some individual observations made at the conclusion of the Rio de Janeiro, Brazil, GIS/Fisheries Symposium in 2008. This box needs little discussion, but it provides a useful insight into some of the perceived trends and/or status in GIS use. From the observations made, it is clear that strong advances are being made in the range, depth and overall sophistication of GIS work. But it is also clear that there is a range of thematic areas into which GIS has barely made any headway. It is anticipated that some of these areas will prove "unavoidable" once both marine spatial planning and an ecosystem approach to fisheries are pursued more vigorously.

BOX 10.3
Observations made at the conclusion of the Symposium in GIS/Spatial Analyses in Fishery and Aquatic Sciences (Rio de Janeiro, Brazil, August 2008)

These observations are not in any particular order and they may apply to more than just marine uses of GIS for fisheries purposes:

- The noticeable use of remote sensing in work based on the Pacific Ocean.
- A wide variation in the complexity of the GIS projects presented.
- Variations in the nature of the more sophisticated work.
- Dominance of ArcView (ESRI) as the GIS-favoured tool – but also GRASS, Manifold, IDRISI, plus other unidentified commercial GIS and Marine Explorer were used.
- It is clear that very large data sets are now more available and being used.
- There was very little concentration on social or economic themes.
- Very little attention was given to sport fishery or recreation angling.
- Few demonstrations of GIS to river fisheries or river habitats.
- No use made of GIS for work on restocking.
- No mention of why attendees chose the GIS software that they utilized.
- Few indications pointing to where GIS-based work has proven to be beneficial.
- The exciting range and quality of GIS work being undertaken.

10.4 CASE STUDIES OF APPLICATIONS OF GIS TO MARINE FISHERIES

Perhaps the most useful way of conveying the usefulness of any methodology or tool is through illustrations provided by case studies. A major reason why case studies are so useful is that they are applications that have been worked through and thus should readily be applicable in different areas or for different species or perhaps at different scales. They can also, of course, be modified in an infinite number of ways to suit any prevailing circumstances. The case studies are as varied as possible and include a variety of GIS-based techniques. The three case studies chosen were:

- a sophisticated example from a developed world area where a fairly large group of research workers was deployed (Section 10.4.1);
- a less sophisticated study in a developing world area involving the extensive use of remote sensing (Section 10.4.2);
- a fairly basic study carried out by a master's level student using precollected data and looking at both habitats and artisanal fishers and their methods (Section 10.4.3).

[234] The Commonwealth Scientific and Industrial Research Organisation.

[235] Fisheries are particularly important to the New Zealand economy and the country has one of the world's premier fisheries management systems.

10.4.1 Towards the use of GIS for an ecosystem approach to fisheries management (EAFM): CHARM 2 – A case study from the English Channel

Original publication reference: Meaden, G., Martin, C., Carpentier, A., Delavenne, J., Dupuis, L., Eastwood, P., Foveau, A., Garcia, C., Ota, Y., Smith, R., Spilmont, N. & Vaz, S. 2010. Towards the use of GIS for an ecosystems approach to fisheries management: CHARM 2 – a case study from the English Channel. In T. Nishida, P.J. Kailola & A.E. Caton, eds. *GIS/Spatial Analyses in Fishery and Aquatic Sciences (Volume 4)*. pp. 255–270. Saitama, Japan, International Fishery GIS Society. [GISFish id: 5490]
Spatial tools: GIS; remote sensing (minimal); Marxan; other digital mapping; spatial statistical tools.
Main issues addressed: Ecosystems/ecoregions; multispecies analysis; habitats; species distributions; biodiversity; human activities; vessel activities; spatial stock assessment; ecosystem modelling; MPA; fishers' behaviour; ecosystem approach to fisheries management (EAFM) and indicators; foundations for an EAF; integrated marine management and planning.
Duration of study: Six years (three consecutive two-year research projects).
Personnel involved: 12 members of an academic research group based at four institutions in the French Republic and the United Kingdom of Great Britain and Northern Ireland.
Target audience: Fisheries researchers, marine scientists, marine ecologists, fisheries and resource managers, local fishers, European Union and other government fishery departments, and the general public interested in marine resources.

Introduction and objectives: This paper presents the results of the third of a linked series of marine resources research projects, all largely funded under the European Union's INTERREG programme.[236] The aim of the CHARM (Channel Habitat Atlas for Resource Management) projects has been to develop materials for a series of atlases and a Web site to help with the resource management of the very busy marine area (the English Channel) located between northern France and the United Kingdom of Great Britain and Northern Ireland. Successive atlases have expanded their spatial and thematic coverage. Passing through this marine area is much of the shipping serving northern Europe, and some of the world's busiest ferry services pass back and forth across the Channel. Additionally, there are holiday resorts around the coast, wind farms are being developed, there is recreational yachting and angling, marine aggregates are being extracted, and there has long been commercial fishing activities. The current demise of fish catches provided a research challenge, i.e. can scenarios be proposed whereby the marine area functions so that all resource extraction or exploitation activities are sustainable and that fishery prospects are improved? Thus, the project is seen as a demonstration of some important considerations that are necessary in taking an ecosystem approach to fisheries management. The paper gives a brief overview of the latest CHARM project, concentrating especially on the role of GIS in creating a wide range of newly mapped resources and developing habitat models and conservation area proposals, especially with respect to managing local fisheries.

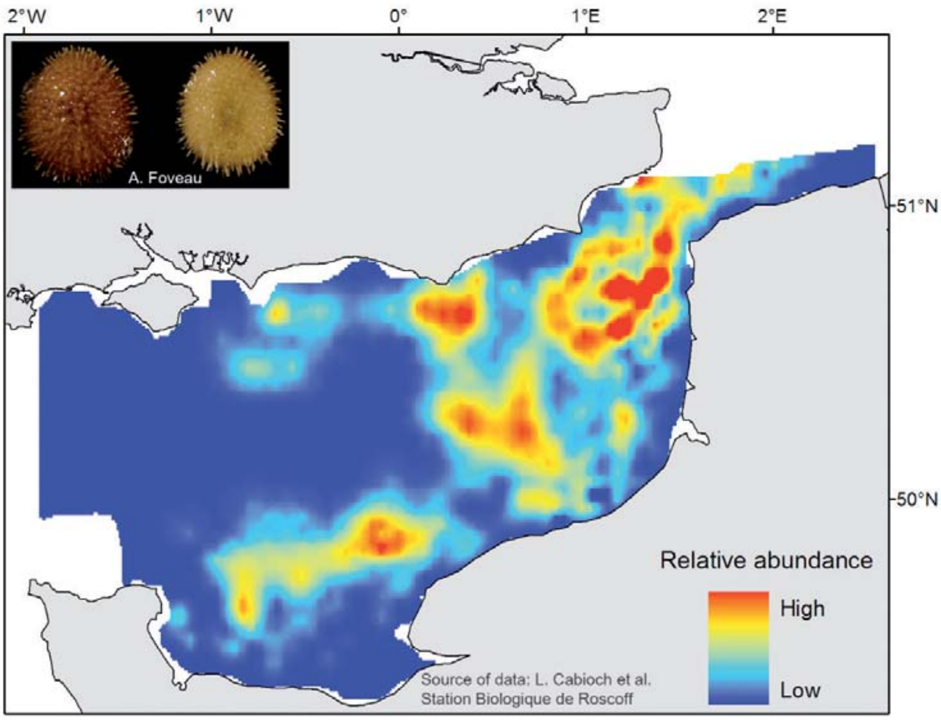
Methods and equipment: Each participating institution had responsibility for different aspects of the research project. For the work reported here, teams were involved with benthic species distribution (the Université des Sciences and Technologies de Lille – Lille University of Science and Technology); developing modelling techniques to establish essential fish habitats, commercial fish distributions and modelling to establish trophic food webs (the Institut Français de Recherche pour l'Exploitation de la Mer [IFREMER –French Research Institute for Exploitation of the Sea]); modelling

[236] The project successfully secured European Union INTERREG funding for a fourth period from 2009 to 2012.

required to show different conservation scenarios and research into various social and legal aspects relating to fishing activities (the University of Kent); and developing a Web-based marine resources atlas (see www.ifremer.fr/charm) (Canterbury Christ Church University). While work was carried out within institutions as described, there was complete integration of activities. This involved frequent project meetings and workshops, stakeholder participation, project reports, academic papers and development of the holistic atlas and Web site. Most of the data on fish distributions came from seasonal fishery surveys, carried out for over 20 years by either the Centre for Environment, Fisheries and Aquaculture Science (CEFAS) or by IFREMER. Additional data sets were needed for more specific subject areas, e.g. physical water parameters, bottom sediment distributions, some biological and chemical parameters, fish catches, fisher perceptions of their activities, etc., and remote sensing data was used for chlorophyll-*a* and water temperatures, and these data were obtained from a variety of sources. All GIS work was performed using the Environmental Systems Research Institute's (ESRI) ArcView 9.2.

Results: Space in the 2010 conference proceedings precluded anything but brief examples of some output from the 626-page atlas (Carpentier, Martin and Vaz, 2009). The atlas includes a wide range of photographic, tabular, graphical, textual, and mapped data and information. Included in the range of maps presented was Figure 10.11, which illustrates the distribution of one benthic species in the English Channel. From the EAF perspective, benthic distributions are a vital component of the ecosystem. It can be seen that this species prefers mid-Channel areas where the higher hydrodynamism (current speeds) generally provide for coarser seabed sediments. The map was constructed using data recorded between 1972 and 1976 from 1 495 sampling stations in the eastern

FIGURE 10.11
Distribution of the echinoderm *Echinocyamus pusillus* in the eastern English Channel, with inset showing the species

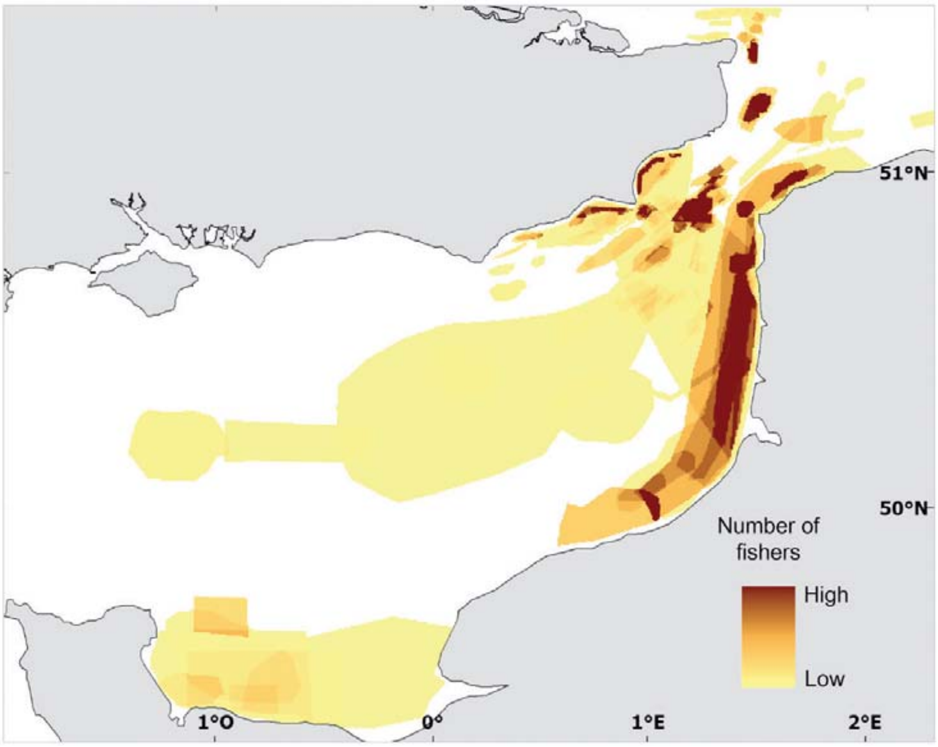


Source: Meaden, *et al.* (2010).

Channel.[237] Production of this map, and others showing species distributions, relied on the kriging interpolation procedure that itself uses a model describing the spatial structure and variation in the data, i.e. the variogram. The use of GIS for creating maps based on quite complex geostatistical inputs is now becoming widespread, and some GIS already contain a range of algorithms for geostatistical analyses.

Figure 10.12 illustrates a relatively unusual aspect of GIS-based output, i.e. the mapping of spatial perceptions. From the EAF perspective, it is important to know where fishers prefer to fish; this is because it will give a good indication of areas that usually provide good catches and where there might be controversy if fishery or other authorities declare these areas to be off limits, perhaps for conservation purposes. Fifty-one fishers from ten ports on either side of the Channel were asked to pencil in on a base map their preferred fishing locations. Figure 10.12 shows the aggregated preferred fishing areas for nine main commercial species. It is clear that inshore French waters are more favoured than elsewhere, and this is a function of there being more fishers on the French side of the Channel plus a general likelihood of the ecosystem providing for an increased abundance here.

FIGURE 10.12
Collective perceptions of fishers from selected ports in south-east England and northern France as to where they fish for nine main commercial species



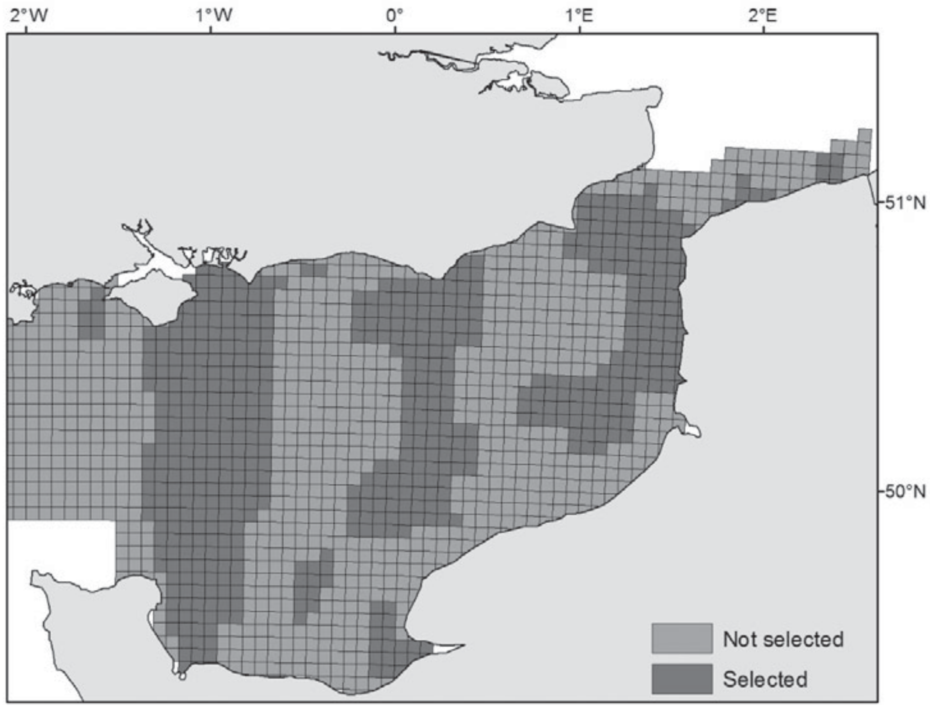
Source: Meaden *et al.* (2010).

Given the demise of commercial fisheries in the English Channel (and many other areas), and as part of an EAF, public authorities are working with other interested parties in an effort to designate MPAs (often conservation or no-take zones). This is a complex matter because the resulting areas and/or zones must often be a function of many competing aims and objectives for use of the marine space. The conservation

[237] Notice that even in the well-studied waters of the English Channel, it is necessary to use fairly old data if other suitable data sets cannot be found.

planning tool, Marxan, has been developed in response to this need.[238] Marxan involves identifying a list of conservation features, which may include important species, habitat or ecological processes, and setting numerical targets for how much of each should be conserved. Data are acquired showing the relative incidence of each identified conservation feature in each cell of the cell matrix that is imposed on the area of study (cell size is optional). A "cost score" is also allocated to each cell, which can relate to any actual cost that might be involved, e.g. loss of earnings from aggregate extraction in cells, extra costs of diverting shipping around specified cells and costs involved in travelling further to fishing areas. Marxan's output is based on setting goals corresponding to how much of the area is required to be conserved and what the total boundary length of the conservation areas should be. Marxan then performs numerous iterations to produce a portfolio of optimum conservation scenarios. Figure 10.13 shows optimum areas in the eastern English Channel whereby 40 percent of the marine area is conserved and where the boundary length[239] is relatively minimized. GIS provides the ideal platform upon which Marxan can function.

FIGURE 10.13
Areas selected for potential conservation in the eastern English Channel given a target of 40 percent of the total marine area



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

Discussion, conclusions and recommendations: There are numerous challenges to work such as that carried out by the CHARM team. These include the lack of data; costs of data acquisition; the fact that data sampling provided only snapshots in time; CHARM methods tend to utilize a "top-down" approach to EAF; the time-consuming nature of some analyses; deciding optimum resolutions to be working at; the difficulty of including all essential EAF aspects; and the infinite complexity of many marine ecosystems. Having stated these challenges, the output actually achieved by the CHARM team allowed for a vastly increased knowledge of the Channel's

[238] See www.uq.edu.au/marxan/index.html?p=1.1.1

[239] This is the total length of the boundary areas shown as "selected" in Figure 10.13.

ecosystems and resource distributions. Although almost all of the mapping work was accomplished with the aid of GIS, it should be mentioned that GIS is far more likely to be an aid to the physical, biological and environmental aspects of EAF, i.e. rather than the requisite work on the economic and social sides of the ecosystems approach. In sum, the authors anticipate that GIS uses will be increasingly developed in an effort to minimize economic and social spatial disparities.

Challenges and lessons from the case study: The case study itself recognized that there are some considerable challenges to be met in doing this type of GIS/EAF work (see above). The authors also rightly acknowledged that their work concentrated almost entirely on the marine physio-biological aspects of the whole ecosystem at the expense of socio-economic aspects. And it was clear from the publication that some thought must be given as to whether an approach to EAF (or, indeed, the ecosystem approach to aquaculture – EAA) work is best directed from the "top-down" or "bottom-up" perspective, i.e. should those who form part of the fishery or aquaculture working environment make the major contribution to aims and specific objectives for the EAF or EAA, or should these contributions come from a range of fisheries and/or marine ecosystems experts? From the GIS perspective, it is clear that the work carried out by the CHARM team was sophisticated, calling for considerable inputs from persons having thorough geostatistical knowledge and practical GIS expertise. The scale of the project was wide ranging in space and time, with data inputs relying on access to national government fisheries survey records stretching over more than 20 years, plus access to a wide range of more general data. The authors believe that the type of GIS work carried out in this project would only be possible from a fisheries research institute or from university teams and that there would need to be considerable funding available. At the "high end" of GIS work CHARM was clearly a valuable project, both for what it achieved in terms of output and as an example of what is possible.

10.4.2 Estimating reef habitat coverage suitable for the humphead wrasse, *Cheilinus undulates*, using remote sensing

Original publication reference: Oddone, A., Onori, R., Carocci, F., Sadovy, Y., Suharti, S., Colin, P.L. & Vasconcellos, M. 2010. *Estimating reef habitat coverage suitable for the humphead wrasse, Cheilinus undulates, using remote sensing*. FAO Fisheries Circular No. 1057. Rome, FAO. 31 pp.
Spatial tools: GIS; remote sensing.
Main issues addressed: Ecosystems; species distribution; habitats; spatial stock assessment.
Duration of study: Two years.
Personnel involved: Four fisheries resources experts, two GIS experts, one remote sensing expert.
Target audience: fisheries managers, fisheries scientists, remote sensing and GIS experts, marine ecologists, governmental fishery departments and conservationists.

Introduction and objectives: The humphead wrasse (Napoleon fish), *Cheilinus undulatus*, is the largest living member of the family Labridae, with a maximum size exceeding 2 m and 190 kg. The species is a protogynous hermaphrodite (i.e. adults can change sex from female to male); these species have a low productivity and occur in naturally low densities in coral reef-associated areas throughout its geographical range in the Indo-Pacific (Figure 10.14). Diminishing stocks in most tropical waters means that the species is cited on the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) Appendix II list and that management and export regulations must be applied.

FIGURE 10.14
Area of distribution of Napoleon fish (within line). The species is closely associated to coral reefs within its range

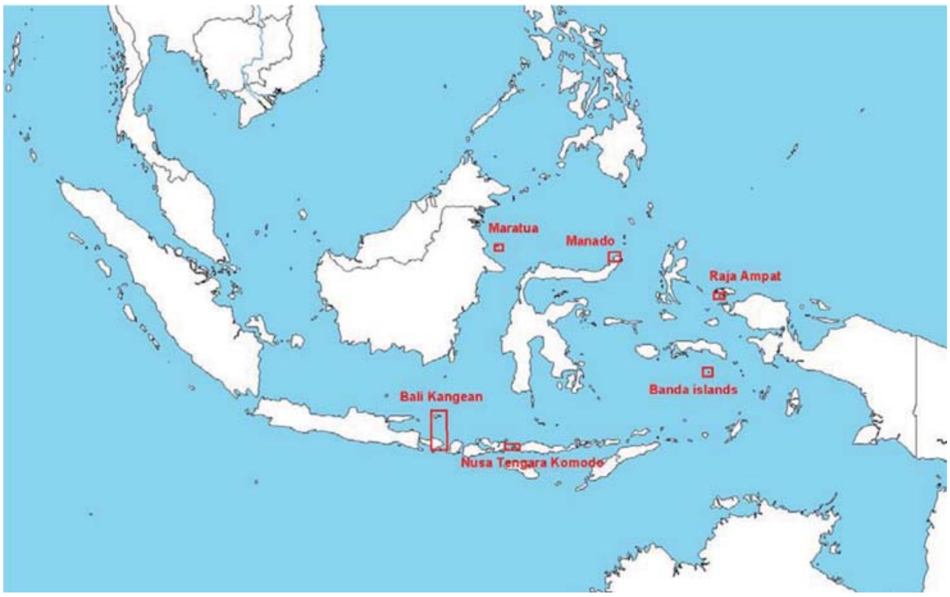
Source: Oddone *et al.* (2010).

This study evaluates the use of freely available satellite imagery, collected between 1999 and 2003, for the mapping of shallow reef areas in order to locate the habitat of humphead wrasse. The habitat suitability mapping for adult humphead wrasse is based on the location of reef edges as discerned from available Landsat remotely sensed images and on the application of a buffered area around the reef edges, where the probability of finding adult humphead wrasse is highest according to underwater visual census (UVS) data conducted during a previous phase of the study. GIS and remote sensing methods are used to estimate the habitat coverage of the species in the Republics of Indonesia, Malaysia and Papua New Guinea, three of the most important exporting countries for the species.

Methods and equipment: The study consisted of two phases. In the first phase, it was necessary to evaluate whether Landsat-7 images could be used to identify the habitat of humphead wrasse in the Republic of Indonesia. To perform this, a set of satellite images was collected for six areas in the Republic of Indonesia (Figure 10.15) that had been previously surveyed for humphead wrasse using UVS. The second phase applied the methodology developed in the Indonesian test phase to calculate the total suitable habitat areas for humphead wrasse in the Republics of Indonesia, Malaysia and Papua New Guinea. Each of these phases is now described in more detail.

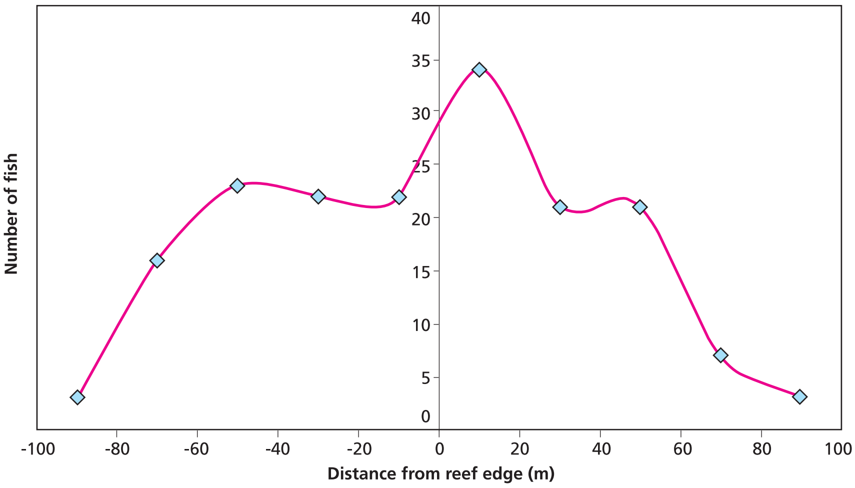
First methodology phase: identifying humphead wrasse habitat – underwater visual survey. Between 2005 and 2006, UVS were conducted in six areas of the Republic of Indonesia to estimate humphead wrasse densities in areas with contrasting levels of fishing exploitation. The diving team used a floating GPS that allowed a detailed tracking of the diving paths at 15-second intervals. The surveys were made in reef edge areas that showed all the typical aspects of the habitat of the humphead wrasse with a focus on adult habitat. Divers recorded the position of all humphead wrasse encountered during the surveys. Figure 10.16 shows the position of 180 humphead wrasse detected during the surveys relative to the calculated position of reef edges. Results indicate that 96 percent of all the fish detected were within a 200-m buffer zone.

FIGURE 10.15
Map showing the extension of the six surveyed areas in Indonesia analysed in this study



Source: Sadovy (2005).

FIGURE 10.16
Distribution of humphead wrasse detected in UVS relative to the position of the reef edge shown in the satellite images



Note: A positive distance means that fish are located towards the open sea (slope area); a negative distance means that fish are detected in the inshore Fore reef zone (see Figure 10.17).

Source Oddone *et al.* (2010).

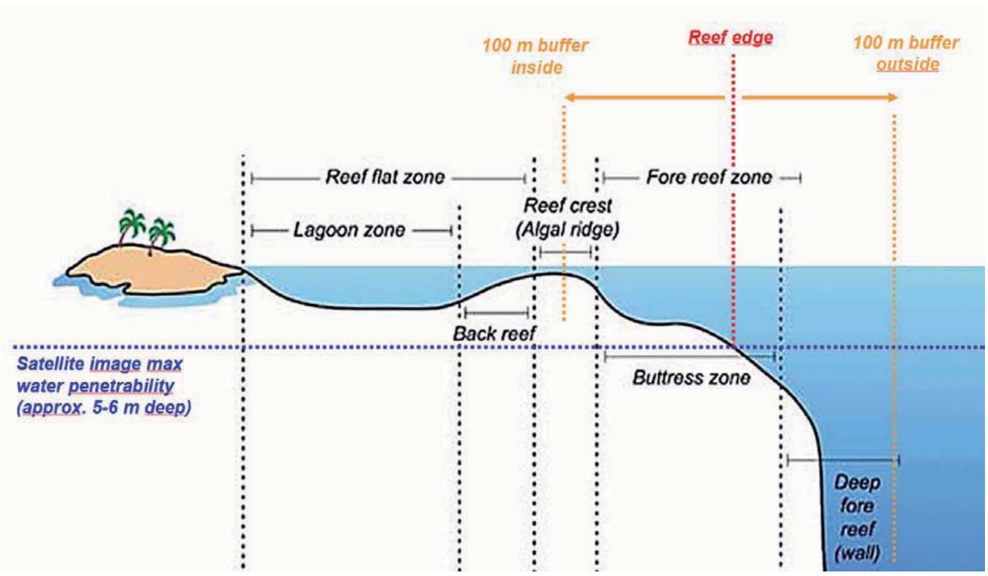
Selection of Landsat images. To perform the initial study, Landsat-7 images available from the Millennium Coral Reefs Landsat Web site (http://oceancolor.gsfc.nasa.gov/cgi/landsat.pl) for the six surveyed areas were downloaded. The authors give a detailed account of why Landsat images were preferred, this being based on a compromise concerning availability, cost, spatial coverage, their medium-scale optical resolution and the wavelengths in the electromagnetic spectrum that are captured. In total, 12 Landsat-7 images were used to cover the study area. Every Landsat image is identified by three numbers that define it in a unique way:

- Track – this number refers to the satellite orbit and can be generalized as the "longitude" of the image.
- Frame – this number represents the reference scene along the orbit and can be generalized as the "latitude" of the image.
- Acquisition date – the parameter that differentiates all the Landsat scenes acquired over the same area (i.e. same track and frame).

Image processing and analyses were accomplished using ERDAS Imagine software because it is fully compatible with ESRI's ArcView GIS software used later.

Definition of habitat for humphead wrasse. Figure 10.17 shows a schematic representation of a typical barrier reef section, with the indication of the reef edge and other main features.[240] The reef edges detected on the Landsat images are in reality the boundaries where the reef disappears from the image into the deeper sea (on average at 5 to 6 m depth). If it is considered that the reef drops into the ocean with a 45° slope inclination, a 100-m buffer would cover an area down to 100 m depth (the limit of humphead distribution) on the offshore face of the reef. The 100-m buffer towards the inside reef would cover the low water reef area. As can be seen in Figure 10.17, in some cases the 100-m buffer may be too wide for islands with narrow fringing reefs, while in others it can be too small and may thus underestimate the actual extent of reef areas. However, overall a buffer area of 100 m on either side of the reef edge seems to best fit the different morphological types of fringing reefs in the Republic of Indonesia. The definition of a more complex buffer (e.g. asymmetrical on the two sides of the reef edge or customized for every single reef area) would create a more difficult and time-consuming methodology whose effects on the overall definition of the habitat area would probably not be significant. It must also be remembered that 100 m on a Landsat image is equivalent to only 3 pixels, which is almost the visual limit of detection of objects in a Landsat image.

FIGURE 10.17
Section of barrier reef with an indication of the reef edge and 100-m buffer area (linear structures are not to scale)



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

[240] In this example, there is a steep reef wall, but this would not be the generic situation of all reef slopes.

Digitization of the potential humphead wrasse habitat. Attempts were made to identify all coral reef edge areas by means of various automatic pixel value or edge detection methods. However, for numerous reasons, these methods were rejected as being unreliable. An empirical procedure was therefore used to map the habitat of the humphead wrasse. First, an operator manually draws (digitizes) the external borders of all the reef areas he or she is able to identify on the Landsat images. Second, a fixed 100-m buffer zone is applied on both sides of the reef edge margins, thus including part of the reef habitat of young fishes and the slope area habitat of adult fishes (Figure 10.18). The extent of the habitat can therefore be calculated based on the area of the polygon formed by each buffered zone.

FIGURE 10.18
Example of identification and manual vectorization of reef edges and automatic buffering on the reef edges in the Maratua Atoll, Indonesia

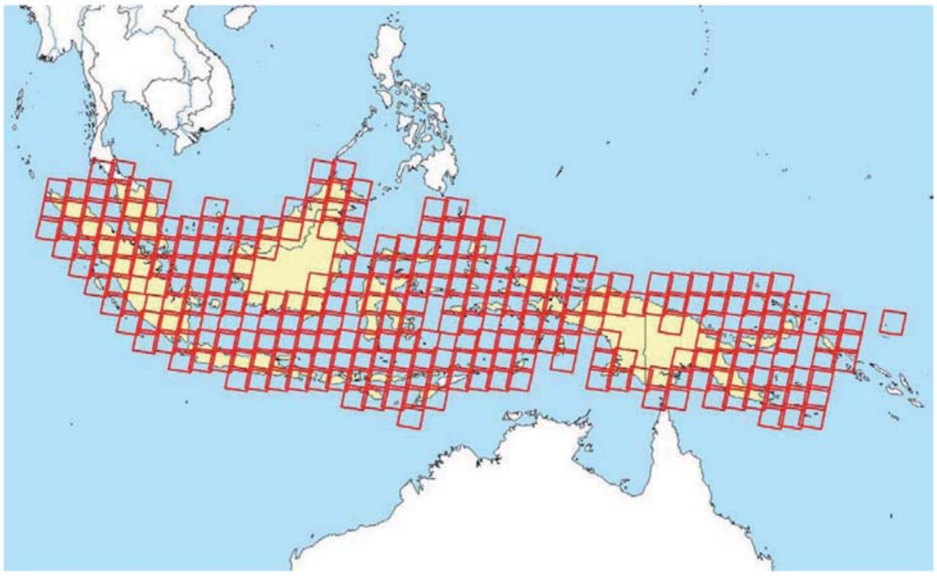
Source: Oddone *et al.* (2010).

Second methodology phase: calculate the total area of humphead wrasse habitat. Following the empirical procedures defined above, the next phase of the study was to calculate the suitable adult habitat areas in the Republics of Indonesia, Malaysia and Papua New Guinea. To perform this work, 279 Landsat-7 scenes covering the entire area of interest were used (Figure 10.19). The scenes were downloaded free of charge from the Millennium Coral Reefs Landsat Web site (http://oceancolor.gsfc.nasa.gov/cgi/landsat.pl). All scenes were based on imagery acquired between 1999 and 2002.

Discussion, conclusions and recommendations: The results of the mapping methods devised were tested against the true location of the 180 humphead wrasse recorded in the UVS survey mentioned above, and it was found that 96 percent of the wrasse were located in buffers defined by the GIS procedures. This was regarded as a strong confirmation of methodological suitability. 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 the Republic of Malaysia, and 5 254 km^2 in the Republic of Papua New Guinea.

It is concluded that, for the purpose of estimating the suitable areas of humphead wrasse habitat, i.e. as a basis for defining population size and sustainable export quotas, the results obtained in the present study are more conservative and appropriate than

FIGURE 10.19
Grid of 279 Landsat-7 scenes used to calculate the humphead wrasse habitat areas in Indonesia, Malaysia and Papua New Guinea



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

previously available estimates. Thus, previous estimates of reef areas, available only for the Republics of Indonesia and Malaysia, were approximately four times larger than the habitat areas for the wrasse calculated in the present study. This discrepancy mainly results from the much coarser satellite imagery resolution used in a previous study by Burke, Selig and Spalding (2002). The methods used and results obtained from this study can be used for other locations and species and they will act as useful information in the siting of MPAs and in any detailed marine ecosystems analyses. Additional information on monitoring and management of humpback wrasse can be found in Sadovy *et al.* (2007) and Gillet (2010).

Challenges and lessons from the case study: The case study recognized some main issues and challenges related to the above approach to mapping. In relation to the remote sensing analysis, they are concerned with aspects such as:

- Reefs that are not well defined or too small to be detected in a Landsat image.
- Areas close to river mouths where the discharge of sediments affects the ability to visualize features below the surface (although areas with high turbidity are naturally unsuitable for coral reefs).
- It is difficult to discriminate between live and dead coral.
- It is helpful if the GIS worker has some experience in remote sensing image analysis.
- Habitat mapping can be a complex and time-consuming work, especially for large and complex areas such as the Republic of Indonesia.

It is also likely that in reality the distribution of humphead wrasse would be affected by other factors than those of the position of the edge of the reef. These include the availability of food, wave strength and height, and existence of algae.

This case study illustrates a valuable and effective methodology for showing some basic uses of both remote sensing and GIS analyses. Both of the main techniques used, i.e. (i) that of using remote sensing imagery as a backdrop for digitizing and (ii) creating buffers around digitized features, are fundamental functions for many GIS projects.

This study could also form the basis of additional GIS-based work that might be carried out given access to appropriate data. For instance, given that an average wrasse density might be established for specific reefs or specific islands or administrative areas, then the total potential biomass of wrasse could be estimated for a known areal unit (which the GIS can calculate). This could give clues to the economic productivity of the area, which of course might be estimated for other extracted species. It is also apparent that if the reef edge can be digitized from the remote sensing imagery, then so too can other useful features. Therefore, the area of lagoons can be calculated, the area of the reef itself, the size of estuaries, lengths of coastline, the size of sand banks in shallow waters, etc. With respect to locations along the reef edge, these could be matched up to perhaps distance from urban areas so as to discern areas at risk from biomass overexploitation and thus in need of enhanced management practices. And the methods described here can certainly contribute to both ecosystems-based local analyses and to site selection for potential marine conservation zones. With the pressure likely to seriously increase on the world's coral reefs, especially in view of enhanced ocean acidification, then comprehensive adoptions of GIS-based methods can only be beneficial.

10.4.3 Spatial assessment and impact of artisanal fisheries activity in Cap de Creus

Original publication reference: Purroy Albet, A., Requena, S., Sarda, R., Gili, J.M. & Serrao, E. 2010. Spatial assessment and impact of artisanal fisheries activity in Cap de Creus. *In* H. Calado & A. Gil. eds. *Geographic technologies applied to marine spatial planning and integrated coastal zone management,* pp. 15–22. Centro de Informação Geográfica e Planeamento Territorial. Portugal. 164 pp.

(This work was presented by the first author in order to complete the requirements to achieve the degree of Master of Science in Marine Biodiversity and Conservation within the ERASMUS MUNDUS Master Programme (EMBC) at the Benthic Ecology Group, Department of Marine Biology and Oceanography (S-236), Instituto de Ciencias del Mar (Marine Sciences Institute) (ICM-CSIC), Passeig Marítim de la Barceloneta, 37–49, 08003 Barcelona, Spain) August 2010. [GISFish id: 6543]

Spatial tools: GIS.

Main issues addressed: Ecosystems; habitats; species distributions; human activities; impact caused by fisheries; MPA designation; social and/or economic impacts; integrated marine management.

Duration of study: Two years.

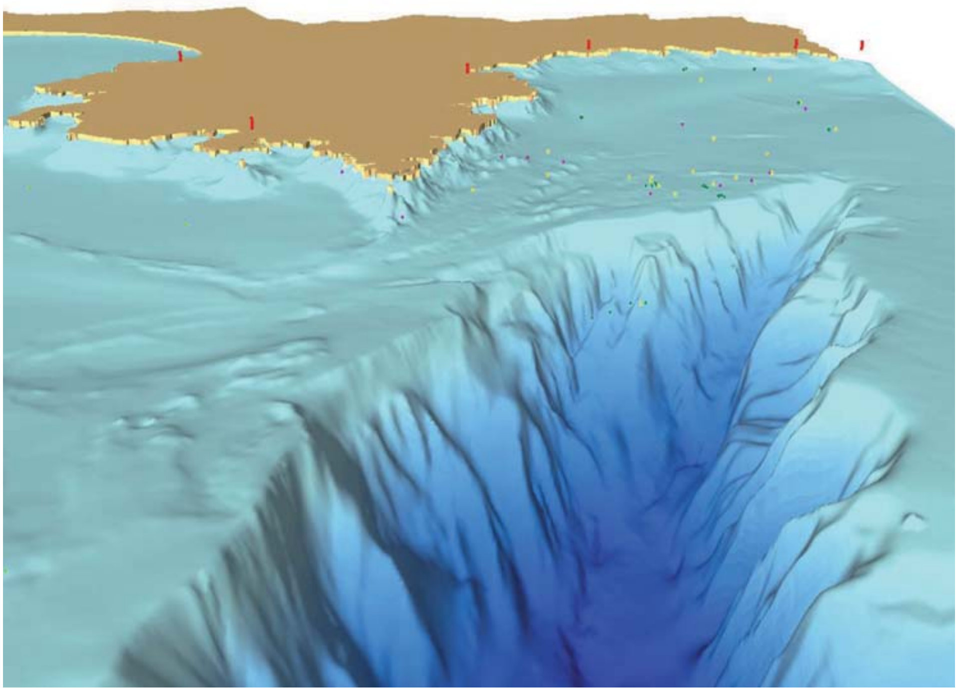
Personnel involved: One master's degree student plus assistance from four academic staff from two institutions in the Portuguese Republic and the Kingdom of Spain, and from the FAO in data collecting, plus other technical assistance.

Target audience: European Union officials, fisheries managers, local fishers, GIS experts, marine ecologists, governmental fishery departments and conservationists.

Introduction and objectives: As with many other marine areas, the Spanish Mediterranean Sea coast has long suffered from intensive and extensive overfishing, which has led to severe stock depletions and widespread habitat degradation. This is especially noticed in the inshore benthic communities that are easily accessible to the coastal communities, though also in some of the deeper benthic communities. There is now a strong recognition that steps need to be taken to reverse this degradation, and there are a number of institutional initiatives aimed at supporting work to improve the situation, for example: the Spanish government and European Commission funding; FAO-Cooperation Networks to facilitate Coordination to Support Fisheries Management in the Western and Central Mediterranean (COPEMED) projects; the creation of MPAs; Natura 2000 initiatives; habitats directives; fishing regulations; and local conservation by-laws.

This case study focuses on the Cap Creus area of north-east Spain. The area was chosen as part of a programme to assess locations for a network of Natura 2000 sites, and this location also offered the potential for the expansion of a small previously designated inshore MPA. It is also seen as being important to safeguard the long-term future of the local area artisanal fisheries. The area has an interesting marine topography resulting from the adjacency of the coastal shelf area and a major marine canyon, thus theoretically providing contrasting fishery ecosystems, a rich species biodiversity, highly variable bottom substrates and a range of ecological niches. Waters are relatively nutrient rich owing to many coastal streams entering the Gulf of Lyon, so marine productivity is potentially high.[241] However, evidence from various remotely operated vehicles (ROVs) and manned submersibles show that much of the shelf area is biologically impoverished. Figure 10.20 graphically depicts the study area with a view looking west directly at Cap Creus. Most of the coastal shelf is less that 150 m deep, but the canyon descends to over 2 000 m and is 95 km long. The area is presumably fished by large numbers of recreational anglers and spearfishers and by commercial fishing vessels, including many artisanal fishers. There is a major problem with the lack of monitoring and enforcement of fishery activities. The main objective of the study was to try to find out more about the impact of the artisanal fishers[242] on the benthic communities by asking questions on the number of the fishers, the main areas fished and species targeted, plus the varied fishing methods used. Thus, it was suspected that the different fishing methods deployed would variably affect different benthic ecosystems and GIS was seen as the ideal tool to identify any important spatial relationships.

FIGURE 10.20
3D bathymetry view looking west over the study area towards Cap Creus, Spain



Source: Purroy Albet (2010).

[241] The authors give very detailed descriptions of the atmospheric and marine processes leading to region-specific hydrological conditions.

[242] It is important to study artisanal fishers as they make up more than 80 percent of the Mediterranean fishing fleet.

Methods and equipment: For this exercise, a wide variety of data had to be acquired. The following were the main data types and sources:

- Social data on the fisheries. These data had previously been collected (in 2000–01) by regional FAO consultants using questionnaires directed at artisanal fishers, and data included fishing seasons, times, gear and/or methods[243], target species, metiers and ports. Where required these data had been georeferenced.
- Substrates, biology, bathymetry data. Acquired from the Spanish National Research Council (CSIC) offices, these data had been gathered for use in previous projects.
- Coastlines, rivers, ports. Data acquired from local and regional sources, such as the Department of Agriculture and Fisheries.

The area under study included an "inner" area (covering the existing MPA) of 216 km^2 and a wider area covering 1 145 km^2. For the purposes of mapping, the whole study area was divided into a grid of 500 m × 500 m cells; this resulted in there being a total of 4 581 marine cells. Any of the data collected under the first two bullets above could be mapped per these 0.25 km^2 cells. Data were entered and stored in a PC running ArcView and ArcCatalog 9.3 GIS (ESRI). Various geoprocessing functions of this software and MGET[244] were used to bring the data into a usable format. The project used the Universal Transverse Mercator (UTM) coordinate referencing system and WGS84 as the geodetic datum for storage and analysis.

Results: The project produced a wide range of GIS output only some of which can be illustrated and discussed here. Figure 10.21 shows how the distribution of fishing methods and/or gear preferred by artisanal fishers varies geographically around the study area. It can be seen that there are some considerable spatial variations. For instance, gillnets are easily the preferred gear type in Port de la Selva, whereas the neighbouring port of Llançà apparently has no gillnetters. Only one fishing method (pots) is used by fishers from all ports. It appears that gillnets are the most widely used method and/or gear, but this is uncertain as the individual proportional circles used give no clue to actual numbers of fishers using each method. It should also be mentioned that there are strong seasonal variations in the gear type used.

In order to detect the degree of impact of various fishery systems (methods or gear), a so-called "overlap value" was assessed for the whole study area. This represented the number of different fishing methods deployed per 0.25 km^2 cell as reported by fishers in the 2000/2001 FAO survey.[245] Figure 10.22 shows the "overlap values" for the main part of the study area. It can be seen that about 60 percent of the marine study area is either not fished at all (white) or is fished using only one method and/or gear (green); this leaves approximately 30 percent as being fished by two methods and some 10 percent fished by three methods. It is clear that there is a general relationship between the distance from the coast and number of fishing methods used, mainly for the reason that some methods can be more easily deployed in shallower waters.

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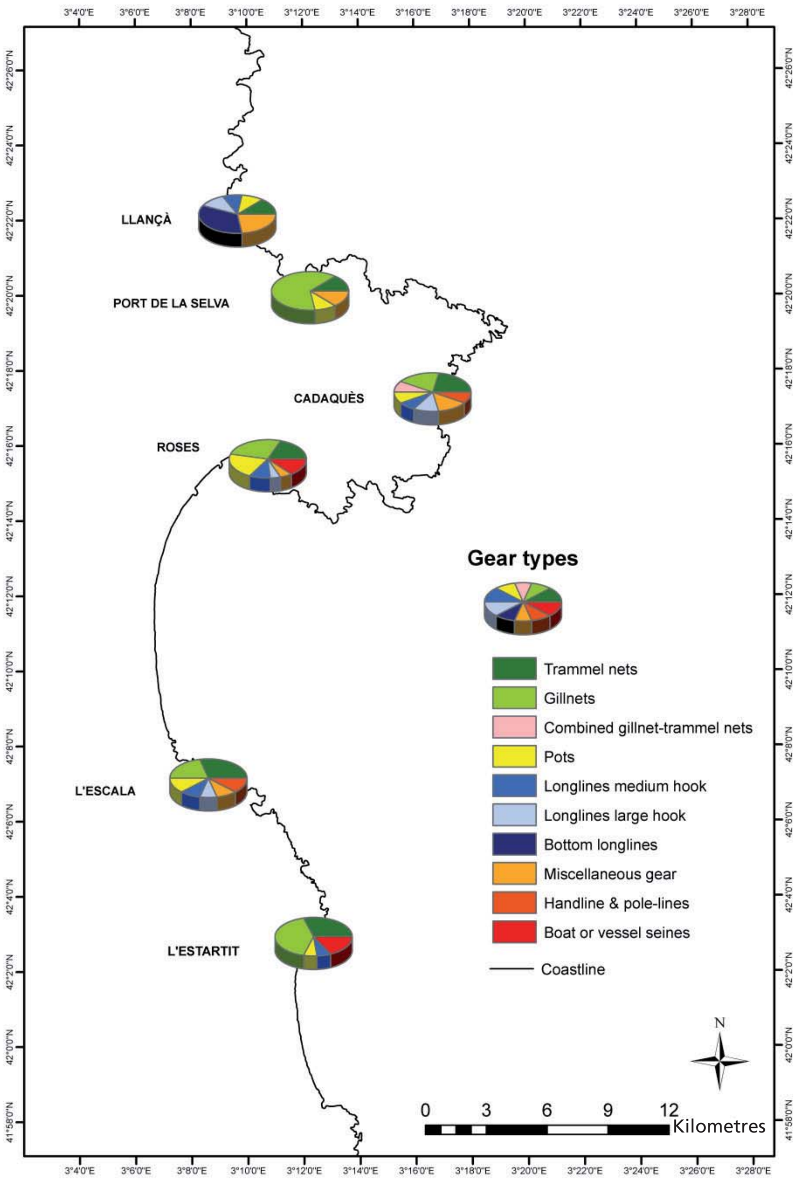
[243] Fishing gear used FAO classification and included trammel nets, gillnets, longlines, pots, handlines and poles, boat dredges and miscellaneous gear (plus some combinations of these).

[244] Marine Geospatial Ecology Tools, developed by Duke University, Marine Geospatial Ecology Laboratory (http://code.env.duke.edu projects/mget).

[245] Minor deployments of particular gear in cells were not counted.

FIGURE 10.21
Gear types used by fishers from the six main ports in the study area

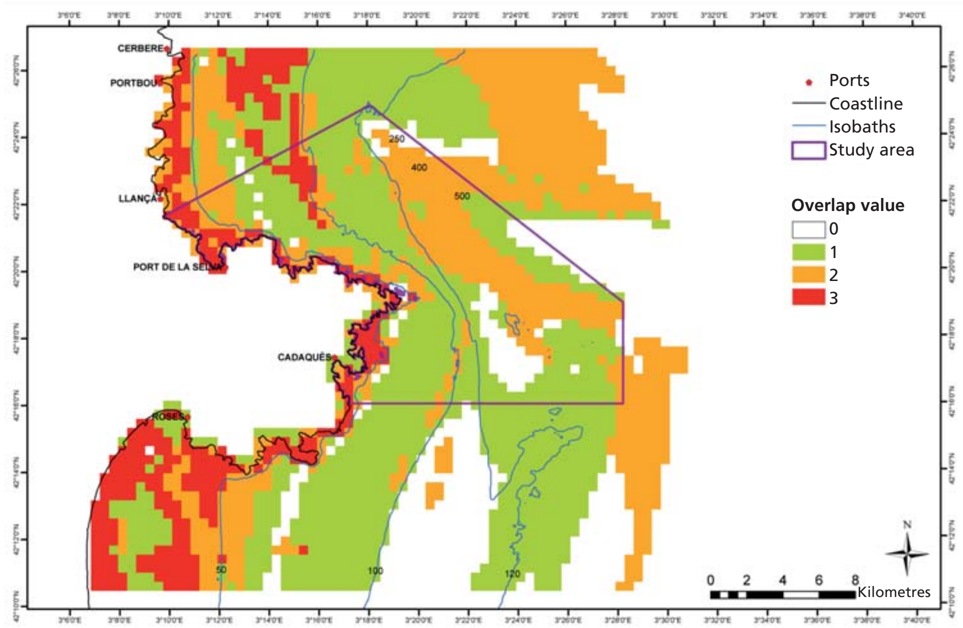


Source: Purroy Albet (2010).

Discussion and conclusions: Figure 10.23 shows the species communities in the Cap de Creus area that the authors consider to be most valuable in conservation terms, i.e. these are mostly the rarer and thus smaller communities that are living along the edge of the canyon, plus a wider area designated as "detritic litoral sandy mud". The authors conclude that these areas have been conserved because they are mainly those areas that have only been subjected to one type of fishing method (or less). Figure 10.23 does indeed show that at least one type of fishing activity, that using trammel nets, mainly appears to avoid the favoured conservation areas[246]. The authors also discuss further factors that might need to be considered when decisions are taken on selecting areas for MPAs or when "no-take" zones for fishing are designated, e.g. the spatial extent and patchiness of fishing activities and the use of seasonal or rotational management zoning. But whichever methods are chosen, it will be important to involve a range of stakeholders and to utilize full decision-making transparency.

[246] Unfortunately, there are no details on the distributions of most of the other fishing methods and/or gear.

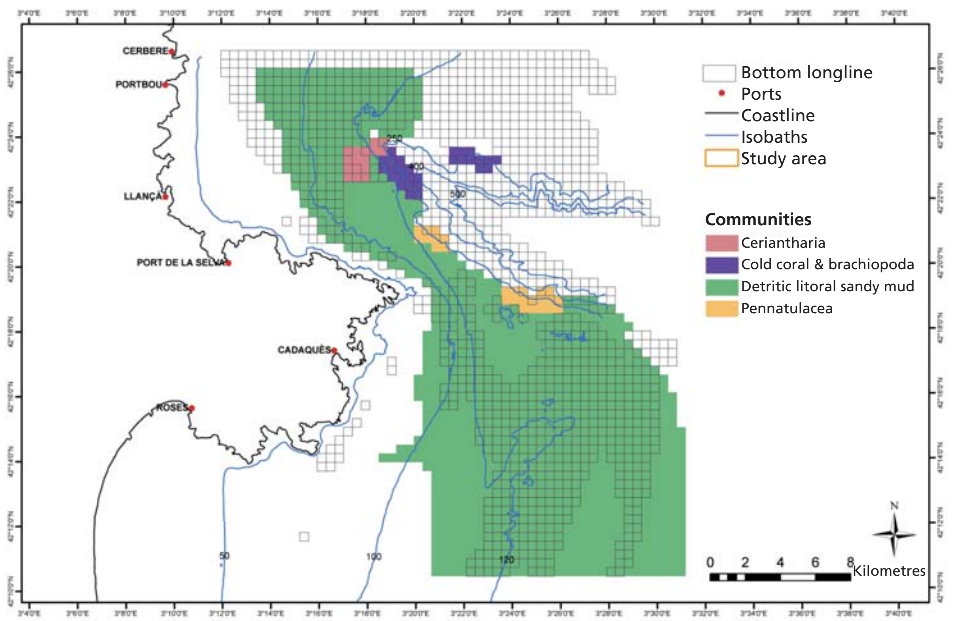
FIGURE 10.22
Number of fishing methods (overlap value) deployed per cell in Cap de Creus waters, Spain



Note: The area enclosed by the purple line is the inner study area, i.e. the existing marine protected area.

Source: Purroy Albet *et al.* (2010).

FIGURE 10.23
Relationship between the species communities most in need of conservation and the distribution of trammel nets in the Cap de Creus, Spain, marine area



Source: Purroy Albet *et al.* (2010).

Challenges and lessons from the case study: From a number of perspectives, this is an interesting case study. The authors acknowledge that there are some limitations that might need to be corrected before the findings could form the basis of future actions. For instance, the study relied on an FAO questionnaire survey covering aspects of artisanal fishing methods and these data would need to be updated. It was also not clear what the relationship was between different gear, fish species and existing benthic habitats and/or substrates. However, the study gave pointers to a range of GIS-based methods and types of analyses that could be deployed, as well as other problems that needed to be overcome in order for the study to be more successful. Particular examples are as follows:

- Because data being used came from various sources, there was the necessity of standardizing projections and spatial scales and probably using standard classifications, e.g. for sediment types.
- Similarly, the data needed to be in the same format and many of the data sets needed to be merged and refined and otherwise made compatible.
- The usefulness of designating gridded cells that cover the area of study. For some data, e.g. data collected in a raster format, this might not be necessary, but if vector-based data are used, then this may be essential. The size of cells may need to correspond to the degree of detail required, any computer-storage capacity and relevant to the resolution or spatial accuracy of the data collection methods used.
- The huge range of possible thematic areas or subjects that could have been included in a study such as this if appropriate data had been available, e.g. the inclusion of recreational angling, the seasonality of fishery activities, the impact of larger fishing vessels and the calculation of various economic cost surfaces.
- It would have been useful to study the nearshore zone in more detail, and to investigate the variable impact of the different fishing gear and/or methods deployed here.
- The difficulties of involving fishers in studies concerning their activities.
- The inefficiency of legislation in controlling at-sea fishery operations.
- It would have been interesting to study the effect of the canyon on fish yields for artisanal fishers.
- The need to utilize modern data gathering methodologies such as fishery logbooks, GPS and VMS.
- Detailing how the results of the study could contribute to a wide range of future marine considerations, e.g. the siting of "no-take" zones or other MPAs, protection of individual rarer ecotypes or habitats, reservation of fishing areas for artisanal fishers, zone allocations for different gears and marine spatial planning.

This study is thus useful at indicating some problems to be avoided and useful lines to be followed, including the huge potential for the success of GIS if access to appropriate data can be secured. Once a study like this one has been accurately accomplished, then it will be an ideal foundation for future follow-up work. It could also be expected to play a large part in any future EAF work and studies relating to MPA selection and the cost benefits of specific MPAs. In places such as this part of the Mediterranean, but also in many other parts of the world where artisanal fishery activities survive, then studies like this one can be crucial for the future success and the livelihoods of the participants.

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)

11.1 INTRODUCTION

Fish production and consumption worldwide are on the increase. While marine fisheries production has remained at about 80 million tonnes per year between 2001 and 2009, production from aquaculture has increased from 35 million tonnes to over 56 million tonnes in the same period (FAO, 2010a). Fish continues to provide a significant proportion of meat protein for much of the world, especially in poorer countries, and annual world consumption per capita has increased from less than 17 kg in 2000 to over 18 kg in 2010 (FAO Statistics and Information Branch of the Fisheries and Aquaculture Department, 2012). The worldwide value of captured fish sold by fishers was about US$94 billion in 2010 and the value for aquaculture producers was US$98 billion.[247] About 8 percent of the world's population (some 540 million) is supported by fishery activities, either directly as producers, indirectly in fishery-related activities, or as dependents. These overall facts and statistics are provided as indicators of the fact that fisheries and aquaculture are both thriving activities and, as such, they will continue to demand a growing recognition as activities in continued need of research and management. However, 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. Additionally, a large range of production types takes place in hugely varied environments and at vastly differing scales. Because of this importance, it is vital that both significant challenges and emerging themes in the use of GIS for fisheries and aquaculture purposes are now considered.

It is important to mention that considerations in this chapter are only directed to major thematic areas of fisheries and/or aquaculture that have a spatial context (though in reality this is the vast majority). There are six additional considerations needing explanation:

(i) In the title of this chapter, the terms "themes" and "issues" are used, and it is important that they are both included. Although these terms have clearly defined meanings,[248] here the two terms will be used almost synonymously. This is because this technical paper is looking at the application of GIS to resolve spatial problems (issues) across a range of topics (themes) associated with fisheries or aquaculture. So, because GIS is being deployed as a spatially based problem-solving tool, there is an automatic implication that within any specific thematic area there must be an issue that needs addressing. However, although "themes" and "issues" are virtually synonymous here, their content can still be classified into thematic areas.

(ii) This chapter includes what could be called "emerging themes" in fisheries and/or aquaculture GIS, although what is being discussed here might also be called "future trends". It seems safer to use the term "emerging" because there is plenty of evidence

[247] Despite aquaculture producing a lower quantity of fish than capture fisheries, the value of output is higher because aquaculture concentrates on producing more highly valued species, e.g. shrimp and salmon.

[248] A "theme" is a topic or a unified subject area; an "issue" is a problem or difficulty.

that these emerging themes will definitely happen, whereas in respect to a vision of "future trends" then these might be open to too much speculation and guesswork.

(iii) Both emerging or future themes can be part of an integrated chain or sequence of events with each link in the chain being its own "theme/issue". For instance, taking the issue of climate change as it relates to fisheries, it is easy to envisage the sequence: "climate change" > "warmer waters" > "species migration" > "different fish assemblages" > "changed fish landings" > "different markets", etc. Any of these "sub-themes" can be an issue by itself, and this simple chain can be made more complex as there will be numerous "side issues" at any point along the chain.

(iv) The "themes/issues" themselves must arise from drivers or catalysts for change, and it is important to briefly identify the causes that are promoting any change. Again these causes (drivers) can be complex and integrated, or be part of a chain, and it is sometimes difficult to differentiate between a "driver" and an emerging "issue" or indeed a "future trend".

(v) It may also be difficult to differentiate between "current issues" and "emerging themes/issues". To resolve this, "current issues" are those that are presently being actively pursued by those working in fisheries or aquaculture management or research, and which will be continued into the immediate and probably longer term future[249], i.e. as described in Chapters 8 to 10. By contrast, "emerging themes" can be considered as probable trends in this field of study that are likely to become more important in the near future. There requires a certain amount of speculation here, but it is important that these themes are included so as to give an idea on the future range of GIS work that is likely to develop. It is probable that some of this emerging work is already receiving attention, though not necessarily with respect to GIS applications per se.

(vi) Emphasis in this chapter has been placed on emerging issues concerning either fisheries or aquaculture that may be rooted in spatial differentiation[250] rather than those relating to GIS or to remote sensing. This is because the latter represent the tools that are used and the main concern is not with investigating how these tools themselves are developing but with how the future of fisheries or aquaculture can be improved through the use of these tools. Having said this, it will be appropriate to mention some drivers that are bringing about change to the spheres of GIS and remote sensing, and in order to match the current issues affecting fisheries and aquaculture (as described in Chapters 8 to 10), a section indicating current issues in GIS has been included (Section 11.3).

In order to conceptualize the progression of the contents of this chapter, i.e. of the emerging themes and the factors influencing them, their logical sequence is shown in Figure 11.1. The boxes highlighted in bold are those that have been discussed in this paper, and the boxes in pink are those discussed in this chapter. It can be seen that spatial themes and/or issues may gradually progress through the "time" dimension (past, present, future) all the while that they remain a relevant issue. During the "present", new spatial themes or issues will join the existing ones, i.e. as various internal or external drivers force progress either in GIS or remote sensing capability, or as new spatial issues arise within the fields of fisheries or aquaculture. Any present emerging themes and/or issues are likely to contribute to future themes and issues, although it cannot be certain which these will be, and over time it is likely that the total number of themes and/or issues will gradually increase.

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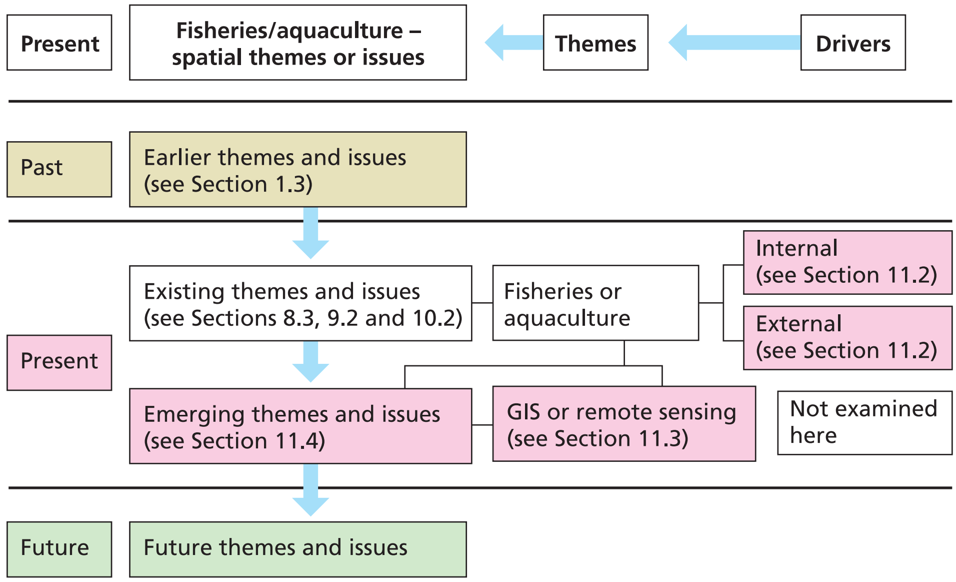
[249] Current issues may prevail for many decades because countries or areas that are at different stages of development will adopt "issues" at different times.

[250] "spatial differentiation" refers to the fact that the distribution of all things, objects, etc., on the planet is variable, as are the natural and human-inspired processes that may be affecting these things and objects. So the distribution of everything on the planet varies from place to place.

FIGURE 11.1
Organization of sections 11.1 to 11.4 showing the sequence of materials covered



11.2 MAIN DRIVERS AFFECTING FUTURE SPATIALLY BASED WORK IN FISHERIES OR AQUACULTURE

Box 11.1 lists the drivers affecting spatial approaches to fisheries or aquaculture research or management-related work. Although the drivers are listed in no specific order, they generally proceed from external to internal (to fisheries or aquaculture), though many of them could be seen as both external and internal, i.e. having direct or indirect influences on fisheries or aquaculture. The processes that contribute to driver success, e.g. mainly research, marketing or political decisions, are not discussed here. Drivers will be of differing importance in different situations; indeed, some of the drivers will be of no relevance at all in some areas or regions. Some of the drivers are very specific but others are very wide ranging, and this list may not be exhaustive. Part of the list includes potential sub-categories of drivers. For reasons of breadth and quantity, detailed referencing in this section has not been undertaken, but useful overall sources include Beddington, Agnew and Clark (2007), Brugère *et al.* (2010), FAO (2010b) and Garcia and Rosenberg (2010).

(a) **Human population growth.** The world population has now passed 7 billion, but within 40 years it is likely to grow to more than 9 billion. This represents a huge potential market increase for fish products. Populations are exhibiting spatial shifts from being relatively dispersed and agriculturally based towards being concentrated in urban agglomerations whose locations are more frequently coastally based. Coastal populations are likely to reinforce market demands for fishery products.

(b) **Changes in atmospheric processes.** Here, the concern mostly relates to climate change and its impact on water temperatures. These impacts are already driving change in natural species distributions in both fresh and saltwater environments. It is not only temperature increases that might be a causal process of change; there will also be stronger winds, higher waves, reduced or increased rainfall, greater seasonal variations, higher sea levels, more species invasions, etc., any of which can influence species distributions, and particularly activities associated with inland aquaculture.

BOX 11.1

Main drivers affecting future spatial approaches to fisheries and/or aquaculture research and management

(a) Human population growth
(b) Changes in atmospheric processes
(c) Contractually based supply chains – marketing – industry consolidation
(d) Fuel and/or energy costs
(e) Education and information
(f) Protein needs, food security and poverty alleviation
(g) Socio-economic development – business opportunities – production costs
(h) Improving governance – responsible fisheries and aquaculture
(i) Capital availability – public and private
(j) Changes in consumption preferences
(k) Ecosystems degradation and environmental awareness – recognition of sustainability
(l) Freshwater access and availability – moves to recirculating systems
(m) Stakeholder participation in decision-making
(n) Certification in fisheries and aquaculture – ecolabelling
(o) Genetic modification of aquaculture species
(p) Demise of many commercial wild fish stocks
(q) Global growth in aquaculture production
(r) Controls on recreational angling
(s) Changes in fisheries management – variable scales of management – reduction of fishing effort

(c) **Contractually based supply chains.** As the scale of fisheries and aquaculture has increased, then the activity has followed usual economic trends with respect to consolidation involving forward and backwards economic integration. This may take several forms, but typically contracts are made between fish resourcers (from wild stocks or aquaculture) so that processors can guarantee continued supplies at agreed standards, or single companies may partake in all stages of the food supply chain. These chains may lead to consolidation of activities into well-established and more concentrated production areas.

(d) **Fuel and/or energy costs.** These drivers affect the economy as a whole, but they are especially important to the cost of larger-scale fishing activities. With very high fuel and/or oil prices now prevailing, and with little prospect of these diminishing much in the future, fishers are becoming increasingly cognizant of where, and how often, they fish. Aquaculture will be differently affected in the sense that there are relatively smaller direct fuel costs, but some associated input and output activities will incur rising energy and/or fuel costs.

(e) **Education and information.** Increases in production will not occur without a sound knowledge of the potential for, and production methods used, in all aspects of either fisheries or aquaculture. So, education must be seen not only in terms of economic factors but also with respect to social and environmental considerations of fish production. Organizations such as the FAO and the United Nations Educational, Scientific and Cultural Organization (UNESCO) place a huge emphasis on the provision of information in order that the wider public can gain access to the fundamentals involved in fisheries and/or aquaculture.

(f) **Protein needs, food security and poverty alleviation.** With the world population rapidly rising on a finite planet and with income levels also rising rapidly in many areas, the quantitative and qualitative demand for all foods is increasing, as are the average costs for food. However, the percentage of the population that still live in poverty remains high. With fish being both widely available and having high-quality protein, then demand is certain to continue to grow. The impacts of this are that there are accelerating needs to manage the production locations for fisheries and especially for aquaculture (which has often to compete for terrestrial space and available water). In poorer rural areas, the opportunities to engage in micro-scale aquaculture production offer a route to increased incomes and to protein security.

(g) **Socio-economic development and business opportunities.** Despite periodic downturns, the world is undoubtedly going through a period of rapid economic expansion. Increasing affluence creates not only higher consumptive demands, but it also provides greater business opportunities. Entrepreneurs will be obliged to make investment decisions which themselves are multifaceted, involving a range of cost–benefit decisions. Probably the main investment decision for aquaculture is that of optimizing location in terms of not only achieving successful production but also in minimizing input costs.

(h) **Improving governance.** Governance includes factors such as establishing legislation, fisheries management frameworks, fishing access rights, aquaculture strategic frameworks, stakeholder participation, political authority, and monitoring and enforcement. Given the overall expansion of fisheries and especially of aquaculture, a large number of countries have seen it as beneficial to make improvements to the overall means by which these activities are controlled, and although some success is being achieved, there is undoubtedly still a major challenge to be faced from illegal, unreported and unregulated (IUU) fishing. Governance can be enacted at widely varying hierarchical and spatial scales, and can impact on the formation of administrative districts, statistical divisions, data gathering considerations, etc.

(i) **Capital availability** – public and private. It is clear that, apart from developments at a very basic subsistence level, the promotion of fisheries or aquaculture must be reliant on affordability and the ability to accumulate capital or credit to cover necessary costs. Apart from these basic requisites, the availability of capital will vary greatly from time to time and from area to area. It is important to note that capital may be more or less available from either public or private funding sources.

(j) **Changes in consumption preferences.** There are many reasons why consumption preferences may change through time, for example, price or availability of fish species, market promotion of species and familiarity with a new flavour. These changes will affect production quantities among species, which in turn may offer relative advantages for production in different areas.

(k) **Ecosystems degradation and environmental awareness.** Severe ecosystems and environmental degradation continues to affect wide stretches of the global freshwater and marine area. With the growing acknowledgement that sustainability needs to be considered with respect to all activities – especially those that depend upon resource extraction – an awareness of the impact of all activities upon the environment is increasingly seen as essential. This will have major implications for both fisheries and aquaculture, both from a need to moderate impacts in spatial areas that are already being exploited and from the essential need to maintain the integrity and sustainability of existing bio-physical systems.

(l) **Freshwater access and availability.** Freshwater is virtually a finite resource[251], and in many parts of the world access or availability of this resource is already extremely precarious. With the growth of both human populations and income, the demand for freshwater is increasing exponentially. Demand for water for agriculture could rise by over 30 percent by 2030, while total global water demand could double by 2050 owing to pressures from industry, domestic use and the need to maintain environmental flows. In some arid regions of the world, several major non-renewable fossil aquifers are increasingly being depleted and cannot be replenished,

[251] Freshwater is not absolutely a finite resource because saltwater can be processed into freshwater at desalination plants, although this is energy and capital intensive.

e.g. in Australia, the Arab Republic of Egypt, Libya, and the Punjab (India). From the perspective of future inland aquaculture, this will be an important location consideration, especially given the need to increase the use of water through multipurpose uses.

(m) **Stakeholder participation in decision-making.** With the move towards ecosystem approaches to both fisheries and to aquaculture production, an increasing number of stakeholder participants may be more or less directly influencing fisheries production activities. This is likely to influence production location, and it will mean that a wider range of socio-economic factors will need to be considered, many of which will be spatially related.

(n) **Certification in fisheries or aquaculture.** This is similar in many respects to contractual supply chains, except that here fish producers are entering into agreements with organizations that have set up some kind of accreditation scheme that may offer a range of qualitative and/or standardization guarantees to participants along supply chains or to final fish consumers. This activity tends to favour more prosperous producers who can afford the costs of guaranteeing quality. Closely linked to the ideas behind certification is a "traceability system", a system that may function on a GIS platform (J. Ferreira, personal communication, 2011). It allows all input factors of production to be traced throughout the production system. In aquaculture, for example, water, feedstuffs, broodstock, workers, processing plants and markets all have a geographical component that can be mapped. If required, management controls can be maintained and specific spatial investigations or analyses can be made, e.g. in the event of a disease outbreak.[252]

(o) **Genetic modification of aquaculture species.** Until recently, this has not been a driver consideration, but there are now moves to develop species that have specific traits. In many cases, these traits will be associated with variable production functions and locations, e.g. climatic factors, water quality, shelf life and appearance.

(p) **Demise of many commercial wild fish stocks.** It has already been indicated that wild fish stocks are often static or declining. This will oblige many fisheries activities to change their preferred location, and many areas may be at least temporarily off limits to fishing as stocks are left to recover. Because productivity from marine sources has probably reached the limit in many areas, this demise in commercial stocks may also encourage a shift to aquaculture production.

(q) **Global growth in aquaculture production.** The approximate six percent worldwide growth in aquaculture per year over the last three decades is indicative of an industry that is having considerable success (Figure 11.2). Entrepreneurs and other investors will recognize this and they may wish to give support to groups who desire to enter into or expand aquaculture investments. There is a sense in which the emergence of aquaculture is simply mirroring the growth of terrestrial-based farming in far earlier periods. However, for example, rapid growth rates may have potential negative effects in terms of land availability and costs, water resources, pollution, environmental degradation, energy inputs and poor knowledge of husbandry. It is, therefore, important for aquaculture to be developed in the context of ecosystem functions and services, with no degradation of these beyond their capacity to be easily restored.

(r) **Controls on recreational angling.** Certainly, in the more developed areas, recreational angling is one of the highest participatory leisure activities, and in many areas it is considered that fish catches by this sector may be greater than commercial catches. Partly because of this impact, governments are imposing more regulations on the activity in the form of closed seasons or areas, licensing, bag restrictions, etc. In the future, it is likely that these controls will increasingly be spatially related.

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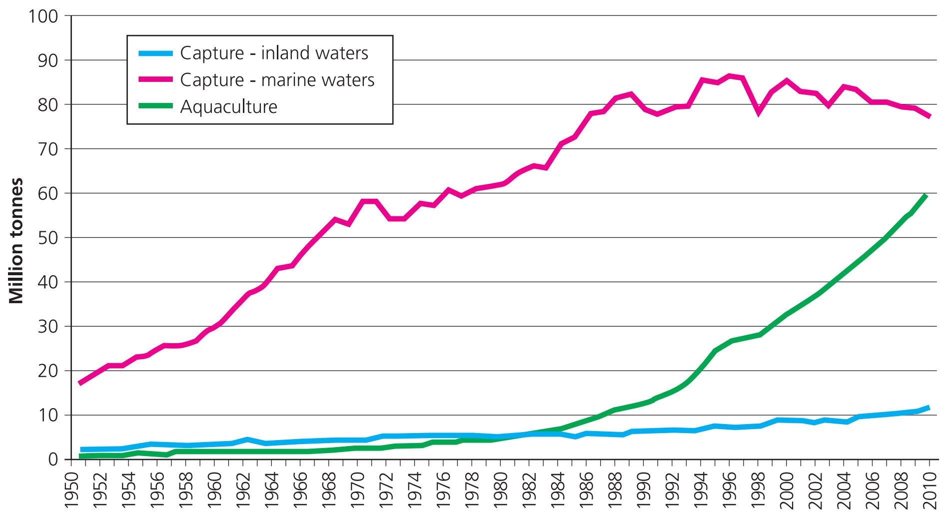
[252] In Thailand, a traceability system is presently being implemented for aquaculture (called "Traceshrimp"). Publications are not yet available on this, but Paiboonrat (2007) provides an example of such a system in use in Thailand's chicken industry.

FIGURE 11.2
A comparison of world aquaculture production (1950 to 2010) with marine and inland fisheries production



Source: FAO Statistics and Information Branch of the Fisheries and Aquaculture Department (2010).

(s) **Changes in fisheries management.** While this is not a new driver, it is certainly one that will rapidly impinge on a greater number of fisheries in a widening variety of ways. Many of the world's fisheries are not being managed in a sustainable manner, and it likely that there will be major moves towards this over the next decade, especially as marine spatial planning and the ecosystem approach to aquaculture (EAA) and the ecosystem approach to fisheries (EAF) are adopted.

11.3 CURRENT ISSUES AND DEVELOPMENTS AFFECTING WORK IN GIS OR REMOTE SENSING

Having briefly described the spatially related drivers for change in fisheries and aquaculture, it is easy to see that their combined influence on fish production is likely to be immense and that the scale of changes may vary enormously from area to area, as will the applications of particular drivers to particular areas. 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 are also driving change (Box 11.2). Many of the issues and trends shown in this box have been around for a number of years, but this does not prevent them from being of current, and probably of future, importance.

It can be seen that many of the developments and issues are concerned with data – mainly because much of the growth has taken place in this area in terms of not only the volumes of data but also in the ways and means of handling data, and in the attempts to make data more "user friendly". In fact, it appears that the emphasis in GIS work may be shifting from "How do we handle the complex software?" to "How do we cope with increasingly larger volumes of data?" However, many of the developments are also centred around geotechnological advances that tend to function in a highly integrated manner, and which may be difficult to isolate into individual developments. Thus, Boyd and Foody (2011; p. 29) note that Zhang and Tsou (2009) refer to "a geospatial cyber infrastructure which integrates distributed geographic information processing technology, high-performance computing resources, interoperable Web services, and sharable geographic knowledge to facilitate the advancement of geographic information science (GIScience) research, geospatial technology, and geographic education."

Despite the interlinked nature of these data and technological developments, an attempt has been made (in Box 11.2) to isolate individual GIS-based developments and issues. Much of the information about current changes, developments, trends and issues can be found in basic GIS texts, and more specifically from Saitoh *et al.* (2011) and Boyd and Foody (2011).

BOX 11.2

Some key current developments and issues with respect to GIS and remote sensing

(a) The continuing advances in computing environments
(b) The development of new spatial tools
(c) Availability of higher resolution remote sensing imagery
(d) Maps as an ideal medium for communication (geovisualization)
(e) Interactive GIS via the Internet
(f) Data ownership and acquisition
(g) Data gathering instrumentation
(h) Advances in geostatistics and data and spatial modelling
(i) Mobile GIS delivery
(j) Continuing standards improvements for data collection and data transfer
(k) The seamless integration of data sets
(l) Accuracy, uncertainty and errors in GIS

(a) **The continuing advances in computing environments.** This development is a "catch-all" issue encapsulating all the advances that are continually ongoing in the world of computing, e.g. the continuing exponential growth in computing power and computing access. It is important to mention this because this trend will continue to ensure that developments in GIS software will expand their functionality and ease of use in the future and there will be relative price reductions in computing environments, making the technology more accessible to more people worldwide.

(b) **The development of new spatial tools.** Similar to the above, but much more specific, are the developments that continue to appear in spatially based tools. These consist of a wide range of software, including many 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.

(c) **Availability of higher-resolution remote sensing imagery.** Although remote sensing imagery has been available for about 40 years, for the first two decades of this period all satellite-based imagery resolution was extremely coarse (> 10-m resolution). However, resolution has improved significantly during the last two decades, opening up many more opportunities for remote sensing use. Indeed, Boyd and Foody (2011) now point out that the current resolution of some satellite systems is at a level of detail comparable to that derived from the use of airborne sensor data. But just as important as enhanced functional capability is the fact that increased competition among remote sensing data providers has led to significant cost reductions of imagery. It is likely that these trends will continue,[253] that future imagery may cover a wider variety of parameters, that delivery times will be reduced, and that there will be improved ease of use of image processing capabilities.

[253] Over 100 earth observation satellites were launched during the first decade of this century, i.e. in addition to numerous new airborne sensing systems (Boyd and Foody, 2011).

(d) **Maps as an ideal medium for communication (geovisualization).** There is abundant evidence that spatially based information is best conveyed in the form of maps and, in order to ascertain optimum ways of communicating via maps, much work has progressed in the integrated fields of scientific visualization, cartography, image analysis, psychology and visual exploration. The map user is now obtaining increasing control over cartographic output through the ability to control legends, symbology, fonts, etc., and through animation visualization tools and photorealistic visualization techniques. Google Earth has bridged the gap between remote sensing experts and non-experts, resulting in greater understanding of environmental issues. The ability to use Google Earth and drill down from the global panorama to the neighbourhood level enables people to better understand natural and anthropomorphic events on a human scale (Corbley, 2007). The increasing functionality behind Google mapping or in-vehicle navigation systems are examples of the progress being made in spatial visualization. All told, significant progress has recently been made in many aspects of map visualization and spatial literacy, and this will continue in the future. There is now a strong recognition that a map really is "worth a thousand words", and increasing familiarization with maps will be aided by a greater range of enhanced map delivery systems.

(e) **Interactive GIS via the Internet.** Over the last decade, interactive GIS via the Internet has been increasingly practised, and there are now a wide range of mapping possibilities that have been established. Of particular importance have been the possibilities around "hot-linking", whereby it is possible to connect to a wide range of additional materials and contexts[254] that are applicable to any number of georeferenced places or areas of interest within a mapped area. The progress in interactive GIS has been very rapid and it will undoubtedly continue to grow in the future,[255] as will the number of people who are able to gain access to the Internet via increasingly faster broadband delivery rates.[256]

(f) **Data ownership and acquisition.** This is an area that has promoted much controversy in the past, i.e. because owners of data have perceived that they should command some rights to "their" data. But there are many problems associated with this so-called copyright. These mostly involve variable rights by different data users, plus rights associated with "amended" or "enhanced" maps or data. Also, different national policies exist. There is undoubtedly a drive towards a greater freedom of access to data sets, but whether this move will prevail into the future is difficult to foresee, although undoubtedly there will always remain data that command a significant price.

(g) **Data gathering instrumentation.** In Chapter 2, an outline was given of some of the data gathering instruments currently being used. The proliferation of an array of instruments will undoubtedly continue and increasingly they will incorporate georeferencing capabilities aided by GPS technology while working in mobile environments. While much data will be collected and distributed from small mobile devices, there is likely to be a greater proportion that is collected via complex systems such as satellite or sonar technologies. There will also be an

[254] At "hot-linked" spots photographs, textual information, graphs and tables, video clips, legal documents, etc., can all be added as supplementary materials to maps. (See further details at ESRI: www.esri.com/news/arcuser/0101/hotlink.html).

[255] The United Nations Environment Programme–World Conservation Monitoring Centre (UNEP–WCMC) (http://imaps.unep-wcmc.org/imaps_index.htm) has developed interactive mapping services, and the Interactive Map Service (IMapS) is an authoritative source of environmental data that can freely be accessed, downloaded if needed, and mapped online to user requirements. A number of thematic or regional applications exist on the UNEP–WCMC Web site (e.g. on the Caspian Sea watershed). Jointly developed by FishBase and SeaLifeBase, AquaMaps is another example of the substantial progress made in online interactive mapping (www.aquamaps.org/main/home.php).

[256] It is also likely that fisheries management generally will be considerably enhanced via non-GIS uses of the Internet (Garcia, 2011).

increase in fixed, automated data-collecting systems (e.g. tethered buoys), and Pompili, Melodia and Akyildiz (2009) describe how 3D underwater acoustic sensor networks are being used to monitor ocean phenomena such as water currents, wave action and pollution.

(h) **Advances in geostatistics and data and spatial modelling.** Major developments in GIS applications to fisheries and aquaculture will come in the coupling (or integration) of geostatistics and spatial models to GIS functionality. Although this is already happening, the further scope is almost unlimited because the models and/or statistical functions are virtually infinite in their utility and usefulness. The main problem with respect to the application of geostatistics lies in the fact that most of this work presently involves a capacity to cope with advanced mathematical concepts, an ability that not all GIS users will share. Most modelling is currently devoted to establishing species or habitat distributions, but of course models can be deployed to help investigations of almost any aspect of fishery or aquaculture work.[257] Some important work in model applications to aquaculture is described in a review by Kapetsky, Aguilar-Manjarrez and Soto (2010) on the "Status and potential of spatial planning tools, decision-making and modelling in implementing the ecosystem approach to aquaculture". Another useful review is that by Ferreira *et al.* (2012) on "Progressing aquaculture through virtual technology and decision-support tools for novel management". Among the examples described by Ferreira *et al.* (op. cit.) is the interesting decision-support system called "AkvaVis" for site selection, carrying capacity and management monitoring that is presently under development (see description of AkvaVis in Chapter 8 and Web site www.akvavis.no). Kapetsky and Aguilar-Manjarrez (2013) note that there is a clear trend for "all-in-one" applications (like AkvaVis) that include: multiple objects (species at different trophic levels and varied culture systems); incorporate multiple functions basic to aquaculture development and management (site selection, carrying capacity, monitoring for management including legal aspects); take into account ecosystem-level spatial boundaries; involve active participation or scrutiny by the public; and produce outputs that are highly relevant to managers, commercial entities and to aquaculture practitioners.

(i) **Mobile GIS delivery.** Although this issue crosses the boundaries of several previously mentioned developments, separate attention is drawn to it because of its special importance. GIS is now escaping the confines of the more traditional computing environments. This first occurred via the use of laptop computers and various notebook devices, but now GIS potential is being realized via the host of handheld devices described in Chapters 2 and 4. However, this mobility of delivery incorporates not only the devices themselves (the platforms), but also the delivery of data and software is enabled via wireless connections to the Internet so that complete mobile GIS functionality is attained. A recent development that attempts to overcome the small- screen problem is the release of Apple's IPad3 whose design aims are to provide maximum portability and mobility with a larger screen size, i.e. 24.5 cm compared with less than 8.0 cm for typical mobile devices (see Flex Mappers, LLC: www.webmapsolutions.com/ipad-mobile-arcgis-part-1). Environmental Systems Research Institute (ESRI) has developed a special version of its GIS software called ArcGIS Mobile that is specifically designed to function on a range of the newest generation mobile devices. Drivers in this direction are certain to continue, with the main directions of development

[257] Other major areas for modelling include site selection for aquaculture, examining the effects of climate change, designating marine conservation areas, examining species movement patterns, selecting restocking locations, etc., and Ferreira *et al.* (2012) suggest that additional areas for future modelling applications include disease spread and control, algal bloom dynamics, certification and traceability and modelling in data scarce situations.

concentrating on map size and optimization of visualizing in a small-screen environment and on high-speed delivery in the broadband communications environment. The potential number of GIS users via mobile computing can now be counted in the hundreds of millions.[258]

(j) **Continuing standards improvements for data collection and data transfer.** A development that is often ignored is that of the increasing adoption of standards. Although standards have long been applied in the spheres of technology or hardware development and have been applied to data handling for over a decade, there is still some way to go in achieving the theoretical optimum in data collection and transfer possibilities. Data standardization enters into a wide range of associated fields, including: thematic class definitions; storage methods and means; data formats; symbology; metadata information; management standards; operating systems; data quality and accuracy; and update frequency. The ultimate aim of data standards improvements is to attain the highest possible levels of "interoperability", i.e. the ability of diverse systems to work together in an integrated manner. Some of the issues that need resolving are still quite complex, e.g. agreements on data classification systems or internationally recognized symbology. However, far more data sets are becoming easily integrated with other data sets and it can be anticipated that this issue will gradually become less of a concern to GIS users.

(k) **The seamless integration of data sets.** Of major importance to all GIS work is the acquisition, management and use of digital data, and it was noted above that the standardization of all facets of data is highly desirable. However, for various reasons complete standardization will never be possible because, for instance, any classification categories and boundaries used may be different according to specific project or management aims. Nevertheless, rapid strides are being made either in developing formats or structures allowing for seamless data set integration or in developing simple algorithms that permit different data sets to be integrated. Specialized software is now available that are typically industry specific, i.e. perhaps concentrating on oil exploration, geology, utilities, etc., and that allow for a range of data integration functions to be performed. The LEACAT Data Cataloguing and Archiving software suite provides an example of the capabilities of this type of software (see Lynx Information Systems: www.lynx-info.com/gis-datamgmt.html). As of late 2011, it is also possible for any data being stored on one digital device to be seamlessly accessible across all of the user's devices (see iCloud at www.apple.com/uk/).

(l) **Accuracy, uncertainty and errors in GIS.** The validity of output from GIS is clearly limited by accuracy, uncertainty and error issues. Unfortunately, certainly with respect to fisheries and aquaculture data, this may often be characterized by GIS having a high degree of uncertainty or error, and lack of metadata may lead to an underestimation or lack of concern about this problem. A clear example of uncertainty is that actual fish distributions may be error prone because either absence or presence of species in a location is often highly uncertain. Data set size may also lead to lack of accuracy or errors because it is almost impossible to establish statistical significance with regard to most marine distributions. Boyd and Foody (2011) provide useful detail on the range of measures that can be taken to avoid accuracy, uncertainty and error-based problems.

[258] According to figures quoted in GigaOM (2011) available at http://gigaom.com/mobile/stat-shot-mobile-computing-has-won-2/, there will be 400 million mobile computers sold each year by 2014.

11.4 EMERGING THEMES RELATING TO SPATIAL ASPECTS OF FISHERIES AND AQUACULTURE

As a result of the previously described drivers, forces are continuously driving change with respect to spatial factors relating to the broad subject areas of fisheries and aquaculture. Given that these are such wide ranging and complex thematic areas, it is likely that a number of themes can be identified as "emerging" from these drivers. Here, an attempt is made to identify the main themes and to classify them into broad headings. It again needs to be stated that there is undoubtedly integration among the identified themes, that the themes can also be considered as "issues", and that the themes are themselves in different stages of "emergence". These stages will vary with both an actual time that may be delineated for the emergence of a theme and with when any group or area first becomes familiar with a particular issue. In stating that these themes are those that are currently emerging as important, it could be argued that they will also form the core of "future themes" in any fisheries and/or aquaculture GIS-based work (see Figure 11.1), i.e. they will be extensions of much of the current work that is being practiced. In this section, discussion of those issues that have already been mentioned in Chapters 8, 9 and 10 as being presently important is not repeated. For additional insights into future themes in fisheries and aquaculture GIS, see Fisher (2010) and Bostock *et al.* (2010). Emerging themes are identified in Box 11.3; they are not defined in any specific order.

BOX 11.3

The main emerging themes in fisheries and aquaculture to which GIS will be applied

(a) The production of different aquaculture species
(b) The potential impacts of aquaculture on the environment
(c) Management of freshwater resources for aquaculture
(d) Offshore mariculture
(e) Growth of inland fisheries and recreational angling
(f) The consolidation of the fishing and aquaculture industries
(g) Rebuilding depleted marine and freshwater stocks
(h) The recording of fishing vessel activities
(i) Evaluating fisheries management practices, including sustainability
(j) Threats and changes to marine and freshwater ecosystems
(k) The standardization of habitat (and other) classifications
(l) Working at variable scales and resolutions
(m) Studies of temporal change in fisheries and aquaculture thematic areas

11.4.1 The production of different aquaculture species

There is some debate concerning what biological species (and types of fish species) would be best produced (farmed) in the future. Basically, there are three main lines of thought here:

- Should the emphasis in developed countries still remain with the production of higher trophic level fish species? Thus, given that these species generally fetch high market prices compared with lower level species and given that high fish farming costs need to be covered, then it is likely that this rationale might be retained into the future. This idea is supported by Christensen (2011), who argues that the future may see the marine area used simply as a "farm" for producing low-value aquaculture feed inputs (fish meal), i.e. because most of the larger fish have already been extracted from the sea and stock recoveries may be very difficult.

- A second line of reasoning is that, because inputs to higher level species rely mainly on high inputs of fish meal derived from capture fisheries, this is inefficient in terms of energy inputs. Therefore, there needs to be a move towards the production of lower trophic level herbivorous species, i.e. as has been practiced for millenniums in countries and areas such as the People's Republic of China and, the Socialist Republic of Viet Nam and Eastern Europe.[259]
- An important third consideration is that there are consumer food preference changes resulting from changing product costs and experimentation in "newer" farmed species, e.g. fish species such as tilapia, pangasius and cobia are presently showing considerable demand increases (Asche, Roll and Trollvik, 2009), while catfish farms in the southern states of the United States of America are suffering production declines because they cannot compete with lower production costs on Asian farms.[260] It is also likely that there will be further successes with the production of colder water species that are suffering from overfishing, e.g. farmed cod and halibut are now being marketed. Consumption preferences are likely to have major impacts on fish farming locations and fish markets in the future.

It can be seen that the balance of changes in production preferences could have significant changes in the spatial organization of aquaculture. This is likely to lead to future GIS-based economic and spatial rationalization work as the balance of production cost advantages shifts from area to area. Other GIS work could also focus on the different physical requirements needed to optimize production location among the different species.

11.4.2 The potential impacts of aquaculture on the environment

Although this might not be strictly speaking an "emerging issue", i.e. because it has long been an area of interest for GIS work, it has been included here both because of the huge increase in its importance that will be occurring as aquaculture rapidly expands and because the range (or variety) of potential impacts is likely to significantly increase. The various case studies in Chapter 8 have hinted that there are a wide range of cultured fish species and that their production uses a variety of production systems. Most of the production systems are sited in aquatic environments that are on or adjacent to terrestrial areas. Because production typically involves the transference of large quantities of water through the production system, then the propensity for causing some kind of environmental impact is very high. Impacts are not only felt at the sites of production because waterborne impacts can be transferred over large distances by running or moving waterbodies. Additionally, the provision of inputs to the aquaculture process can cause environmental impacts thousands of kilometres from production locations. Aquaculture production does not have to be detrimental to the environment, as can be seen by the inland pond culture techniques that have been applied sustainably in the People's Republic of China for at least 4 000 years. However, as can be seen from Figure 11.2, over the last three decades aquaculture production has increased at previously unprecedented rates, and it is this that has given rise to environmental concerns.

According to FAO (2012e) (see www.fao.org/fishery/topic/14894/en), the main impacts of aquaculture on the environment are:

- discharging of suspended solids into the water;
- nutrient and organic enrichment of recipient waters leading to a build up of anoxic sediments and to eutrophication;
- a loss of coastal habitats, e.g. wetlands and mangroves, through the construction of shrimp ponds;

[259] The debate about species production preferences is discussed in Tacon *et al.* (2010).

[260] According to the United States Department of Agriculture, total live weight production of catfish from farms in Mississippi State went down from 355 million pounds in 2004 to 249 million pounds in 2009.

- the salinization of agricultural and drinking water supplies;
- land subsidence owing to groundwater abstraction;
- pollution owing to the misapplication of chemicals;
- the release of disease pathogens and parasites into surrounding waters;
- the use of fishery resources as feed inputs.

With the increased demand for the high-quality (and high-value) foods that are produced by the range of aquaculture practices, there are strong possibilities that production will become more intensive. If inappropriate or poor-quality management and planning practices prevail, as is so frequent in too many areas, then this intensified production has a strong probability of causing increasingly negative results. Further details of environmental impact assessment and monitoring in aquaculture can be found in FAO (2009a).

Just as in marine fisheries (FAO, 1995b), FAO suggests that a strong commitment to responsible aquaculture is needed. This commitment must come not only from producers, but also from consumers and various government authorities. Special consideration must be given to the better management of aquaculture developments that might affect sensitive habitats, such as estuaries, mangroves, wetlands, riparian fauna and vegetation, or specific breeding and nursery grounds. It is also essential that environmental impact assessments are carried out before larger-scale enterprises are developed and that the development guidelines contained within them must be strictly adhered to. There is an argument made for terrestrial-based, more intensive production systems using recirculated water. This is because of the possibility of exacting very strict controls over the production processes. It is easy to see that GIS has the potential to play a major role in helping to reduce any potential environmental impacts from aquaculture development. For instance, there is a range of GIS-based modelling that can simulate environmental effects of discharges made from production facilities (Kapetsky, Aguilar-Manjarrez and Soto, 2010). Most of this modelling should be used before aquaculture facilities are constructed, though modelling can also be deployed to assess remediation possibilities, or to work out maximum acceptable quantities of negative discharges from fish farms. The appropriate application of GIS work in this field could see a rapid decline in the negative effects on the environment.

11.4.3 Management of freshwater resources for aquaculture

In this section, the concern is mostly with freshwater provision because at present this is a much larger issue than that of sustaining supplies of salt water for mariculture purposes.[261] Having said this, it is clear that marine algal blooms are a major constraint on aquaculture in various marine areas, and that GIS is being used as a means of monitoring this (see Section 6.8.2). The concern here is also with the effect of the environment on aquaculture, which is being discussed here because nearly all environmental effects on aquaculture will be "delivered" via the prevailing water resources.

As the world's population increases and the planet becomes warmer under the effects of climate change, the demand for freshwater increases at an accelerating rate. While many areas still have water in abundance, the variety of areas that see a water deficiency is constantly growing. Water has been scarce in traditionally dry areas, but these scarcities are now occurring in places where water tables have sunk to impractical levels; where underground supplies have been completely exhausted; where tropical rain forests (and other areas) are experiencing previously unknown droughts; or where people have abstracted water at rates that are unsustainable. Clearly, this deteriorating situation means that less water may be available in the secure quantities needed for aquaculture, and there may be increased competition for available water resources. These factors are certain to have an effect on water costs.

[261] It is important to note that freshwater supplies will also influence brackish-water aquaculture.

As mentioned in Section 11.4.2, there is the potential for aquaculture to have an impact on the environment, but as inferred above, there is also the important consideration of environmental effects upon aquaculture. Here, the concern is mainly with the effects felt in riverine or lacustrine environments, i.e. mostly fresh- or brackish-water situations – environmental effects felt on aquaculture in marine waters are mentioned in Section 11.4.4. Because aquaculture uses water as the production medium, then any environmental effect is likely to be delivered via the water entering the culturing site. Ideally, the environment will be providing high-quality water in sufficient quantity on a constant and sustainable basis. In some systems, the water will also deliver (usually supplementary) nutrient supplies. However, there are a number of ways in which the environmental impacts on aquaculture can be negative:

- Especially during periods of high water flow in a catchment, turbidity levels can be high and this can suppress feeding activity.
- Disease pathogens can be transported by water, sometimes from neighbouring aquaculture facilities.
- A range of point source or more diffuse pollutants can be delivered to the production facility, e.g. sewage effluents, inadvertent point source leaks, farm-sourced chemicals, oestrogens, toxic algae, etc.

Before establishing an aquaculture facility, the investor should take the precaution of checking past environmental incidents in an area, or at least have a good idea of what potential problems are sited upstream, and there should be emergency plans that can be activated in case of any environmental incident.

Planning for water management is, therefore, increasingly necessary in a large number of areas. GIS offers a number of models and procedures that can assist with this, and it is certain that this modelling will be more important in the future, especially given the fact that water is a ubiquitous asset that needs to be shared across the wider community (e.g. Jenness *et al.*, 2007a,b). It is also certain that more use will need to be made of recycled water. For aquaculture, this will be in the form of recirculation systems. Already such systems exist though they are largely experimental and on a small-scale. To an extent, such systems make the siting of aquaculture independent of large water supplies and thus alternative location preferences may become available and/or profitable.

11.4.4 Offshore mariculture

During the past decade there has been a trend to move mariculture further off-the-coast. Traditionally, aquaculture practices were very much terrestrial based with all early fish production being in land-based artificial or natural ponds. As production intensified, it moved towards artificial structures such as earthen or concrete raceways on land, and then into various pens or cages that were located in shallow inshore waters or in highly sheltered lakes, lagoons, estuaries or fjords. These nearshore locations were chosen because of easy access for various management purposes and because of the shelter that could be offered from storms and high energy waves. However, recently it has become clear that facilities based in open marine waters might offer a number of advantages. Kapetsky and Aguilar-Manjarrez (2007) note that the advantages can take several forms, for example:

- fewer environmental impacts (to water quality, bottom sediments, other species, etc);
- decreasing conflicts with other on-shore or near-shore activities;
- more consistent quality of water supplies;
- fewer incidents of harmful algal blooms;
- large potential for industry expansion;
- greater potential for economies of scale;
- reduced visual impacts.

It is clear that there would also be drawbacks, such as increased capital and servicing costs, difficulties of monitoring and security and the need for greatly strengthened holding structures. It is also clear that there are likely to be considerable efforts put into optimizing cage structure, design and functionality, and the outcome of this might be that a wide range of systems are developed for different culturing regimes and locations. Figure 11.3 gives an example of a submersible cage structure for finfish offshore mariculture. The balance between costs and benefits with respect to offshore mariculture may still be uncertain, but given the need to greatly expand fish production, then further movement of mariculture facilities into open waters is certain to increase.

FIGURE 11.3
A typical "aquapod" submersible finfish structure being used for mariculture

Source: Ocean Farm Technologies (2012).

It is clear that the siting of offshore cages cannot be done without a great deal of careful analysis, and as all of the factors that need consideration have a strong spatial component, GIS and remote sensing will clearly have an important locational role to play. Among the factors that need to be considered are the direction of prevailing winds, location of any regular shipping routes, depth of water (cages and longlines need to be tethered), strength of tidal and other currents, distance to servicing facilities, other competing water resource users and adjacency to conservation features. Given these potential restrictions, many countries are already investigating their coastal zones in an effort to identify open sea areas that might serve as suitable offshore cage sites/zones, and they may also be using GIS to identify the optimum species for culture given the prevailing conditions. With Marine Spatial Planning already being instigated or considered, then it is clear that cage and longline location may well become part of an integrated marine strategy. A useful study of how coastal countries might investigate the potential for open ocean aquaculture using a low-cost GIS is provided in Chapter 4 of Kapetsky and Aguilar-Manjarrez (2007); see also Kapetsky and Aguilar-Manjarrez (2010) and Kapetsky, Aguilar-Manjarrez and Jenness (2013).

11.4.5 Growth of inland fisheries and recreational angling

Much of the concern in this technical paper is with commercial marine fisheries and with various forms of aquaculture, and this is because by far the largest proportion of consumed fishery products is derived from these sources. However, it has been pointed out (FAO, 2010a) that the activities of inland fisheries and of recreational angling are increasingly worthy of discussion. Although precise figures are hard to come by,[262] and reporting remains unreliable, FAO shows that inland fisheries grew from 8.6 million tonnes in 2004 to a record 10.1 million tonnes in 2009, with some 61 million people being involved in the sector. However, "the poor state of knowledge on inland fishery resources and their ecosystems has led to differing views on the actual status of many resources. One view maintains that the sector is in serious trouble because of the multiple uses of and threats to inland water ecosystems. The other view holds that the sector is in fact growing, that much of the production and growth has gone unreported and that stock enhancement through stocking and other means has played a significant role." (FAO, 2010a; p. 9).

Inland fisheries take place in both impounded waters and natural lakes, plus in various categories of naturally flowing freshwater. Fish are caught for both food and recreational purposes. Until recently, management of this sector has been minimally applied, with the interest in developed countries largely being centred on where closed seasons could be implemented (by fishery, season or area) and on issuing of fishing licences, with receipts from licence payments often being fed back to support a fishery. But with declining catches in many areas, with increasing number of fishers and with environmental degradation, it is frequently necessary to instigate more intensive forms of management. In developing countries, facts concerning the status of inland fisheries are often unreliable, but it is known that irresponsible fishing practices, habitat loss and degradation, water abstraction, drainage of wetlands, dam construction and pollution (including eutrophication) often act together to the detriment of these fisheries. It is urgent that these problems are addressed because the future importance of fish production from the inland sector is recognized as a means to helping poverty alleviation and food security. Little GIS work has been done in this sector to date, but significant increases are likely in the future.

The recreational fishing sector is characterized by huge diversity, i.e. in terms of the number or proportion of participants per country, methods of fishing, species targeted, sites fished, degree of management, intentions of fishing, environmental impacts, capital inputs to the fishery, etc. There has been little quantification as to the extent of this fishing sector in terms that allow either a comparison between countries, total volume of catches, total numbers involved, etc. The only data available consist of various short time scale or small-area surveys,[263] and these offer no standardization in terms of methodology employed. However, it has been estimated that in many fisheries, the quantity of fish caught by recreational anglers now exceeds the total of commercial catches (Ireland, 2010). This is especially so in the most advanced economies.[264] Again, past management practices have been minimal, but according to Ireland these advanced country fisheries are unlikely to thrive in the future without greatly increased management interventions. It appears that the future management of these fisheries offers vast scope for the use of GIS, certainly at localized scales.

[262] The extent and reliability of data collection for inland fisheries is highly suspect, with one-third of countries providing no data to FAO.

[263] For examples see Beckley, Fennessey and Everett (2010), Veiga *et al.* (2010) and Ireland (2010).

[264] Ireland (2010) reports that in Western Australia nearly one-third of the total resident population are recreational anglers.

11.4.6 The consolidation of the fishing and aquaculture industries

Over at least the last two decades there have been contrasting movements in terms of the scale and organization of fish production. These changes have affected both the capture fishery industry and fish farming. With a whole range of movements towards economies of scale, production consolidation and agglomeration and vertical integration, there is undoubtedly a much higher proportion of total fish output coming from larger-scale production facilities or operations. The securing of increased aquaculture space comes about either through the merging of neighbouring production facilities (clusters of farms), through deliberate zoning, or through the development of new facilities. Regarding capture fisheries, consolidation has mostly come about through cooperative vessel ownership groups or through mergers whereby individual vessel owners form business partnerships in order to take advantages of reductions in working costs. Whatever the means, it may be vital to examine aquaculture location preferences in terms of site advantages or limitations, and consolidation in the capture fisheries may have spatial effects in terms of the changing number, dispersion and fortune of "growth poles".[265]

However, in contrast to the moves towards industry consolidation, in the case of aquaculture there is a perception that this activity can either form an additional strand to existing farming practices or that an income can be achieved from access to a relatively small land holding. This has led to a growth in the number of small and even micro facilities, usually in the less-developed economies. These movements towards both larger- and smaller-scale operations in aquaculture have been well documented for the Asia-Pacific region in NACA (2007). Again site selection for such activities is extremely important if enterprises are to be successful.

As with changes in production scale, there will inevitably be changes in production practices. For aquaculture, ponds, pens, cages, raceways, etc. all have varying physical requirements and GIS will continue to be an asset in establishing preferred production practices for specific locations. With increased consolidation, it is also likely that increased emphasis will be given to a range of factors important to site selection that may not be directly connected to production per se, e.g. aesthetic factors, access factors, rights to land, and other socio-economic factors that are compatible with the EAF and/or EAA, any of which may be introduced into spatial modelling exercises. With a more complex array of inputs to aquaculture,[266] it is also likely there will be a higher degree of specialization in the future, and many farmers in rapidly developing countries will choose to give greater emphasis to increasing incomes through their aquaculture facilities. Perhaps the greatest impact on farming production practices will come from what are known as "Good Aquaculture Practices" (GAP). This means that standards and certification schemes are being introduced, which will have the effect of promoting consumer trust in products and will ensure sustainability of production methods used; however, these GAP practices will also raise production costs.[267] This may force many smaller fish farmers out of business and farms may consolidate into larger enterprises. In marine fisheries, some of these changes in production practices will also occur, e.g. certification schemes, ecolabelling and changes in working conditions, and there will be additional concerns such as safety at sea, training needs and increasing bureaucratization of the working environment. For marine fisheries, general moves towards consolidation will have less of a spatial impact than it does for aquaculture.

[265] Growth poles are locations of concentrated economic activity from which wealth may disperse outwards to surroundings locations.

[266] This includes aquaculture skills, energy, supply or market linkages, pelleted foods, insurance and hygiene practices.

[267] Further details on the FAO's guidelines to certification can be found at FAO (2012f): www.fao.org/fishery/topic/13293/en

11.4.7 Rebuilding depleted marine and freshwater stocks

For many years, large numbers of freshwater rivers and lakes have been restocked with a range of fish species that accord to desired local species mixes. Restocking has usually been a response to reductions in fish numbers owing to the overfishing caused by often unregulated freshwater angling, though sometimes it has been necessary to restock following pollution incidents, disease outbreaks or stresses caused by drought, etc. Restocking may also be necessary where ecosystem balance needs correction, or simply where new fisheries have been created. The amount of attention devoted to restocking marine or estuarial waters has been far more restricted, yet depleted fishery resources not only have a severe impact on economic activity and on food availability, but they are also likely to give rise to instability in marine ecosystems as trophic relationships become unbalanced or changed. There are also problems concerning the large areas that might need to be stocked (and the costs involved in this), plus the considerable uncertainties as to the viability of restocking or the requisite cost–benefit advantages that may accrue. It seems certain that the future will see increased efforts to restock marine areas, but this is unlikely to be carried out without extensive GIS-based analyses whose aims are to establish factors such as the optimum time for restocking, optimum species mixes, quantities and costs involved and locations or sites that would be preferred. Higher-value species such as lobsters are already heavily restocked in many marine areas, but it is still questionable as to how far down the food (or recreation) value chain restocking might be viable. But stock improvements will be a complex issue to resolve because local ecosystems may already be changed in ways that are virtually impossible to amend. Additionally, factors such as climate change will prevail against returning individual marine ecosystems to their former condition. Already there is some considerable scepticism that stocks can be returned to former levels (Froese and Proelfs, 2010),[268] and initially it will take considerable GIS-based modelling expertise to demonstrate optimum carrying capacities for local marine species combinations, though attempts at doing this will certainly be forthcoming.

But of course in many cases depleted stocks of fish can also be rebuilt by improved management techniques, and attempts at doing this have been practiced for many decades. The methods deployed are variable and may include:

- reducing fishing effort or fishery power;
- applying various systems of output quotas;
- implementing no-take fishery zones or other conservation areas;
- instigating closed seasons.

While in practice any of these management methods should positively impact on fish stocks, too often stock levels are not rebuilt and this may be because there is insufficient monitoring of fishery areas (to prevent illegal or overfishing), or because the methods deployed are not stringent enough, or agreement cannot be reached on the real state of the stocks, or because it is difficult to compromise between scientific and/or environmental observations and the livelihood of fishers.

One reason for the failure to rebuild marine stocks is simply that there is insufficient understanding of the natural factors that are controlling species distributions. Although this facet of fisheries management and research is already being pursued, it will become of increasing importance in the future. For instance, Kaplan *et al.* (2010) note that until recently the ability to implement and assess spatial marine management approaches has been limited by a lack of information regarding processes that bind marine ecosystems, including habitat locations, larval and adult movement, trophic interactions and fisher behaviour. However, recent advances in habitat-mapping technologies, genetics, marine microchemistry, animal tracking and numerical modelling have greatly enhanced the knowledge of these processes. For instance, MacKenzie *et al.* (2011) have recently

[268] Two important stocks that have never returned to previously high levels are the cod stocks of Newfoundland, Canada, and the large yellow croaker in the People's Republic of China waters.

shown that, as the carbon isotope composition of animal tissues varies with sea surface temperature, the marine location occupied by individual fish can be identified by matching time series of carbon isotopes measured in tissues to sea surface temperature records. Using this technique, the authors were able to identify where salmon from different United Kingdom rivers had been feeding in the North Atlantic Ocean. Although these advances have yet to be fully integrated into management decisions, they have the potential to revolutionize spatial marine management. Nevertheless, this revolution will require advances in the ability to share and integrate data into models of marine ecosystems. No doubt the future will see great efforts in this direction.

11.4.8 The recording of fishing vessel activities

For a number of years, FAO (2010a) has recognized the need to have a global database of fishing vessels, and that in the future this is likely to be extended to having a record of their activities – fishing locations, catches, landings, etc.[269] In an era when overfishing and illegal fishing are worldwide problems, there are a number of obvious reasons why the activities of fishing vessels might need to be recorded. These reasons could be associated with management, research or science, or for the vessel owner's purposes. The recording of vessel activities can be an on-board activity carried out via fishery logbooks or through observer activities. They can also be external through observations from fishery patrol vessels or aircraft, or, indeed, they can be based on vessel monitoring systems (VMS), which rely on external observations that collect data via on-board electronic equipment and communication satellites. At the present time, VMS-based recording is mostly restricted to larger commercial fishing vessels operating in territorial waters, and the data captured does not positively discriminate between fishing locations and other vessel movements. Despite this, many attempts have been made to establish vessel fishing locations based on calculations of vessel speeds (see Figures 10.6 and 10.7). Finally, fishing vessel activities can be recorded through direct interviews with fishers. In an era of overfishing and the need to take on EAF advice, from the social and economic perspectives especially, it is important that fishers are able to explain and record their fishing ground locations as allied to species and perhaps to some measure of catch volume. Figure 10.12 gave an example of such fishing ground mapping, but work is now in progress to improve the sophistication of such techniques (des Clers *et al.* 2008; des Clers, 2010).

Because electronic data capture equipment is now becoming more sophisticated, miniaturized and ubiquitous, the possibility of gathering more precise data on vessel activities is becoming viable even for relatively small vessels, e.g. the European Union made fishery electronic logbooks mandatory on all commercial vessels more than 15 metres in length in July 2011, and on all vessels from 12 to 15 metres in length from January 2012.[270] For the first time, this will make a large proportion of total European commercial fish landings instantly able to be recorded and georeferenced.[271] Not only will e-logbooks be supplying real-time landings data that can be matched to haul locations and subsequently matched to

[269] There are ongoing discussions with the IMO regarding this initiative and it would appear likely to emerge in the near future.

[270] From January 2010 all European Union commercial vessels more than 24 metres were obliged to complete electronic logbooks, and European Union Directive 1077/2008 stated that from July 2011 all commercial fishing vessels more than 15 metres would need to do the same. As set out in European Directive 1224/2009, as from January 2012, all vessels between 12 and 15 metres would be required to use electronic logbooks, and vessels between 10 and 12 metres will optionally be allowed to use them.

[271] Unfortunately, the data being captured only requires that fish "landings" are recorded, and given that the European Union fisheries require the discarding of over quota or undersized fish, then catches could be considerably greater than recorded landings. However, the European Union fishery authorities are indicating that in the future all catches will need to be landed (see footnote 22).

quantity landings of each species, but this information can then be mapped at levels (resolutions) that can provide useful and precise information on fish extraction rates per unit of marine area. Though theoretically this capability is already attainable, the widespread use of such systems is rarely achieved for reasons of data privacy and perceived intrusiveness,[272] the complexity and costs of the systems, and for reasons associated with obtaining widespread agreement. However, it is clear that the possible value of the derived data to the fishery management and research sectors will be huge, i.e. in that it offers the potential for an essential data source to be integrated throughout the data hierarchies contained within the EAF. A useful summary of the uses of VMS and e-logbooks can be found in Gerritsen and Lordan (2011).

11.4.9 Evaluating fisheries management practices, including sustainability

Fulton *et al.* (2011) have recently highlighted the increasing complexity of ways in which fisheries might be managed. For instance, very different approaches would be taken if management used a top-down approach compared with a bottom-up approach. Fulton *et al.* further note that even in well-managed fisheries where sole jurisdiction exists, significant numbers of stocks are still overfished, and where stocks are shared (or in high seas fisheries), the situation is much worse. Sources of uncertainty for fisheries managers include: resource dynamics, e.g. recruitment variability; catch misreporting; poor fleet monitoring; dubious stock assessments;[273] political pressure on management decisions; incorrect adoption of management procedures; and inappropriate fishing methods. Mackinson *et al.* (2011) add to this list by noting the importance of more frequently engaging with stakeholders as part of a move towards effective governance. Because by far the largest total marine area is that of the so-called "high seas",[274] the effective management of these seas is highly important. These areas are managed by 18 regional fisheries management organizations (RFMOs). The effectiveness of RFMOs in conserving the fish stocks has been recently questioned by Cullis-Suzuki and Pauly (2010), i.e. because many stocks have significantly declined. The results of surveys by these authors show that two-thirds of stocks fished on the high seas and under RFMO management are either depleted or overexploited and thus are considered as being poorly managed. The use of GIS is likely to be invaluable in addressing many of these issues.

It is important to mention that management practices in many areas are undergoing urgent reforms. For instance, after criticisms about the lack of success of fisheries policies in European waters (Khalilian *et al.*, 2010), the European Union launched reforms of its Common Fisheries Policy in 2009.[275] Thus, management reform policy areas that are likely to emerge in the European Union and perhaps other regions include:

- fleet overcapacity;
- regionalization of fishery policies and management;
- protection and promotion of small-scale fisheries;
- licensing of recreational angling;
- locationally based fishing effort (or other output) controls;
- adjustments of fishing subsidies;
- banning of fish discarding;
- improvements in stock assessment capabilities;
- on-board monitoring of catches through closed-circuit television (CCTV).

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[272] There are signs that some fishers are becoming less concerned with what has been regarded as "bureaucratic intrusiveness" by fishery authorities, e.g. see paragraph 13.10 of the Scottish Government: www.scotland.gov.uk/Publications/2010/11/02103454/15.

[273] Beddington, Agnew and Clark (2007) note that the status of stocks in some of the world's best-managed fisheries has still to be determined.

[274] Marine waters that are beyond the 200-mile exclusive economic zone of coastal nations.

[275] Details of the stages in the European Union legislation for policy changes can be found at the European Parliament: www.europarl europa.eu/oeil/FindByProcnum.do?lang=en&procnum=INI/2009/2106.

It is clear that any of these management areas are spatially linked and can thus be examined, analysed, mapped, etc., via the use of GIS.

It is also important from the management perspective to mention that we are now living in an era when sustainability must lie at the root of all activities, especially those that are concerned with resource production or extraction and energy creation, and to this end the number of national and international marine conservation organizations is proliferating.[276] Marine users generally, and fisheries managers more particularly, must be aware that each action they permit by those who they manage will have a variable impact on the marine space and marine resources. The fishery authorities in New Zealand are so aware of the importance of spatially based planning that they have set up a specialist "spatial allocation" team to carry out a range of tasks, including the assisting of applications for new aquaculture space, marine reserves, freshwater fish farms and aquatic transfers.[277] Cotter and Lart (2011) have recently drawn attention to the important matter of the risk to aquatic ecosystems of different fishing practices, e.g. it is well known that trawling can severely degrade benthic ecosystems, and they advocate careful comparative analyses of different methods of fishing in order to ascertain those that are most sustainable under different conditions and that are targeting different species. Another management measure that is likely to come to future prominence, and one in which GIS offers the potential for a range of analyses, is that of the introduction of effective forms of rights-based management. With species populations in many aquatic environments being critically low or endangered, as are some important marine and freshwater habitats, all management actions will need to increasingly imbue a sense of sustainability. The use of GIS will play an important part in this through allowing spatial manifestations of resource distributions that may be of important or of critical concern to sustainability to be entered into spatial analysis and modelling.

11.4.10 Threats and changes to marine and freshwater ecosystems

The world is witnessing a slow but observable exponential increase in threats to all aquatic ecosystems. Clearly, these threats can be from many quarters and occur on vastly differing scales, and only the main threats can be briefly discussed here.

- It has been reported that within the central Pacific Ocean there is now a vast gyre consisting basically of "plastic garbage" (e.g. Dameron *et al.* 2007; Yamashita and Taminura, 2007). Similar concentrations of "refuse" occur in other oceanic areas. This has accumulated from materials brought down by rivers, washed from shores or discarded from ships and smaller vessels. Much of this material forms a major hazard to marine life. Thus, the plastics undergo photodegradation in the surface layers of the sea, eventually breaking down into extremely small particles. Many species then ingest these particles, and bioaccumulation of toxic organic compounds occurs as compounds are progressively passed up the food chain in quantities that are markedly concentrated at each trophic level.
- Many seas, especially those that are predominantly enclosed, e.g. the Adriatic, the Black Sea and the Baltic Sea plus many lakes, rivers, estuaries or fjords, are suffering from severe oxygen depletion (hypoxia) at lower depths. This largely results from a reduction of dissolved oxygen (DO), i.e. down to levels such that aquatic life cannot be supported. The reduction of DO itself is caused by pollution or by stratification of the poorly mixed water column in areas where freshwater inputs may be high.

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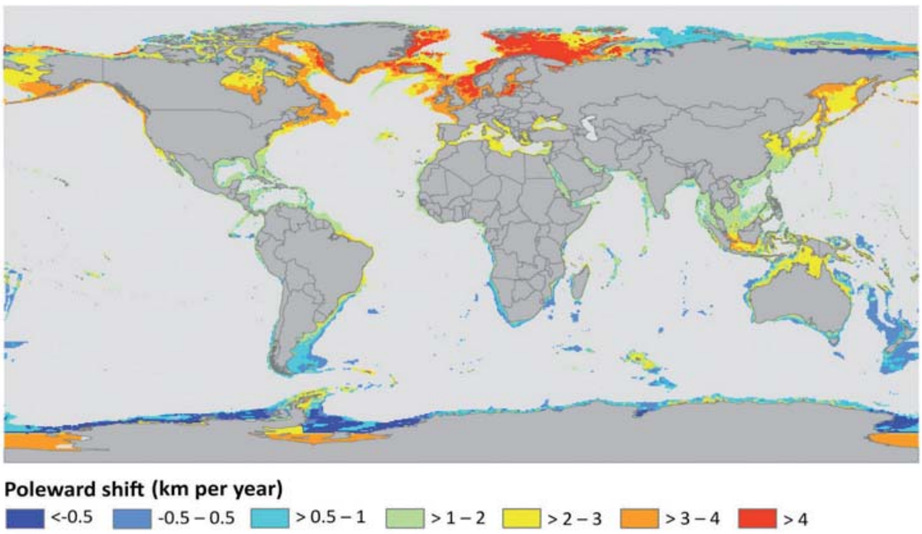
[276] Major marine conservation organizations include: The Deep Sea Conservation Coalition; Marine Stewardship Council; Marine Conservation Society; Marinet; Ocean2012; and World Ocean Council.

[277] See details at http://fs.fish.govt.nz/Doc/21837/Spatial%20allocation%20across%20fisheries%20 sectors.pdf.ashx – accessed 10 December 2012.

- Biosecurity is the management of biological risks in order to protect the health and well-being of animals, plants and people and to maintain the functions and services of ecosystems. Biosecurity as applied to aquaculture is best explained by the following extract from FAO (2010b). "As aquaculture intensifies and diversifies, the biological hazards and risks to farmed animals, people and ecosystems also increase in number and diversity, with potentially serious consequences. Some of these hazards include infectious diseases, animal pests,[278] public health concerns on residues and resistance of antimicrobial agents, zoonosis,[279] invasive alien species, release of genetically modified organisms and biosecurity risks posed by climate change. The growing number, complexity and seriousness of these risks have driven the development of the concept of biosecurity and its increasing application. An integrated strategy to manage biosecurity, business, environmental and social risks will better promote sustainable growth of the aquaculture sector." The management of biosecurity will be heavily dependent on adequate data, nearly all of which will need to be spatially referenced.
- The evidence for climate change is now overwhelming. In most marine areas, this is causing waters to become warmer, which is causing sea-water levels to rise through ice melt and thermal expansion, i.e. such that they are likely to be at least 1 metre higher by the end of this century. Warmer waters (marine and fresh) will undoubtedly cause species migration shifts[280] as fish, etc., respond to water quality and to food availability changes. Pereira *et al.* (2010) have predicted that there will be a latitudinal range shift for demersal marine species of up to 4 km per year from 2005 till 2050 (Figure 11.4), and that pelagic species will migrate even faster because of higher water temperatures nearer the surface.[281] There are other climate change consequences that will impede species distributions, such as increased storminess

FIGURE 11.4
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).

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278 Note here the huge concern over the effect that farm-caged salmon might be having on wild salmon through spread of diseases, parasites infections, and the threat of genetic weakening if inbreeding occurs.

279 Zoonosis is any infectious disease that can be transmitted from non-human animals to humans.

280 A recent account of the dominant species shift occurring in Icelandic waters can be found in Stefansdottir *et al.* (2010).

281 Cheung *et al.* (2009a) note that species turnover rates at any single marine station could be over 60 percent between 2010 and 2050.

and wave heights, and increased marine acidification as larger amounts of carbon dioxide are deposited into the seas. Additionally, the effects of climate change will severely impact marine ecosystems such as coral reefs,[282] and, to a lesser extent, specialist aquatic habitats such as mangroves, coastal lagoons and deltas. All of these bio-physical changes will impact upon the social, cultural and economic lives of fisher communities,[283] and recent studies have indicated some likely effects of climate change upon both fisheries and aquaculture, e.g. Handisyde *et al.* (2006); Cochrane *et al.* (2009). In an interesting and important recent case study, Jeffers (2010) noted that the Arctic is currently undergoing unprecedented shifts in marine species, and climatic conditions in the region are changing at a rate nearly twice as fast as those at lower latitudes. This is bringing unprecedented alterations in an area that is extremely important for fisheries. Ecological and socio-economic alterations will have a significant effect on fisheries governance structures and on interactions between Arctic countries and could potentially destabilize existing management regimes. Positive changes to fishery stock compositions and distributions may also lead to conflicts between Arctic nations owing to overlapping jurisdictional claims, unregulated fishing and a lack of multiregional agreements. The current Arctic regulatory and governance framework is not sufficient in scope and flexibility to adequately address future fishery changes brought on by climate change.[284] Clearly, the varied effects of climate change will be another potent area for spatial analyses.

- Often associated with climate change and biosecurity, another major threat to aquatic ecosystems is that caused by invasive species. Within marine ecosystems species, invasions are almost impossible to control, and warming waters are seeing accelerations in these species movements. Some invasions have occurred for different reasons, e.g. species have accidently escaped from fish farms, or they have been purposefully released, or newly constructed waterways such as canals or seaways have created pathways for migration, e.g. the Suez Canal has allowed many species to move from the Red Sea into the Mediterranean Sea. Invasive species often lack natural enemies and they may introduce pathogens that are transmitted to native species. In some cases, invasive species may not be a problem, but in far more cases they both upset naturally existing ecosystems and they slowly impact on existing fishery regimes. It has been suggested that the concept of alien species might be changed to that of "naturalized species" or "established exotic", i.e. because of the near impossibility of reversing the situation once invasion has been successful. Thus, in terrestrial farming, almost all species cultivated are not local and/or native. Undoubtedly, the impact of aquatic alien species has been highly variable, and it needs careful monitoring. The Conference of the Parties to the Convention on Biological Diversity in 2008 invited relevant international organizations to work together to fill the gap in the international regulatory framework on invasive alien species, and reaffirmed the need for capacity and expertise to deal with invasive alien species in many countries, especially in developing countries (Shimura, Coates and Mulongoy, 2010).
- A range of other spatially variable threats include "Abandoned, lost or otherwise discarded fishing gear"; point source pollution from a wide range of sources; increased resource extraction from marine or riverine areas; flow modification in rivers; natural perturbations in species numbers, e.g. explosive populations or species-specific disease events; and increases in El Niño type events, any of which are legitimate and deserving subjects for spatial analyses.

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[282] Butchart *et al.* (2010) estimate that the condition of 38 percent of all corals has deteriorated since 1980 and that 38 percent of reef corals are at a high risk of extinction.

[283] A full range of climate change impacts are given in FAO (2010b).

[284] Jeffers (2010) further explains the range of governance changes that must be introduced, including overhauling the Arctic Council and establishing a new Arctic Ocean regional fisheries management organization.

A summary of all aquatic ecosystems changes can be found in Polunin (2008). The spatial impact of these existing but rapidly accelerating threats and changes will clearly be very significant and solutions are only likely to be successfully sought via expertly managed spatial analysis. One of the ways in which future GIS will progress is through "cumulative impact mapping" that will involve modelling combinations of the various threats as a means towards understanding and perhaps ameliorating the threats.

11.4.11 The standardization of habitat (and other) classifications

Because we live and work in such a complex social, economic and environmental world, then any analyses of our bio-physical or economic activities will oblige us to simplify the subject matters being studied. This essentially means that a classification method must be used, i.e. grouping similar objects or themes into a number of identified categories – which themselves might vary according to the analysis being carried out. For example, finfish species may be classified into pelagic, demersal and benthic species, or perhaps into species that are considered as being of high, medium or low trophic levels. It is important to mention that classifications can be both of a non-hierarchical basis (e.g. pelagic, demersal, benthic) or hierarchical (high, medium, low). Classification introduces problems associated with standardization, which may include:

- The number of classes to be used.
- Where to draw borderlines between classes.
- The basis on which classification is best based.
- Different classifications may be needed for different purposes.

Because of these problems, it has often been extremely difficult to be precise on any categories used and to obtain agreement on the standardization of classes.

To briefly illustrate this, a particular problem encountered in carrying out GIS work, especially that which is associated with habitat modelling and various ecosystems analyses (in both river and marine waters), is that of habitat classification. It is clear that in both marine and freshwater environments, it may be essential to establish mapped layers in which habitat characteristics can be plotted; Box 11.4 gives a hierarchy of requirements for a good habitat classification system. This box also gives a useful clue to the range of reasons why agreement on classification standardization may be important. Given that precise habitat characteristics are almost infinite, then much work has gone into identifying and trying to agree to these classifications (Todd and Greene, 2008; Al-Chokhachy and Roper, 2010; Guarinello, Shumchenia and King, 2010). Despite this work, as yet, there is no international agreement on standard marine habitat classes,

BOX 11.4
Requirements of a global marine habitat classification system

The requirements of a global marine habitat classification may be listed in the following order of importance:

1. Facilitate data and information exchange and interoperability.
2. Comprehensive glossary of terminology.
3. Be hierarchical.
4. Enable capture of marine habitat information from existing Ocean Biogeographic Information System data sources.
5. Enable capture of marine habitat information from potential Ocean Biogeographic Information System data sources.
6. Relevance to end-users, including conservation, fisheries, researchers and educators.
7. Use simpler terms and avoid jargon.
8. Be consistent with existing use of terminology in marine ecology.
9. Be possible to relate to existing marine habitat classifications.

Source: Costello (2006).

though a number of well-developed classification systems exist.[285] In the future, habitat classifications might serve to offer standards by which alternative locations can be assessed and judged, and no doubt habitat classifications will need to be monitored and moderated – so there is much future GIS-based work to be done in this area. It will be clear to the reader that the standardization of classifications of all types could bring enormous benefits to GIS use in fisheries or aquaculture. This is especially true when it comes to the exchange of data. However, it must be borne in mind that universal classification is only ever likely to be practical at the top end of any hierarchical classifications. Thus, further down a classification gradient the items being classified are increasingly likely to be unique to specific areas and thus not subject to international standardization. Once agreements have been reached on a wide range of standardized data classifications, then this will mean that the exchange and use of data sets will be greatly expedited allowing GIS work to be both broadened and more universally understood.

11.4.12 Working at variable scales and resolutions

There is now a rapidly accelerating rate at which data is being captured directly by either managers or researchers who are working specifically in fisheries or aquaculture fields or by others who are working in parallel fields or in associated technologies. There is unlikely to be a halt to this rising rate of data acquisition and of course data will be acquired on an increasing range of relevant themes. An abundance of data provides opportunities not only for a wider range of GIS-based analyses but also for the opportunity to carry out analyses in far more detail and at a wider variation of scales. This may be extremely important in the sense that, with the adoption of EAF/EAA, the fisheries and/or aquaculture researcher is obliged to consider a greatly increased range of ecosystems any of which may be considered at micro through to macro scales. Until recently, the lack of data has frequently meant that scale and resolution options have been severely curtailed. Many GIS workers have found that data for any specific project may only be available at mixed scales, i.e. perhaps varying from detailed remote sensing imagery to highly generalized socio-economic data where single values may be assigned to complete political or administrative areas. Extreme caution needs to be applied when mixing input data at different scales. Improvements in software will allow for easy switching (or "sliding') between scales and users will soon learn to optimize scale and resolution choices for specific analyses or themes.

To illustrate future trends in scale and resolution, it is worth briefly examining the single field of bathymetry. Most readers will be well aware that the world's marine areas are highly varied in terms of depth. While vast regions of the world's oceans consist of abyssal plains (or basins) where depths are typically in the range of 3 500–4 500 m, marine areas also consist of smaller geomorphic units that are typically highly varied in depth, form and texture. Examples of such units include continental shelves, coral reefs, deep ocean trenches, seamounts and mid-ocean ridges. It is immediately clear that the scale and resolution required for a study of part of an abyssal plain will be significantly different than that required, for instance, for any coral-reef-based study. Traditionally, data on bathymetry have been obtained from either single- or multi-beam echosounders. These utilize sonar technologies that are capable of reading the time taken for an "echo" to travel from the source transducer, typically mounted on the hull of a vessel, to the sea bottom and back again, and from this recorded time the depth can be calculated. However, recently bathymetry is making use of LIDAR[286] technology that itself makes use of a high-powered laser to transmit

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285 For instance, in the United States of America, the National Oceanographic and Atmospheric Administration (NOAA) has developed the NatureServe classification and in the European Union the EUNIS system is the best developed marine habitat classification.

286 Light detection and ranging. Recent developments in LIDAR are well explained in Boyd and Foody (2011).

electromagnetic energy, again measuring the time taken to get from the platform being used to the seabed. LIDAR can be mounted on the hull of a ship or on low flying aircraft. Using LIDAR up to 14 million measurements per hour can be captured in waters up to 70 m in depth,[287] and discriminating to 50 cms resolution (Kearns and Breman, 2010).

It can be appreciated that this detailed and superabundant data can allow for spatial analyses at multiple scales and for identifying underwater features, and GIS-based output can include contour-based mapping as well as 3D bathymetric models. The exponential increase in data from numerous capture source instruments that are directed towards most aquatic themes means that the potential for GIS-based work across a full spectrum of scales and resolutions is likely to feature prominently in the coming decades. However, deciding on optimal scales and resolutions to be working at can still be a challenge to GIS work, as is shown in Section 12.3.

11.4.13 Studies of temporal change in fishery 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. Thus far, very little attention has been given to this subject, partly because spatial changes in fishery activities have not been considered as important, and aquaculture (at least on a large-scale) is only a recent development and has thus not yet developed a history of change. However, it should now be recognized that both GIS and remote sensing have been active as important spatial technologies for over 40 years, and this is time enough for the original results (outcomes) of research applications to be revisited with the aim of examining change detection and the validity of some of the early GIS and/or remote sensing work.

With respect to GIS work, it may be important to revisit early studies in an attempt to show the progress that may have accrued over time. So, what was the validity of any early GIS work? Were the results accurate? Were they useful? How do they compare with analytical output that is being achieved today? It is surely useful for any branch of science to see where it has been and to be able to identify and assess progress (or not!). In many cases, the original digital data sets might still exist and clearly these could be easily used as the basis for spatial comparisons with present output. With respect to remote sensing work, there is much useful work that will be achieved. Thus, it is widely appreciated that change detection has been well deployed in terrestrial situations whereby, for instance, the areas of clearance of mangroves for shrimp pond construction have been shown and the rates of this clearance have been calculated. Similar work can be usefully undertaken in aquatic environments. Examples of change detection that rely completely on satellite derived data of aquatic themes include:

- Changes in the extent of coastal biotopes. Here, the main themes might be mangrove destruction; diminishing of deltaic areas under sea-level rise and/or coastal erosion; bleaching or destruction of coral reefs; loss of seagrass beds, etc.
- Spatial changes in temporary phenomena such as red tides, chlorophyll concentrations, water temperatures, seasonal aquatic vegetation, etc.
- Changes in the distribution of sediments in rivers and especially estuaries.
- The number of, and fluctuations in sizes of, inland waterbodies, i.e. mainly shallow lakes sited in semi-arid areas.

This type of remote sensing analysis can be simple to accomplish and can be very useful, especially in forming one of the essential inputs to model development and to future forecasting and planning.

[287] 70 m depth is very relevant to most mariculture production.

12. Overcoming the challenges to fisheries or aquaculture GIS work

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12.1 INTRODUCTION

Given the wide range of thematic areas that are encapsulated within the three broad areas of "GIS", "fisheries" and "aquaculture", and thus the spectrum of knowledge that must be absorbed, it is not surprising that there will be challenges to working within any of these areas. This is especially the case given that the work is being attempted 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. In this chapter, the purpose is to be both descriptive of a wide range of challenges and to attempt to provide useful clues as to how the challenges might be overcome. It needs to be mentioned that none of the challenges are absolute barriers to GIS work; instead, most challenges are problems that GIS users should be aware of in order that special consideration can be given to the best ways of dealing with them. Much of the material used in this section originates from Meaden (2004) (where more detail can be found), though the coverage of the material has been extended and updated, especially as it relates to tackling and hopefully overcoming the main challenges.

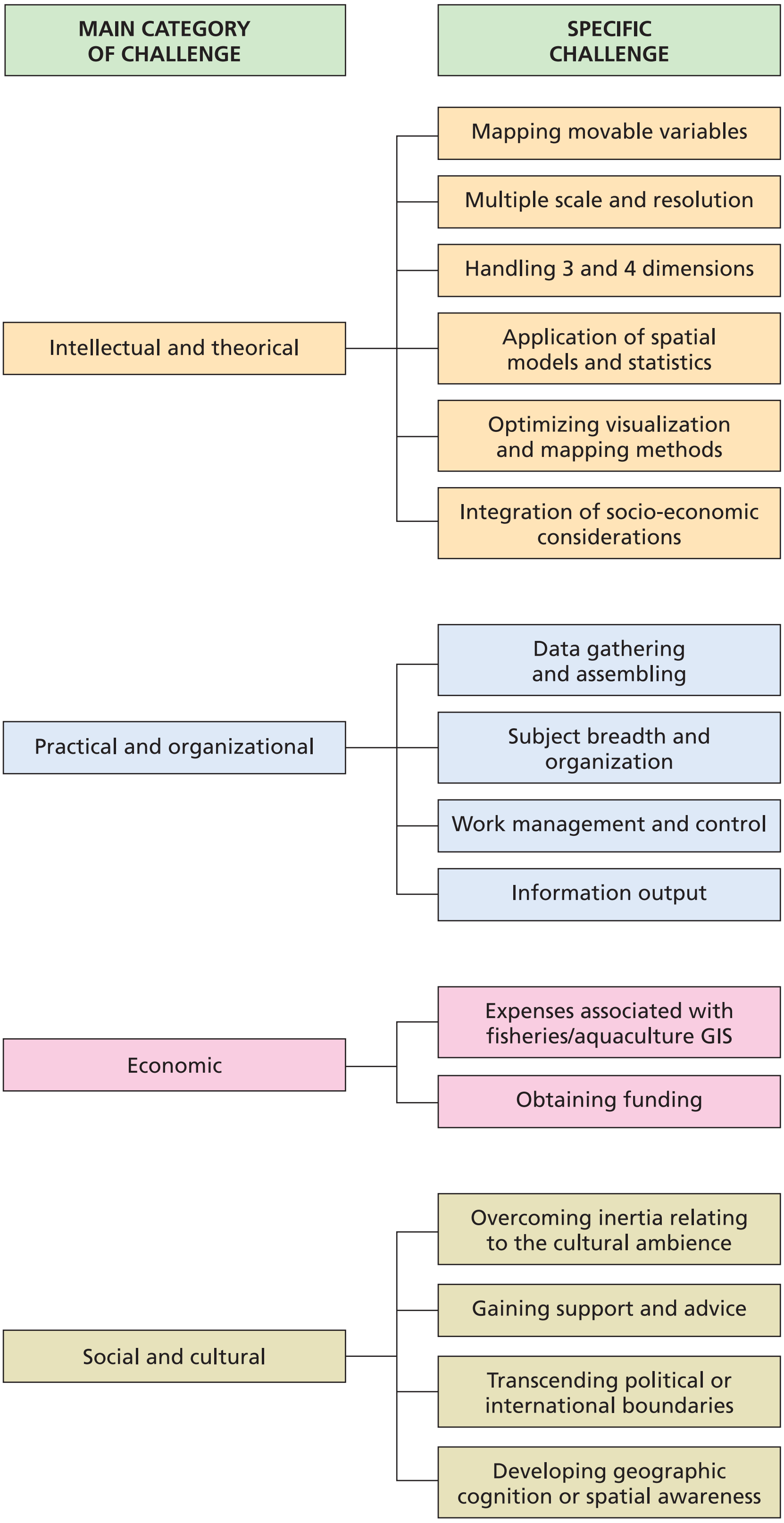
Figure 12.1 provides a schematic diagram showing the main challenges facing the use of GIS for fisheries or aquaculture purposes. Looking at the challenges by main category headings, it is clear that most can be broadly considered as being practical concerns, and, as such, they are likely to vary greatly according to the individual circumstances of GIS users. However, it is important also to note that there are a number of intellectual and/or theoretical challenges, and this demonstrates that the application of GIS requires some considerable thought and perception plus academic training and experience. The rest of this chapter will provide brief insights into the 16 specific challenges listed. Space prohibits detailed referencing, though much of this can be obtained from Meaden's (2004) original work.

12.2 MAPPING MOVABLE VARIABLES

The majority of all GIS work is devoted to spatial analyses of the terrestrial terrain. This is a much easier milieu in which to work (compared with aquatic areas) as the great majority of the features and objects being mapped are static. In aquatic environments, it is not only most of the objects being mapped that move,[288] but it is also the environment within which they exist (the water) that moves. In fact, the only static objects may be permanent features associated with the river, lake or marine area bottom such as coral reefs, seamounts, trenches and solid substrates plus shorelines or river banks, which may only show very gradual change. Even many of the bottom features, e.g. gravel, mud and sand, will be subject to varying degrees of movement. Notwithstanding these difficulties, attempts must be made to map moveable species or objects because without this information very little aquatic-based GIS work could be achieved.

[288] The objects being mapped are typically aquatic animal species, but they can also be fishing vessels whose movements can be digitally recorded.

FIGURE 12.1
Categories of challenge facing fisheries and aquaculture GIS



Source: Adapted and updated from Meaden (2004).

Species movements exhibit different degrees of predictability and this can have a corresponding effect on mapping. For instance, salmon and whale migrations might be highly regular, and many of the larger ocean current or river water movements are also relatively regular. At the other extreme, it is likely that many occurrences of plankton blooms, or the foraging movements of fish, or the positions of ocean fronts are all highly irregular or chaotic. Therefore, the challenge for the GIS worker is – How best can process or object movements be mapped? Clearly, with the progression from regular movements towards chaotic movements, the mapping task becomes more difficult. For the mapping of many species movements, one answer lies in the frequency of data collection; thus, many species have annual cyclic movements perhaps between spawning and feeding areas, or they make other known seasonal migrations. For these species movements, less locational data may need to be collected. For situations where movements are chaotic and unpredictable, then the use of GIS for mapping might be solely for research purposes, i.e. it may be inadvisable to make positive decisions based on GIS output.

Careful thought must be given to the resolution or scale used for mapping of movement, i.e. this must equate to a resolution that can best discriminate important movements. For larger marine animals, including mammals, turtles and reptiles, it is often possible to fit tracking devices that record movements with time, and this can provide good insights into trends for any dominant or regular movements. There is now a body of academic work being deployed into aquatic animal movements, and some interesting GIS-based animations have been produced showing periodic snapshots of movement through time (Pittman and McAlpine, 2003; Rogers and White, 2007). Recent developments in studies of movement are allowing models to be developed that can predict where species are likely to be at given temporal intervals, and there is software that can be integrated to GIS that provide movement analysis tools, e.g. Animal Movement Analysis – ArcView Extension.[289] Given time, it is certain that additional models will accrue that give strong clues to the range and rates of movement recorded for many of the cyclic or seasonal movement patterns that occur with respect to both inland and marine waters.

12.3 MULTIPLE SCALE AND RESOLUTION

Scale is concerned with the relationship between distance or area on a map and the corresponding real size of the area under consideration, 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 take place across a spectrum of scales and resolutions, and there has been a long history of discussion on the appropriateness of the scale of study. Figure 12.2 shows how some time and space bio-physical scales vary within the marine environment, and it is clear that any GIS fisheries-based work might need to gather data at vastly differing scales. A good illustration of the scale problem is provided in Feist *et al.* (2010), who use GIS in an attempt to resolve the optimum scale for studying Pacific salmon and their preferred habitats in the Columbia River basin in the United States of America. Contrasting scale of analyses are also shown in Chapter 9 where Section 9.5.1 provides an example of GIS being used at a microscale (study of a short section of a single stream), whereas Section 9.5.3 showed GIS being used at the whole state level within the United States of America. At any of these scales, GIS analyses can be extraordinarily complex in terms of data needs, models applied and the knowledge of natural processes required by the project participants. Schneider (1998) notes the importance of scale because:

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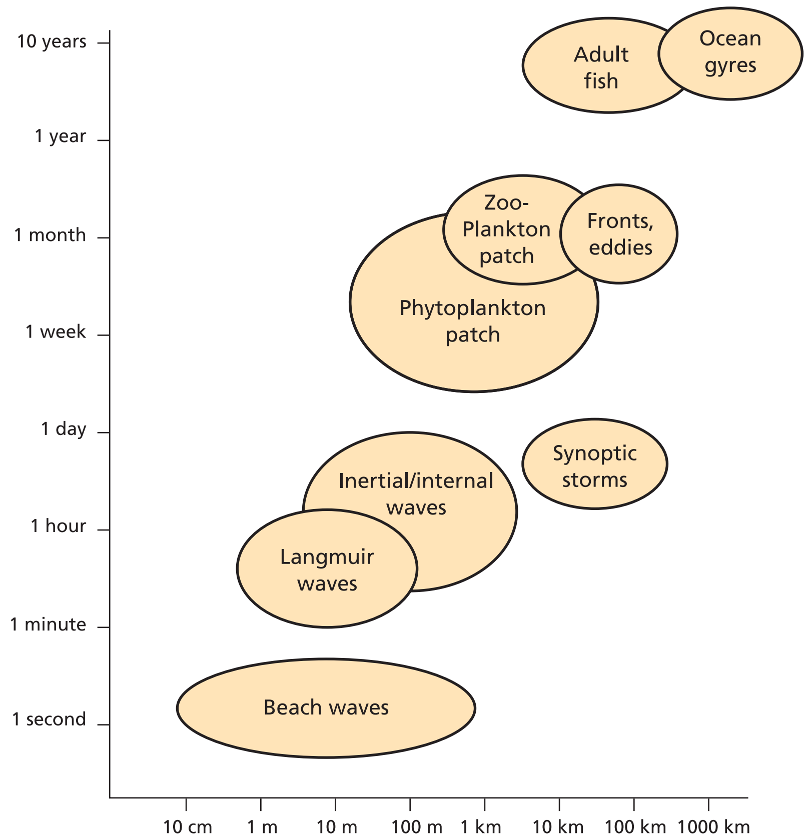
[289] This software derives from the seminal work by Hooge, Eichenlaub and Soloman (1999) and is available free of charge from the United States Geological Survey: http://alaska.usgs.gov/science/biology/spatial/gistools/index.php/animal_mvmt.htm#Introduction, though it is unlikely to be updated.

- spatial and temporal patterns depend on scale;
- experimental results cannot be extrapolated to other scales;
- biological interactions with the environment occur at multiple scales;
- population processes often occur at scales that are difficult to investigate;
- environmental problems arise through propagation of effects across scales;
- there is no single characteristic scale for research.

Fisheries science is concerned with processes that operate at all scales and it is important to determine the optimum scale at which to carry out research and mapping projects and thus spatial analyses. This is because many distributional patterns can only be discerned at appropriate scales. Finding the optimum scale might only be accomplished through trial and error, though clearly project scope and type of process will give sensible clues to an appropriate scale or resolution. However, there will often be complications because projects need to function at varying scales, and with the emergence of the ecosystem approach to fisheries (EAF) and the ecosystem approach to aquaculture (EAA), this problem is likely to be exacerbated.[290] As cautioned in Section 11.4.12, sometimes input data for a single project are only available at highly variable scales. The use of such mixed-scale data should be avoided if at all possible, especially if the thematic area being studied includes production functions that have highly variable spatial distributions.

FIGURE 12.2
Varying time and/or space scales for selected physical and biological marine variables



Source: Adapted from Dickey (1990).

[290] Ecosystems function at a range of scales from highly local to global; therefore, there is a need for a nested approach with different approaches to management according to scale. The EAF/EAA guidelines provide a common, coherent and practical framework for policy-making and promote a process of enhanced sectoral management at different scales, taking full account of environmental limits and the interests of other resource users and stakeholders (FAO Fisheries Department, 2003; FAO, 2010b).

If work proceeds using mixed-scale data, then the GIS output will be highly generalized and completely lacking in precision and reliability. Other questions arise, such as the optimizing of temporal scales, i.e. over what period should a study last and what might be the best time and/or space intervals between data sampling times and/or points? With respect to resolution, it is easy to appreciate the nature of the challenge by thinking of the simple perceptual problem of "How many data points (readings) are needed to construct a statistically valid single-time surface temperature map of the Pacific Ocean?" A single answer is impossible to state because it depends on the resources available for data gathering relative to the accuracy required for the map. All GIS-based projects involve similar scale and resolution challenges. A useful guide to the subject area concerned with creating maps (and their validity) based on different sampling strategies, scale, resolution and interpolation methods, mainly with respect to species distributions, is given in Rempel and Kushneriuk (2003).

12.4 HANDLING 2.5D, 3D AND THE 4TH DIMENSION

It is probable that proprietary marine (and other aquatic) GIS programs have been slow to develop because of the challenges of handling 3- or 4-dimensional mapping. Thus, terrestrial GIS work is mostly confined to just the two horizontal dimensions plus the fourth dimension of time, and most of the mapping can be readily accomplished. GIS are also capable of working in what has been called "2.5D", i.e. the two horizontal dimensions plus a height dimension that is fixed to the ground elevation (altitude), and imagery of ocean bathymetry is typical of this output (see Figure 10.20). But the majority of GIS fisheries work[291] is obliged to consider the true third dimension (in the marine case – depth), perhaps to analyse or map varying water temperatures by depth, or the location of schools of fish, or perhaps the depth and location of tagged marine species. While it is feasible to construct database facilities that store, manipulate and carry out statistical functions using x, y and z data, it is clear that maps produced on a flat surface cannot easily display information on all three axes at the same time. So the challenge for GIS work is how best to illustrate true 3-dimensional data. A number of attempts at 2.5D, 3D or 4D marine mapping have been made, and these attempts have usually taken one of three approaches:

(i) Using GIS software that contains embedded applications for producing 2.5D displays (typically of bathymetry). Examples of the first approach include "Marine Explorer" (described in Section 2.3.2), and EASy (Environmental Analysis System), which is a research-focused GIS having the capability to view, analyse and store diverse types of marine data, and the data can be displayed in 2.5D utilizing time, depth and added geospatial information[292]. A further major 3D product is Environmental Systems Research Institute's (ESRI) ArcGIS 3D Analyst, which allows viewing of large sets of data in three dimensions from multiple viewpoints, the querying of surfaces, and the creation of realistic perspective images that drape raster or vector data over a surface.[293]

(ii) Using specialist software applications that can be independent or integrated to GIS to plot a range of 2.5D to 4D imagery.[294] With respect to this second approach, showing the third dimension of variables that are continuous in 3D space, e.g. water temperature, salinity and pH. These can be shown via a series of static images through parallel "slices" of the area under study, with "slices" being at any prescribed orientation or distance frequency. These "slices" could of course be animated, for instance, to show how water temperature changes with incremental changes in

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[293] Aquaculture is not usually concerned with the third dimension, though with offshore mariculture coming to prominence, this will be changing.

[292] Details on EASy are available at www.runeasy.com.

[293] Details at ESRI: www.esri.com/software/arcgis/extensions/3danalyst/index.html.

[294] The use of the term "maps" has been deliberately avoided here because most of the output from these 3D applications tend to be diagrammatic or they show oblique 3D images.

depth. An example of these specialist software applications is IDV produced by UNIDATA and which is freely obtainable,[295] and Booth and Wood (2004) show one of a series of convincing 3D images (that can be animated) illustrating the distribution of the hoki catch off the west coast of New Zealand's South Island.

(iii) Use of specialist 3D or 4D marine databases that have been developed for storing marine data and that are linked to GIS to achieve mapped output. However, attempts at the mapping of objects that are in the 3D waterbody but which are non-continuous have been more difficult to resolve. Figure 12.3 is a recent attempt at this, one that also includes a 4D (time) element. The figure shows aggregated herring catches from 2006 to mid-2010 along survey tracks in the Norwegian Sea and Arctic Sea areas bordered (clockwise) by Svalbard (top right), the Kingdom of Norway, Scotland, the Republic of Iceland and Greenland (top left).[296] Each year's catch per sampling point is shown by proportionally sized located circles.[297] It can be perceived that catches might have been at different depths, and although this depth data could easily be captured (recorded), it would be difficult to illustrate this on a paper map. Other interesting and novel attempts at true 3D displays have been reported by Wood and Baird (2010).

Examples of this third approach, i.e. using 3D specialist marine databases that can be integrated to most proprietary GIS, include "Ocean Database" by Oceanwise, Hampshire, the United Kingdom of Great Britain and Northern Ireland,[298] and "ArcMarine" by ESRI of Redlands, California, the United States of America.[299] It is relatively easy to show the time (4^{th}) dimension, either through time sequential video-based animations or through a simple series of regular interval, static images. Additional information on various aspects of 3D or 4D GIS work can be found in Wright *et al.* (2007) and in Abdul-Rahman and Pilouk (2010).

In the realm of aquaculture, some progress has been made in recent years with regard to the use of 3D. For example, Moreno-Navas (2010) and Moreno-Navas, Telfer and Ross (2011a,b) developed a model in a 3D hydrodynamic model (MOHID) to predict coastal environmental vulnerability for Atlantic salmon cage aquaculture, the outcomes from which were subsequently imported into ArcView 3.2. This 3D hydrodynamic model, coupled to a particle-tracking model, was applied to study the circulation patterns, dispersion processes and residence time in Mulroy Bay, Co. Donegal, Ireland, an Irish fjord (shallow fjordic system), an area with important aquaculture activities. The results of this model could be used to facilitate decision-making for site locations and these could be integrated with wider ranging spatial modelling projects, such as coastal zone management systems and effective environmental management of fish cage aquaculture.

Of interest to note is the use of time series animations, effectively 2D + time and generated within GIS, for assessing aquaculture development potential. The Institute of Aquaculture in Stirling, Scotland, presents two examples (in the Argentine Republic and the People's Republic of Bangladesh) and to show the flood cycle over long-time periods, based on data from the Moderate Resolution Imaging Spectroradiometer (MODIS) operated from the Aqua and Terra satellites.[300]

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295 Details on UNIDATA: www.unidata.ucar.edu/publications/factsheets/2010sheets/IDVHandout.pdf.

296 Produced using "Eonfusion" software by Myriax Pty Ltd. Tasmania, Australia (www.eonfusion.com/uploaded/263/13400529_19eonfus ontechnicalwhite.pdf).

297 Data on herring catches was supplied by the International Council for the Exploration of the Sea (ICES) and are based on acoustic measurements of stock biomass. The data are visualized through the use of Eonfusion V.2.1 software. No indication is given on the scale of the proportional circles.

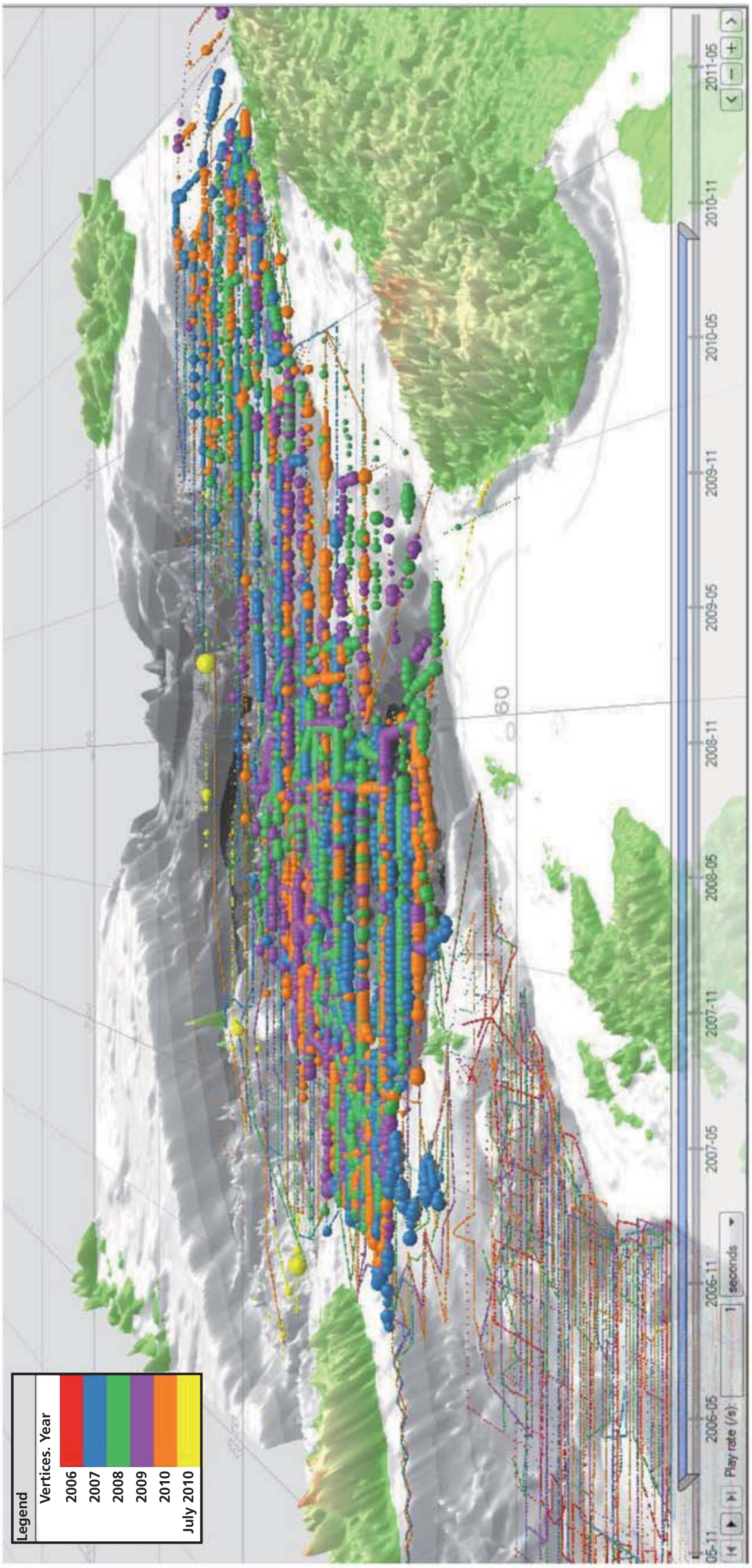
298 OceanWise: www.oceanwise.eu/Ocean_Database_latest.pdf.

299 A detailed presentation of ArcMarine is available at www.esri.com/industries/marine/docs/arcmarine_techwork09_final.pdf.

300 See examples for the People's Republic of Bangladesh at www.aqua.stir.ac.uk/GISAP/gis-group/neil_climate, and Río Paraná, the Argentine Republic at www.aqua.stir.ac.uk/GISAP/gis-group/daniel.

FIGURE 12.3

4-dimensional image to show aggregated herring catches in northern Atlantic and Arctic Ocean waters from 2006 to mid-2010



Source: Gastauer (2010).

12.5 APPLICATION OF SPATIAL MODELS AND STATISTICS

As with most other areas of scientific investigation, the spatial analyses of themes relating to fisheries and aquaculture are subject to modelling and spatio-temporal, geostatistics and other statistics, and this gives rise to a range of intellectually complex challenges. For present purposes, spatial statistics and spatial modelling can be considered as one, i.e. because the challenges posed are virtually the same as are the methodologies employed by GIS (and other modelling software) to meet modelling requirements. So 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. As an example, Figure 10.5 and the accompanying text in Section 10.2.4, explained how a statistical model was developed by Eastwood and Meaden (2004) to account for the variable abundance of sole (*Solea solea*) eggs in the English Channel area, and other examples of modelling have been given in Chapters 7, 8 and 9. Once established, a model can be used again in similar situations (or at different times), having been suitably adjusted to suit perhaps different species or changes in geographic area. Once suitable models have been developed, they can be integrated to most GIS, either internally via appropriate functions or externally through specialist software, including a wide range of modelling tools. Some advantages of modelling within a GIS include:

- The raster data structure provides an ideal platform for many spatial modelling procedures.
- Most GIS have built-in, or self selecting, formulas that can be used.
- It is easy to add extra variables that might influence or improve the models.
- A range of types of weightings can be applied during modelling.
- Temporal iterations can be accomplished to achieve dynamic modelling.
- GIS is ideal for exploratory data analyses.
- GIS can easily accommodate scale, time or area changes.

Notwithstanding these advantages, spatial modelling and the use of geostatistics can be a challenge for many GIS users. Developing the models frequently relies on a strong mathematical ability. For instance, in developing the type of model shown in Figure 10.5, it was essential that the lead author understood the detail of regression quantile techniques, and most modelling requires a strong background in algebra as well as geostatistics. Another challenge is to be able to positively identify the variables that are influencing distributions. While in many cases these variables may seem fairly obvious, there will be occasions when distributions will be influenced by unexpected factors. It is not always easy to have access to sufficiently detailed data distributions on all of the required variables, and it has already been stated that gathering additional data within aquatic environments can be an expensive challenge. A further challenge is one that faces many geographic surveys and that is the problem of spatial autocorrelation and the identification of true dependence or independence between variables. Much modelling also tends to be scale dependent. A statistical problem that may be often encountered, but also probably frequently ignored, is that of securing statistical significance of the data being used. Frequently, expensive marine surveys are compelled to utilize minimal amounts of sampled data, and in some instances GIS fisheries output is likely to be based on very questionable mathematical (statistical) significance. In order to overcome challenges relating to modelling, it is recommended that familiarization with, and use of, some of the spatial analysis tools be made. A wide range of free analysis tools are listed in Spatial Analysis Online.[301] Other spatial modelling tools have been developed[302] and a worked model, developed to establish suitable fish habitat in a reef environment, is given in Granados-Dieseldorff (2009). Additional useful reading includes Kanevski

[301] Spatial Analysis Online: www.spatialanalysisonline.com/SoftwareFree.pdf.

[302] See Geospatial Modelling Environment (www.spatialecology.com/gme) and Stanford University (www-sul.stanford.edu/depts/gis/tools.html).

and Maignan (2004), Maguire, Goodchild and Batty (2005), Hengl (2007), Wright *et al.* (2007) and Aguilar-Manjarrez, Kapetsky and Soto (2010).

12.6 OPTIMIZING VISUALIZATION AND MAPPING METHODS

It is clear that the basic ways in which GIS conveys its output is via tables, graphs and dominantly maps. In order that any of these illustrative methods puts across a clear message, it is most important that the message conveyed is both accurate and perceptually easy to synthesize. For maps, this is especially important. Good-quality cartography should follow a number of basic rules concerning legend construction and content, scale delineation, number of classes used, word placement, etc., though there is freedom within the rules to accommodate individual mapping styles and preferences. The challenge for GIS workers lies in constructing well-designed cartographic input data and to achieve output maps that form acceptable and comprehensible visualizations.

In constructing good visual images, the GIS operative is able to gain some support from most GIS software in that all mapping functions include preset styles that are typically acceptable to most map recipients. Within these basic styles, there is adequate freedom to adjust images in many ways. The greatest challenges to good visualization occur with respect to the following:

- Classification. Here, the challenge is to find suitable numerical boundaries between classes or to establish acceptable classes among non-numeric themes.
- Data representation. It is usual to show symbols on maps and these must be chosen with care so that they are meaningful in terms of easy comprehension.
- Font size, style and placement. Font size must be a compromise between legibility, the number of names (words) on a mapped area, and the need to avoid clutter and inappropriate name placement. Styles should invariably be relatively plain.
- The information to include. This will be a balance between including generally important features and those that are related to the thematic content of the map.
- Colour arrays. Users should avoid too many colours, and "bright" colours should be used sparingly (if at all).
- Fuzzy boundaries. Because much mapping output may be with reference to widespread marine areas and to features that are moving, e.g. currents, fronts, sandbanks, then there is often a problem of boundaries that might be indeterminate or changeable. For instance, the classification of habitats in streams has given many problems in terms of their delineation, and exactly which part of the North Atlantic could be called the "Gulf Stream", and how can a species range be exactly defined?

It can readily be seen that good-quality visualization is no easy matter to achieve and a large amount of research goes into this field. This research is both from a purely cartographic perspective but more frequently from a psychological viewpoint. The problem here is that all individuals have differing perceptual aptitudes and thus one set of maps will not suit all. Putting this another way, there is no such thing as "the best visualization", although there certainly are good maps and bad maps. It might be of interest for readers to peruse the large number of maps in this manual to see that they also may have very individual preferences.

The problems of visualizing any 3D marine features on a 2D-mapped surface have been discussed and ways in which problems might be overcome have been indicated. It has also been suggested that animations or map series are suitable ways of exhibiting distribution changes over time. But additional problems may still be of concern to cartographers. Thus, imagine the complexity of mapping a coral reef surface or features within a typical rock pool. Here, there can be almost infinite variability within a small area, yet all the variables might be of importance to the visualization. Where possible, visualization here is best achieved through the use of annotated photographs or pictures and videos can be linked to Web-based mapping delivered via the Internet. From this description, it is probably easy to deduce that scale is very relevant to what is being shown. So, at a broad scale, a coral reef can easily be delimited as a linear feature on a map (as in Figure 10.18), and a rock pool may be shown as being part of an area of the intertidal shoreline. It is also true that all mapped features will have to be variably portrayed on a map according to the scale of the project area. Useful sources to help with the challenges of visualization include Cartwright, Peterson and Gartner (2006), Ghadirian (2009), Kraak and Ormeling (2010), Robinson (2010), and any number of general books on cartography.

12.7 INTEGRATION OF SOCIO-ECONOMIC CONSIDERATIONS

As has been mentioned frequently throughout this technical paper, all future work in respect to the management of fisheries and/or aquaculture will need to adopt respectively an ecosystem approach to fisheries (EAF) or an EAA. The implications of this are wide ranging and they have been discussed in many publications, for example: FAO Fisheries Department (2003); Christensen, Aiken and Villanueva (2007); Carocci *et al.* (2009); FAO (2010c); Aguilar-Manjarrez, Kapetsky and Soto (2010). The use of an ecosystem approach to either fisheries or aquaculture means that optimization of the management of either of these activities will involve a consideration of social and economic factors as well as the more direct bio-physical factors that have been traditionally recognized as controlling these activities. So, it is now very clear that a sustainable future for both fisheries and aquaculture can only be achieved if full recognition is given to matters such as the provision of paid 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 approach to management, therefore, considers the whole of a fisheries or aquaculture ecosystem and not just the immediate production environment.[303] However, this approach presents some quite distinct additional challenges with respect to the use of GIS. Recall here that whatever data are used in any spatial analyses, the data have to be capable of being mapped to a reasonable level of precision. Some of the challenges to working with social and economic data can be exemplified as:

- Socio-economic factors may be difficult to categorize into agreed classes, e.g. imagine drawing areas on a map exhibiting different "degrees of wealth". So, different means of assessing wealth may result in quite different pictures of "reality" being portrayed by the different maps (Minot, Baulch and Epprecht, 2006).
- Exact socio-economic values may be difficult to measure and to attribute to exact locations.
- Existing social data are often scarce in most areas, and may only exist at a small scale (very generalized) for complete administrative areas.
- Many participants in projects may be reluctant to divulge social or economic information.
- The breadth of social information is extremely wide and judging the relative relevance of information or data may be difficult.
- Social or economic spheres may be far broader than the bio-physical production spheres that have traditionally been used in management. This has implications for the scale of a project. Where should boundaries be drawn between neighbouring ecosystems? How easy will it be to work across administrative boundaries?
- Many fisheries or aquaculture activities take place in very mixed social and/or economic areas, or conversely the fishing or fish farming activities themselves may be very diverse within a single geographic area. How can the exact stakeholder mix best be determined?

[303] A useful and succinct summary of the EAF approach is available at FAO (2012g).

- Much of the social data may be subjectively and differentially construed by the different players (stakeholders) in the fishery or aquaculture activities.

Generally, it would be true to say that socio-economic data integration presents greater challenges to GIS work than does the use of traditional bio-physical data.

Although the challenges of incorporating socio-economic considerations into GIS-based project work might seem daunting, these challenges are certainly not insurmountable and they will be gradually overcome. It might be anticipated that most of the initial GIS projects involving full ecosystem approaches may be somewhat tentative and exploratory, i.e. lots of decisions will be made that may lack certainty and lots of experimentation may be necessary. Initially, there may be little other option than the use of "trial and error" techniques, whereby input variables and/or data are constantly adjusted or experimented with. It is useful if this GIS work can be carried out in situations where the results expected are fairly certain and thus the degree of success can be reasonably estimated. It is also useful if GIS workers who are attempting to integrate socio-economic data can form working alliances with other groups who might be using GIS for a range of social or economic-based tasks. These alliances might become a form of regularized networking. Now that whole ecosystem approaches are being adopted in a range of natural science or resource-extraction-based disciplines, networking will be easier and it is likely that specific GIS-based training or workshops will begin to proliferate, i.e. concentrating not only on mapping per se but also on social and economic concepts, issues, methods and resources. As with some of the other challenges to GIS work in fisheries or aquaculture, it will be beneficial to consult the FAO Web site for literature and more especially for relevant resources on EAF and EAA, e.g. see GISFish. Finally, many of the models that are associated with ecosystem approaches to fisheries or aquaculture are now incorporating socio-economic considerations (see NatureServe),[304] and it is likely that this will be a significant area for future model development.

12.8 DATA GATHERING AND ASSEMBLING

Although data provision lies at the heart of all GIS work, and thus its means of provision might have been thoroughly researched and provided for, this is very far from being the case. Indeed, data gathering and assembly could well be the greatest practical challenge that workers in GIS must regularly resolve. Upon starting any GIS project, data needs must be identified and this can be problematic given that the subject matter being investigated is likely to be conceived as "a problem" which itself must involve uncertainty – and this is likely to be relative to what are the exact causative factors (or production functions – see Section 3.2) about which data are needed. When this is established, it is still necessary to make decisions on a range of other factors such as:

- By what means can the data best be obtained?
- From where can the data be obtained?
- Are there existing suitable data?
- How much data can be afforded?
- To what precision is the data needed?
- What standards are required in terms of structure, format, projections, classifications, etc.?

The challenges facing data gathering and assembly can best be further reviewed under the subheadings of primary and secondary data challenges (Box 12.1).

Despite the numerous challenges associated with data gathering and assembly, huge advances have been made over recent years in data provision. In Chapter 3 reference was made to the vast array of data providers. Chief among these has been the availability of data sourcing and delivery via the Internet, and Boxes 3.9 and 3.10 gave clues to some of the main data sources. Many large data centres have been established that usually

[304] NatureServe: www.ebmtools.org/faqs.html# Question 16 Fisheries.

concentrate upon specific themes or geographic areas. There are many specialized projects or programmes in place that are seeking data to resolve identified marine problems. Remote sensing via a continually expanding range of satellite and airborne sensors is providing vast quantities of marine data as are various sonar acoustic devices. Other data gathering technology is being deployed, such as the tagging of a range of marine species, the tethering of marine buoys on the surface, in the water column or on the seabed, the implementation of electronic fisheries logbooks, and the deployment of automatic or manned submersible vessels. The assemblage and storage of this exponentially increasing data supply is accommodated via ever larger digital storage devices and servers.

BOX 12.1

Some challenges to gathering and assembling data

Acquiring primary data for marine projects (marine fisheries or mariculture) will offer more challenges than for inland fisheries or inland aquaculture projects. These challenges include:

- There may be large costs and time considerations as much data comes from the marine environment.
- Survey vessel booking schedules may need adhering to.
- Specialized data-gathering equipment (and sometimes skills) is often necessary.
- Gathering data may be impeded by the weather or marine conditions.
- From what size area should data be gathered?
- What is the ideal sampling strategy and can the strategy provide statistically valid data?
- All data may need 3D georeferencing.
- Who will be responsible for storage and upkeep of each data set.

Some major challenges associated with the collection of secondary data include:

- Many data sets must be paid for, and prices can be high reflecting data-gathering costs. Data costs may have a severe impact in many developing countries.
- There are many parts of the world for which data do not exist or there are very few data available, and these facts may be difficult to establish.
- Some data have strict copyright rules that apply. If this applies to mapping data held by central mapping agencies, access to copyright freedom is usually granted for research purposes.
- There may be a range of barriers to sharing data (privacy and confidentiality issues, licensing and ownership issues, liability issues and broader data sensitivities).
- Marine or fisheries data are often four dimensional and can relate to any of numerous variables and areas. The chances of obtaining suitable data may be low unless the user requires more commonly held baseline data, e.g. on water temperature, bathymetry, river, coast and lake outlines.
- There is great diversity in the types of data that may have to be acquired: physico-chemical, geological, meteorological, socio-economic and biological data; all have to be integrated, and analyses and information may be necessary that draws on any combination of these variables.
- There will be large variations in the standards of metadata provision (see Section 5.5). Effectively, this means that users will find much more information available about some data sets than others.
- Data have frequently been collected at an inappropriate resolution for a planned project, or the data are out of date or have been collected at the wrong season, or are somehow of a dubious quality.
- Simply coping with the deluge of marine and fisheries data that are now being captured. This includes the organizing, storing, documenting, publicizing and disseminating of data, plus a range of challenges in using such a diverse range of data.
- Use of the Internet for data collection incurs an expectation that the user will be familiar with English as an international language for communications.

12.9 SUBJECT BREADTH AND ORGANIZATION

The core subject application areas covered by this technical paper, i.e. "fisheries", "aquaculture" and "GIS", must be recognized as "non-pure" areas. Thus, although each of these areas is easily identified, their very existence is intrinsically and essentially linked to many other main subject areas, including, for example, oceanography, marine ecosystems, climatology, agriculture, biology, remote sensing and various branches of information technology and marine construction. The necessity of working in this extremely wide applications area substantially increases the complexity of the work undertaken in terms of the overall knowledge required, the linkages and communications channels that must be established, and the range of information and data that might be required. As if these challenges were not sufficient, over the last decade they have been significantly increased through recognition of the necessity for marine spatial planning and for an adoption of an ecosystem approach to both fisheries and to aquaculture.

GIS is typically applied to either fisheries or to aquaculture for management or research purposes, and it may be pursued in both the public (state) or private sectors. Although some of the work will be carried out in large, centralized governmental offices, by far the majority of management or research takes place in relatively small, fragmented and isolated institutions or consultancy companies, e.g. small government research stations that are coastally located or a range of universities that may specialize in GIS per se or in any of the sectors mentioned above that may be integrated to fisheries or aquaculture. So, most of the work being pursued in these fields is small scale and extremely scattered, and these conditions are not conducive to optimizing the chances of successful and well-tested applications. Added to these challenges is the fact that change can be very rapid in the associated technology fields, especially those applying to computing and remote sensing. These changes can be very costly, not only for those developing the technologies but also for groups who may be required to constantly reinvest in new hardware. So, simply keeping abreast of all that is going on is a challenge in itself.

How might challenges associated with the breadth and organization of the fisheries and aquaculture GIS fields be addressed? This is being challenged on several fronts, some of which have already been alluded to. Thus, in Section 4.8.3 information was given on a wide range of published information, with Box 4.11 specifically indicating publications that could be valuable in addressing the wider area of fisheries and aquaculture GIS; Section 4.8.4 covered the important mode of information dissemination via conferences, workshops and exhibitions; and Section 4.8.5 covered other support groups including professional organizations. Box 10.2 also gave leads on the major organizations carrying out research in the area of fisheries-based GIS work. Additional to this support, there is that offered through FAO's Global Gateway to Geographic Information Systems, Remote Sensing and Mapping for Fisheries and Aquaculture (GISFish). There is undoubtedly a rapidly growing recognition that the planet is becoming increasingly crowded, and that "spatial optimization" is of increasing importance in a world where sustainability is of the essence. GIS and remote sensing are being recognized as two of the ideal tools to bring this about, and the timely appearance of the Internet as a vehicle for information acquisition, for data exchange, and for interactive GIS can only serve to reduce the challenges of subject breadth, fragmentation and isolation that were previously prevalent.

12.10 WORK MANAGEMENT AND CONTROL

This challenge is connected to the previous one (Section 12.9), but whereas that looked at practical and organizational factors from a widespread viewpoint, these challenges are at the scale of an individual GIS worker or small organization. As was mentioned in Section 12.9, it is likely that the majority of fisheries- or aquaculture-related GIS work will be carried out within small institutions or small groups within such organizations. Effectively, this is likely to mean that GIS projects are carried out by either a single individual or at most just a few people. Workers on projects are thus obliged to carry out all or most of the many tasks necessary for the successful completion of a project. It is often a challenge to be able to undertake this, if only because of the great breadth of knowledge that must be acquired and because it is quite likely that any human support is fragmentary, not readily available, and thus could be difficult to access. Also, when working individually or as part of a small team, if there are several different GIS projects to be undertaken, then this could greatly expand the range of challenges. Clearly, GIS personnel working under any of the conditions described here need to have a fair degree of initiative, probably a technological aptitude, and would require the confidence to experiment and/or to seek advice from a wide variety of potential sources. There could clearly be a very sharp learning curve.

The challenges concerned with work management and control must be resolved through advice and help from someone at management level within the institution, or through "teaming up" with GIS offices or personnel working in other public or private sector departments. Thus, as hinted in Chapter 4, it will be crucial that the GIS work is fostered and encouraged by a "manager" or "champion" who has a distinct interest in, and understanding of, the requirements for attaining successful GIS output. He/she will need to offer the required guidance and to make certain that all physical working requirements are met, including access to further training, advice and support. If, perhaps due to the size of the institution or the nature of its working environment, these challenges are difficult to resolve, then serious consideration must be given to establishing different working patterns within the institution or even to working collaboratively with other groups or organizations where know-how, capacity building or technical support might exist. If these solutions are not practicable, then it may be necessary to contract out any required GIS work.

12.11 PROMOTION OF GIS OUTPUT

The concern here is with the promotion of any output achieved from the use of GIS. It would be fair to say that this output does not tend to get wide recognition, certainly with respect to the scale of the spatially based problems that are associated with worldwide fish production. What are the challenges associated with achieving a higher threshold of output recognition? These can be identified as:

- There are very few fisheries and/or aquaculture conferences or workshops that might act as showcases for the work being done.
- Much of the output from fisheries or aquaculture GIS work is of a highly specialized nature and thus only gets to a very small audience.
- Much GIS work only appears in what is termed the "grey literature" – these might be an array of little known, limited distribution publications.
- Because GIS is basically a tool for spatial analyses to help resolve problems, then it is the problem itself that rightfully attracts attention. Therefore, GIS might not be mentioned in any "key words" listing.[305]
- The vast majority of GIS output is only passed to decision-makers. It is unlikely to be published or it may simply be displayed in internal reports or in a few published papers.

Given the scale of needs for the resolution of space-based problems in fisheries or aquaculture, there is certainly every reason for this output dissemination problem to be resolved. It is mainly through the publicity on what is possible that other GIS workers will find out about what to them may be new creative possibilities.

[305] This problem is likely to be exacerbated in the future as GIS use becomes more mainstream, widespread and ubiquitous. Thus GIS will not be recorded in publication titles or in key words, and thus may not be easily detected by search engines.

It has already been noted that there is a growing list of fisheries-related publications covering GIS plus a limited number of other "publicity outlets". However, it is the Internet that offers the greatest scope for finding out about the potential of fisheries and/or aquaculture GIS. A large number of sites are conveying the data for use in GIS, and possibly a larger number of sites are publishing outputs from research and other GIS projects. Of special note is FAO's GISFish Web site, where there is the opportunity to submit case studies and to read about other fisheries or aquaculture GIS-related projects.[306] There are rapidly increasing chances to undertake interactive fisheries GIS mapping and analyses and this will become even more commonplace in the future. Ferreira *et al.* (2012) report that there are currently 1 800 items on YouTube (a video-sharing Web site) under the theme of "aquaculture", and that there are Web sites emerging (e.g. http://longline.co.uk/winshell) where interactive aquaculture-based simulations can be performed. Another spur to fisheries or aquaculture GIS work will be with the increased demands placed on GIS by the need for both marine spatial planning and for the EAA or EAF. Additionally, there is likely to be far greater output from various types of spatial and geostatistical models that will accrue in the effort to reverse environmental and ecosystems degradation. And finally this push for sustainability will see the worldwide appearance of various kinds of marine conservation zones, and these are certain to be sited with respect to decisions based upon the output achieved by GIS. It can be anticipated that exposure to GIS will rise quite markedly in the near future.

12.12 EXPENSES ASSOCIATED WITH FISHERIES AND/OR AQUACULTURE GIS

A recurring theme throughout the technical paper is that the implementation and pursuance of fisheries or aquaculture GIS might be an expensive applications area, and various reasons have been given as to why data costs are likely to be especially high, i.e. perhaps amounting to 80 percent of the operating costs for a GIS project. These high costs are mostly associated with vessel charter needs for any survey/sampling work. Other high data costs might be for satellite imagery plus the purchase of other off-the-shelf digital data sets. Apart from data costs, there may be initial high capital expenses for acquiring the system's hardware and software. There could then be an array of operating costs involved in rent, salaries, office overheads, equipment upgrading or replacement, training, consultancy fees plus other maintenance and support costs. For those operating in developing countries, these costs can be seen as prohibitive, certainly relative to other costs, to resources available and relative to what is obtained as an output for the monetary inputs made, i.e. GIS may not be perceived as a priority, certainly when measured on the basis of a cost–benefit analysis. It is more than likely that high costs have been a major reason for the slow growth in GIS in developing countries, especially when these costs are virtually all related to high "western" prices.[307] Without some financial investment in GIS, not only might there be an inability to undertake specific projects requiring spatial analyses, but also the country or region, in a much wider sense, will be lacking in the capacity to realize or understand the importance of the spatial dimension, or to have the personal or material infrastructure available to pursue this work. It is likely that only in those developing countries where fisheries and/or aquaculture play a prominent role in the economy will there be a positive incentive to implement GIS. Even in developed economies it might be hard to justify the inclusion of the necessary funding, especially for those areas or regions where fisheries or aquaculture might be a marginal activity.

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[306] ESRI also welcomes case studies on a range of applications (see www.esri.com/showcase/case-studies/index.html).

[307] Readers should be reminded that costs do not have to be high to initiate GIS work. If projects can be implemented at a small scale, then start-up costs are quite low; there are substantial quantities of spatially based freeware available; and many data sets can be freely obtained and remote sensing imagery costs have significantly reduced in recent years.

For countries, regions or organizations where finance plays a severe challenge to the adoption of decision-making technologies such as GIS, it is suggested that there are a number of approaches that can and have been successfully taken. It is always advisable to start with small, simple GIS-based projects and the costs implications here can be very low indeed, especially if existing hardware can be used. There is often the opportunity of sharing facilities with other computer users or GIS software users. A careful investigation should be made on the possibilities of using free and open source software (FOSS), especially since some of these consist of extensively developed GIS packages (Section 2.3.3). Use should be made of Internet search engines as a way of locating data needs. The editors of this technical paper are continually being surprised at exactly what data are "out there". For inland aquaculture GIS purposes, the national mapping authorities may be able to provide many data requirements, and what they cannot provide could perhaps be obtained from government offices or from universities or research establishments. Clearly, there is a need to be both imaginative and flexible in the search for inexpensive data (and other) inputs.

12.13 OBTAINING FUNDING

Despite the fact that fisheries is probably the world's second largest economic activity (after agriculture) in terms of the numbers directly or indirectly employed, and certainly the most widespread in terms of its spatial extent (and thus possible impact), the fact that the activity largely takes place within a small-scale or semi-subsistence economy means that it seldom is able to generate surplus income that can finance anything other than the most fundamental needs. This is also often the case in more developed economies. Therefore, funding for activities such as "fisheries GIS" must invariably come from government sources – though occasionally funding for GIS as applied to aquaculture investment might come from private sources. Much fisheries-related GIS work in developing areas must rely completely on donor support. During the current world financial crisis, then many funding sources have dried up completely, especially as many governments have cut back on state funding across all departments. Funding for activities where financial rates of return are difficult to verify is likely to suffer additional disadvantages. Therefore, any cost–benefit analyses on the value of GIS to fisheries or aquaculture are invariably difficult to substantiate. Similarly, funding is difficult to acquire if it is for purposes where the utility of the system is difficult to prove, i.e. success can be only a "subjective evaluation" – with output from different projects varying enormously in their utility. The challenge for the GIS enthusiast may be to convince their organization that GIS is very much more than a "luxury, peripheral add-on".

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. So, one challenge is to make certain that GIS-based output is appreciated and is well received at the workplace by all important sectors. 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. The possibilities for doing this must be high, especially as Chapter 11 has emphasized that assistance given to developing countries must be a response to a perceived "issue", and it is more than likely that part of the issue is rooted in spatial dis-equilibrium (see Section 1.1). At a time when spatial matters are coming to the fore through approaches such as marine spatial planning, EAA and EAF, it should be easier to convince budget holders within organizations of the paramount importance of spatial analyses. To this can be added the plight of so many of the world's fisheries (see Chapter 1), so it could be argued that any financial outlay on GIS is a very small outlay (price to pay) relative to the success that would be achieved if successful spatial allocation models could be developed. The marine space could then be sensibly partitioned so as to suit all stakeholders, thereby allowing for a range of aquatic activities to be sensibly and positively sustained over a longer planned period.

12.14 OVERCOMING INERTIA RELATING TO THE CULTURAL AMBIENCE

The less obvious challenges that are shown in Figure 12.1 as being "social or cultural" can now be reviewed. These challenges are really concerned with the "working milieu" of the country or area in which the GIS work is being undertaken, plus the "social or cultural ambience" that might prevail in either the country, or more specifically, the workplace. To some extent these challenges relate to levels of economic development, though importantly they also relate to the set of working norms that prevail at any level of development. Most of the challenges here are less direct than other challenges, though it is important to describe these since they may strongly pertain to individual areas or circumstances.

It is easy to believe that both the cultural ambience and working milieu may not be conducive to GIS adoption in some institutions and/or in some areas of the wider working world. In the first place, what are the chances of a "GIS champion" ever emerging from those groups or institutions that may be seen as inward looking, especially with respect to technological adoption? Even if they do emerge, it is reasonable to suppose that many "champions" of GIS will have a hard time selling the idea in establishments where outdated or entrenched attitudes may persist. This might especially be the case where little evidence of GIS success has ever been presented at the managerial level, so what reason might the institution wish to give for adopting GIS when it (the institution) has survived for possibly long periods of time without it? There may also be strong reticence by many who are participating in capture fisheries, to passing on geographic information to others about the locations and records of catches, i.e. as would be demanded from, for instance, the submission of fisheries electronic logbooks. Fishing locations are sometimes long-held secrets allied to understandable beliefs that livelihoods may be dependent upon keeping this knowledge a secret both from other fishers and from the authorities. In a surprisingly large number of areas, there is natural hostility to what scientists or politicians might do with data handed over to them. It appears that there is often a poor appreciation among international institutions and donor organizations as to the realities of working with sophisticated information technology systems in developing countries where these technologies may have little real relevance to the cultural setting.

There are a number of potential ways of overcoming challenges relating to inertia and the prevailing cultural and working ambience. It is important that some of these challenges can be tackled from either a "top-down" or "bottom-up" approach. In reality, a "top-down" approach means that measures are taken to introduce those who are in positions of control and management (within perhaps an institution or at senior government level) to the potential that GIS has to offer in solving problems relating to the spatially based challenges that may confront either fisheries or aquaculture in their administration (geographic) area. Any challenges might need to be resolved by those working for development agencies, donor institutions or through FAO, and can be instigated via workshops, seminars, demonstrations, etc. For a recent example of this approach, see FAO/Regional Commission for Fisheries (2011).

The "bottom-up" approach to overcoming challenges relating to prevailing cultures or to the working ambience involves a completely different strategy. Here, the idea is to "engineer" a demand for change from within the country or organization. This might be carried out through education schemes, probably at university level, through the dissemination of ideas about spatially based management, GIS, etc., via the Internet or other means of communication, or through middle-level employees approaching management with well-supported ideas on how progress can be expedited through technological innovation and thereby through GIS implementation (see Chapter 4). The adoption of ideas that may bolster either "top-down" or "bottom-up" approaches may be fostered by perceptions of the poor status of local fisheries and/or aquaculture, and by any consequent requirement to consider marine spatial planning and ecosystem approaches to both fisheries and aquaculture. Another approach that appears to have a strong potential for breaking down (or penetrating) social or cultural barriers is that of getting fishers or aquaculturists to work with scientists as a means of appreciating their often opposing perspectives on managing their activities. A good example of this is the Fisheries Science Partnership that was established by the Centre for Environment, Fisheries and Aquaculture Science (CEFAS, 2012) in the United Kingdom of Great Britain and Northern Ireland in 2003. The aim of this partnership is to build strong and productive relationships between scientists and the fishing industry, and to achieve this, an annual programme of cooperation has been successfully pursued over the last 11 years.[308] Other approaches at working in partnership with other marine sectors or competing resource users are becoming apparent as the trend towards designating sizable portions of the seas as marine conservation zones or protected areas is now accelerating (see Section 10.2.6).

12.15 GAINING SUPPORT AND ADVICE

This subject area of "gaining support and advice" has been listed in Figure 12.1 as an area where challenges to pursuing GIS for fisheries or aquaculture are likely to be encountered. This is certainly very much the case with many GIS workers, usually working in more isolated circumstances or perhaps in areas or institutions having limited resources, and who are finding it difficult to gain access to the support and advice that they should have. As this subject area has already received much coverage in Section 4.8 of this technical paper, there is little reason to discuss this further here. However, it is worth mentioning that support for GIS and/or remote sensing work will probably be much higher if these tools:

- can be integrated as essential elements of wider projects, e.g. climate change implications for fisheries and aquaculture; strategic planning for offshore mariculture development, etc.;
- focus on issues/themes that illustrate the many benefits that the use of these tools can provide to support problem solving and decision-making, e.g. see the case studies presented in Chapters 8, 9 and 10 of this publication;
- are designed to match the needs, interests, finances and capacities of the target users or stakeholders.

12.16 TRANSCENDING POLITICAL OR INTERNATIONAL BOUNDARIES

It is clear that all of the world's political borders will have been established without regard to factors that control the distribution of fishes or the ecosystems in which they live. Fish species may each have different but complex life cycles that often involve stages where they either undertake extensive migrations or where they inhabit perhaps spawning, nursery or adult areas, each of which may conform to different types of ecosystem. By contrast, most maritime nations will have jurisdictional boundaries (exclusive economic zones) that either extend for 200 nautical miles out to sea or that end along agreed median boundaries between neighbouring countries in areas where the extent of the marine space is limited.[309] This duality of marine space division (natural ecosystems versus political jurisdiction) may lead to sources of challenge with regard to resource management, and especially where the more mobile marine species are concerned. It is clear that this dichotomy is likely to have important implications for

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[308] Centre for Environment, Fisheries and Aquaculture Science (CEFAS): www.cefas.defra.gov.uk/our-services/fisheries-management fisheries-science-partnership.aspx.

[309] There are also areas known as the "high seas" that are located more than 200 miles from the coast of the nearest territorial claimant nations. In these areas, 17 regional fisheries management organizations control the fish resources.

any GIS work in terms of setting spatial boundaries for analyses, for acquiring funds, for the management of projects, for the content of projects, and for data resourcing.

Many attempts have been made to achieve regional fisheries cooperation between neighbouring counties or within groups of neighbouring countries. For instance, in waters of the European Union, there is the Common Fisheries Policy that sets out the fishery rules for all 27 European Union member countries, and in the Caribbean the fisheries management for 38 island states is under the control of the Caribbean Regional Fisheries Mechanism (CRFM). However, to a substantial degree, these attempts at regional cooperation have been unsuccessful, and this has required constant initiatives to try to improve the situation. As with some of the other challenges, it is likely that the instigation of both marine spatial planning and EAF and/or EAA considerations will have the effect of "concentrating minds", and it is to be hoped that far greater regional cooperation will ensue in the future. Without strong cooperation in many geographic areas, then ideal applications for most GIS projects are unlikely to ensue.

12.17 DEVELOPING GEOGRAPHIC COGNITION AND SPATIAL AWARENESS

A final area of challenges to GIS work on fisheries or aquaculture concerns geographic cognition and spatial awareness. Basically, what this is referring to is an appreciation of geographical thinking and perception. Readers may not appreciate exactly what this means, but it is almost certain that readers will consider themselves as either good or bad at "reading maps". Map reading essentially entails many of the basic skills necessary for geographic cognition. Other aptitudes exhibited by persons having good geographic cognition include:

- Able to identify and prioritize which are the spatially based production functions that may control fisheries and/or aquaculture processes.
- Ability to understand which combination of production functions can best lead to successful analyses.
- Able to identify and explain different zonations among different activities.
- A grasp of what locations are suitable for the establishing of various kinds of activities.
- A sound "atlas" type knowledge of the local area and of main countries or continents.
- Being able to quickly grasp or to visually discriminate the implications shown by any mapped distributions.
- Knowing the best types of analyses that could be applied in spatial situations.
- A recognition of spatial patterns such as clustering, adjacency, ubiquity, contiguity, etc.
- An awareness of any patterns, surface trends and zonal forms across a real or mapped area.

The ability to recognize many of these cognitive geographic ideas provides an extremely valuable insight into most GIS work. It allows the GIS worker to have a feel for the sort of work or project that can best be undertaken, as well as allowing the final output from the GIS to be evaluated with respect to the validity of the work, i.e. is this output believable?, and what the spatial implications might be for any management decisions, e.g. this mapped distribution tells me that x, y and z need doing. But perhaps a more widespread problem concerns the lack of appreciation that many (perhaps most) of the problems concerning either fisheries or aquaculture may be rooted in spatial differentiation; thus, fisheries managers and others may often not appreciate the importance of the geographic perspective, i.e. the paramount importance of being able to "assemble" the required balance of production inputs at any chosen location. In fact, this is a problem that goes much further than the fisheries or aquaculture spheres. For almost every productive pursuit on this planet, there are better or worse locations in which to be productively engaged. Location is usually the key to business success. Optimum locations provide the best aggregate combination of those production functions that are essential to business success. Moving away from optimum location centres means that more and more problems are encountered with respect to the factors of production, and this reasoning can apply to actual human production activities, e.g. aquaculture, or to resource gathering activities such as fishing.

An area that has received little attention is that of securing awareness of the importance of spatially based planning (and therefore GIS) among higher levels of management or governance. Thus, it appears that the underlying importance of location and spatial association is a subject that is little appreciated at strategic planning levels. It is likely that workshops, seminars, reports and other meetings devote a good deal of attention to a range of thematic areas and issues concerning fisheries or aquaculture, but it is thought that these are rarely posited within a spatial context. So there is a need to couch themes and issues within this spatial context and to highlight the fact that GIS is available as a very versatile tool for use in analyses, descriptions and explanations of probable imbalances in the relationships between production functions (see Section 3.2). An appreciation of the importance of spatial considerations is clearly beginning to be recognized as witnessed by the emergence of EAA and EAF and by the perceived necessity for marine spatial planning at both regional and international levels (see Section 12.16 above). Aguilar-Manjarrez, Kapetsky and Soto (2010) give further observations on capacity-building measures that need adopting in order to improve spatial awareness (and thus GIS use) at various levels of management and governance.

Although it is doubtful that thorough geographic cognition can be taught, obviously the aim of school geography lessons was to instil some of these perceptual traits into the students. If readers find that these traits are almost completely lacking, then it is unlikely that they will ever succeed as GIS workers. However, if they do have some (or a degree) of the traits exemplified, then it is always possible to enhance geographic capabilities through reading more general geography texts, journals or better-quality magazines, or even watching many of the natural world or geographically based programmes on television. With respect to a lack of awareness of the fact that the failure of so many production activities is due to spatial dis-equilibrium in the factors of production, then it is the job of those people already working in GIS to spread this message via publications such as this, and via the many resource, guidance, support and training means described in Chapter 4. Perhaps it is fortunate that geospatial data collection devices based on integrated global positioning systems (GPS) are proliferating and that a GeoWeb environment is emerging on the Internet allowing for the integration and sharing of geographical information and data on a scale that might have been unimagined just a decade ago. So, without realizing it, Google Earth, cell phones, GPS-based navigation systems and iPhone and iPad mapping facilities are all helping to create and enhance geographical cognition and spatial awareness.

13. Conclusions

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J. Aguilar-Manjarrez (FAO Aquaculture Branch, Rome, Italy)

FAO's flagship fisheries publication "*State of the World Fisheries and Aquaculture*" (FAO, 2010b) addresses a range of contributing factors giving rise to the present global situation in fisheries and aquaculture. In its foreword, the publication highlights the encouragement of "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." To a great extent, it is these factors that are addressed by this publication. Thus, this technical paper has covered a range of material in the following subject areas:

- fisheries and aquaculture (in their broadest sense);
- the wider marine environment and ecosystems;
- the range of hardware and software that in combination constitutes the basis upon which spatial technologies function;
- the requisite digital data allowing the systems to function;
- GIS and remote sensing methodologies;
- and a range of parallel developments that are integral to the successful operation of GIS.

Within the context of these integrated fields, it has also been important to discuss how their integration occurs, how the GIS and remote sensing systems might best be initiated and implemented, the personnel that might be required, issues and challenges that might arise, where operational advice could be sought, as well as giving a large number of examples and case studies of the application of GIS and remote sensing to aquaculture, inland fisheries and marine fisheries. Additionally, it has been necessary to cover this material at a conceptual level allowing newcomers to the subject areas to readily comprehend what is being explained.

The predecessors of this technical paper (Meaden and Kapetsky, 1991; Meaden and Do Chi, 1996), published nearly two decades ago, arose from a perceived need to promote the new spatial technologies of remote sensing and GIS that were then beginning to "take-off", i.e. as a means to both promoting better management and to enable spatially based research to move forward. At that time, it was already clear that fisheries had reached a plateau with respect to marine landings, and that aquaculture might provide an alternative means of providing for the increasing demand for high-quality fish protein. Over these last two decades, both GIS and remote sensing have indeed contributed towards improvements in fisheries and aquaculture, with there being a wide range of "decision-related" output that could not otherwise have been obtained. However, during this period, it is also true to say that the overall situation with respect to the aquatic environments in which fish are produced has not improved.

In Chapter 1 the serious situation prevailing with respect to fisheries was outlined, but given the fact that the ecosystem approach to aquaculture (EAA) and the ecosystem approach to fisheries (EAF) strategies are now prevailing, it is necessary to think more broadly about the spatially based challenges to optimizing productivity from aquatic resources. Thus, as well as problems facing fisheries directly, the marine environment must contend with factors such as the imposition of additional rules and regulations, various kinds of pollution, disturbances along the coastal zone, disputes over resources, rapid changes in the natural environment, continuing human developments in the marine space and species invasions. A way of realizing these challenges facing fisheries and aquaculture environments is seen in the recently perceived need for marine spatial planning. This planning can be exemplified by a new European Union document (European Commission, 2012; p. 13) noting that "The challenges and potential of the European seas, coasts and oceans are manifold and complex. Economic sectors active on or near the seas are interacting with other sectors in complex value chains. The list of sectors relevant from a maritime perspective is near endless. As a start, we can distinguish six maritime functions, each of them with a broad socio-economic value:

1. Maritime trade and transport;
2. Food, nutrition, health and ecosystems services;
3. Energy and raw materials;
4. Living, working and leisure in coastal regions and at sea;
5. Coastal protection and nature development;
6. Maritime monitoring and surveillance.

In many locations, it is likely that all future approaches to managing marine areas will be those that are required to integrate most or all of these functions, certainly in areas where conflicts are starting to emerge. A further recent document illustrating the large array of consideration in marine spatial planning is the 'Atlas of maritime spatial planning' covering all the Kingdom of Spain's territorial waters (Suárez-de Vivero, 2011). This >300 page atlas portrays, at relevant scales, all the ways in which Spanish marine waters can be subdivided for different jurisdictional, physical, biological, and management purposes. There is no doubt that GIS will be the technological basis on which this marine spatial management will best function.

Given this broadening approach to fisheries and aquaculture management, at various places in this technical paper attention has been drawn to the facts that: (i) one of the most promising tools for analysing these spatial problems is GIS; and (ii) the great majority of the challenges faced by the marine, inland and other aquatic domains have a strong spatial component. A major proof of these claims lies in the extraordinary growth in the whole field of GIS[310], i.e. to the extent that it is now successfully deployed, and is thriving, across a wide range of applications areas. Chapters 8, 9 and 10 described in detail some of the means by which GIS are being successfully used to meet a variety of challenges faced by aquaculture, inland fisheries and marine fisheries and, as demonstrated in Chapter 11, the breadth of spatially based themes or issues that are now in need of urgent attention, or are presently "emerging", has grown significantly, a trend that is likely to continue. However, although published work using GIS and remote sensing can demonstrate the utility of these tools, for the success and expansion of fisheries and aquaculture GIS-related work, it is essential that project results are disseminated to decision-makers and stakeholders in ways that are easily understood. For these reasons the reader can be confident that GIS will play a significant future part in addressing spatial issues.

GIS usage is concentrated within North America, particularly in the United States of America. Evidence has shown that an overwhelming number of GIS studies are carried out in this one country, and that the reasons for this might lie in the inherent advantages that this country offers. To an extent this is true. The United States of America undoubtedly has a wealth of resources with which to address research projects having high inputs of advanced technology-based methods, including people with the required expertise. This country is also where much of the research and development into GIS, remote sensing and the parallel technologies is carried out and is implemented. Other reasons why the United States of America dominance occurs are due to the number of conferences that take place there, the opportunities to publish the results of research studies, and the consequent ease of dissemination of knowledge about GIS.

[310] The ARC Advisory Group forecast that sales of GIS software will increase by 50 percent between 2010 and 2015 (www.arcweb.compress-center/2009-09-18/geospatial-information-systems-market-to-grow-50-over-next-five-years--1.aspx).

There is evidence, however, that other countries are now beginning to make rapid progress with respect to the application of spatial technologies to fisheries and/or aquaculture. This is especially true regarding the applications in the field of aquaculture. As has been mentioned before, one reason why aquaculture applications may be more widespread is the fact that this activity is often seen as another terrestrial farm-related activity, thus allowing terrestrial-type GIS analyses to be performed. Countries that are now emerging as newer GIS users are mostly the rapidly developing countries, especially those in east and south Asia. It is expected that a further significant expansion of GIS projects in these rapidly developing countries will occur mainly as a result of:

- the need to utilize GIS for EAA and EAF based projects, especially to confront problems arising from environmental degradation;
- an increasing awareness of the importance of the spatial perspective with respect to problem solving;
- the need for marine spatial planning in heavily populated coastal and marine environments;
- the increasing competition for freshwater in all food production sectors that supply high-demand products;[311]
- the need to ensure better food security for increasing populations, especially in areas where marine fish output is unlikely to grow;
- a dissemination process whereby information on the success of GIS is rapidly spread;
- the rapidly declining prices for GIS hardware, data gathering devices and remote sensing products;
- many Asian countries having strong cohorts of their population who excel in their interest and use of digital technologies, and there is an existing capacity to adopt GIS and other spatial tools.

Within those developing countries where economic growth is typically slower, there are indications that GIS use is now being taken up both for fisheries and aquaculture development.[312] For instance, some African countries are already making good use of GIS. The case study by Asmah (2008) in Chapter 8 illustrates the use of GIS to assess the "development of potential and financial viability of fish farming in the Republic of Ghana", and according to R. Asmah (personal communication, 2012), plans are currently under way in the Republic of Ghana to make practical use of GIS tools that are available for aquaculture development[313]. In the Federal Republic of Nigeria, a national aquaculture strategy was published showing where GIS has been used to identify high potential aquaculture zones (Federal Ministry of Agriculture and Water Resources, 2008). However, much of the fisheries and aquaculture GIS work undertaken in developing countries is not being published,[314] and thus does not appear in FAO's Aquatic Sciences and Fisheries Abstracts (ASFA) database. Given this emerging awareness on the usefulness of GIS, it is essential that the required capacity-building measures are in put in place allowing for easy and successful adoption of the range of expertise that GIS infrastructure require. Aguilar-Manjarrez, Kapetsky and Soto (2010) provide detailed information on additional considerations that might be deployed in order to enhance the capacity for pursuing GIS-based work in the

[311] Freshwater availability on a per capita basis is rapidly dwindling, and in many cases, so is its quality.

[312] See, for instance, articles by Aguilar-Manjarrez (2011) and Crespi, *et al.*(2011) in the FAO Aquaculture Newsletter, No. 48, December 2011 (www.fao.org/docrep/015/i2647e/i2647e.pdf). During the training courses reported by Aguilar-Manjarrez (2011) for the Network of Aquaculture of the Americas and by Crespi *et al.* (2011) for the Aquaculture Network for Africa, the participants informed that the Member Countries of these networks are either already using GIS or planning to use GIS for the development and management of aquaculture.

[313] See also Mensah (undated), who reports on the need for, and a justification of, the implementation of remote sensing, GIS and an aquaculture spatial database in the Republic of Ghana to be hosted by the Fisheries Commission of the Ministry of Food and Agriculture.

[314] Publications may also not be in English and these have less chance of getting international recognition.

emerging economies. It will be increasingly important that the use of GIS can be made in conjunction with multidisciplinary teams whose expertise includes knowledge of EAF and EAA. This technical paper is a significant contribution to these needs.

For the least developed or more remote regions of the world, it may be some time before the widespread use of spatially based technologies for fisheries and aquaculture development and management is achieved. Thus, except in a few core urban locations, these areas are unlikely to have the infrastructure allowing the essential technologies to be available; there will be little access to necessary information needs; data will be scarce or, indeed, absent; and many areas will in any case be inhospitable and sparsely populated. Therefore, for the most part, there will be little necessity for problem-based spatial analyses in these areas.

For GIS to be successful, under most circumstances it is essential that the whole system has been carefully and correctly implemented; indeed, this is why the technical paper devotes a considerable amount of detail to GIS implementation in Chapter 4. In this chapter, guidance and advice is given on a step-by-step basis to all the major facets that must be considered to enable GIS operational success. Chapter 12 described a wide range of challenges and attempted to provide useful clues as to how the challenges might be overcome. To this end, and on a wider note, it is relevant to conclude this technical paper with a table that provides main answers to the questions "What do I need to consider in order to get my fisheries or aquaculture projects started?", or alternatively, "What is the way forward to successful GIS work?" Table 13.1 offers important clues not only to tasks that need to be thought about but also indications of the "activators" who might best accomplish these tasks.[315] Tasks have been differentiated between "Establishing the existing situation" and "Establishing an enabling capability". Varying situations in different workplaces mean that tasks cannot be exactly ordered or prioritized.

Each of the questions posed in Table 13.1 is likely to initiate a whole sequence of further questioning and research, some of which might involve external help and perhaps weeks of investigation. This technical paper clearly indicates where additional support can be obtained. The dissemination of appropriate information mentioned in the table might be through various media, such as the Internet, leaflets, workshops, conferences, training manuals, and this dissemination should be appropriately pursued at more senior levels among not only those working directly in fisheries and aquaculture but also among workers in associated activities, such as other stakeholders. Wherever GIS or remote sensing methods are to be deployed, it is essential to remember that these applications can be designed to work at a wide variety of scales. "Scales" can best be viewed in two main contexts:

- Functional or operational – which relates to the financial and personnel inputs into the whole system, or in terms of the volume of, or degree of sophistication of, the outputs achieved by the system. A valid functional GIS or remote sensing output can be obtained by one person working in comparative isolation at a small single-site workstation, while at an intermediate scale there can be institutions or consultancy companies working probably in a single "cluster" of workers, and at a large scale a group of multidisciplinary experts will probably be achieving high levels of sophisticated output at a national or international operational level.

  This huge range in system operating capabilities represents a significant bonus for GIS, as does the easy ability to upgrade the systems whenever the means or needs to do so are available. Therefore, there is no need for large expenditures or for sophisticated spatial work to make good use of GIS or remote

[315] It is likely that management will be involved in almost all activities, but the amount of involvement will vary considerably according to local circumstances.

TABLE 13.1
Suggested main tasks for taking fisheries or aquaculture GIS work forward

Tasks	Activators		
	Managers	**Operative**	**External**
Establishing the existing situation			
How much knowledge is there about GIS use or its potential in my workplace or country?	X		X
What is the existing GIS capability in my country?	X		X
Is GIS being used for existing fisheries or aquaculture work, and is this information being published?	X		
What type of spatial problems might exist in fisheries or aquaculture in my country or in any local areas?	X		
What back-up resources are available locally to support GIS work?	X	X	
What is the spatial distribution (or inventory) of support facilities for fisheries or aquaculture, e.g. fishing ports, processing plants, farming ponds, transporters, main markets, etc.?	X	X	
What are the possibilities for collaborative GIS projects with other regions, or other users of the marine or aquatic space?	X		
What knowledge exists on developing trends in fisheries or aquaculture such as EAF, EAA, and marine spatial planning?	X	X	
Establishing an enabling situation			
Disseminate information on the importance of optimizing locations for aquaculture facilities.	X		X
Disseminate information on the fact that "spatial disequilibrium" lays at the root of most problems confronting aquaculture and/or fisheries, i.e. the environment is often out of balance.	X		X
Disseminate information on the value of GIS and other spatial technologies and tools.	X		X
Disseminate information on important emerging issues such as EAA, EAF and marine spatial planning.	X		X
Investigate and then implement the appropriate capacity to operate GIS at selected sites, including hardware, software, personnel, back-up and support, etc.	X		X
Ensure that at each selected GIS site someone is there to "champion" the GIS work (see Chapter 4).	X	X	
Ensure access to appropriate GIS-related training, experience, knowledge, information, conferences, workshops, etc.	X		
Put into place rigorous data collection, storing, security, and updating methodologies.	X	X	
Provide or develop examples or case studies of successful GIS projects in fisheries or aquaculture and make them available to share (perhaps through FAO's GISFish).		X	X
With respect to fisheries or aquaculture, identify spatially related problems and prioritize GIS-based projects.	X	X	
Establish collaborating networks in terms of communications, but more importantly of physical working (effort sharing).	X	X	
Investigate opportunities for any cost reductions via the use of freeware GIS and the sharing of expertise with other departments.	X	X	
Develop time line or workflow patterns for all GIS project work.	X	X	
Have in place multidisciplinary back-up teams who can advise, for instance, on matters not directly related to fisheries or aquaculture, such as the social and economic issues implicit in EAA and EAF.	X		

Note: External activators are likely to be GIS consultants, FAO Web sites such as GISFish, or a range of other relevant Web sites.

sensing tools, and the work undertaken can certainly involve considerations relating to both EAF and EAA and other important emerging areas.[316]
- The geographic area covered by a project – which could range from a world scale to a highly localized scale. At a large scale, the work of Aguilar-Manjarrez and Nath (1998) shows the use of GIS to illustrate the large potential that exists for inland aquaculture in most parts of Africa, and Kapetsky and Aguilar-Manjarrez (2007) have shown the potential for mariculture in most countries having access to marine waters. At the other extreme, small-scale GIS-based work in this technical paper has illustrated studies that were focused on a small reach within a single stream (Le Pichon *et al.*, 2006), or on a small marine area where various management problems needed resolving (Purroy Albet, 2010). The ability of utilizing GIS and remote sensing across vastly different spatial domains is enormously useful in terms of data resource inputs to GIS, in terms of geographic cognition, and as a means of initiating collaborative working with neighbouring regions or countries.

In summary, GIS and remote sensing have much to offer in the fisheries and aquaculture fields. The production of fish demanded in a more affluent world, whose population is increasing by 80 million per year, will be an accelerating challenge to meet. Meeting this challenge will require radical improvements in fisheries and aquaculture management, and these improvements are beginning to be adopted through approaches that involve spatial planning and an ecosystem approach to both fisheries and aquaculture. Given these facts, it is easy to envisage that GIS in developed world scenarios will, in the not too distant future, be linked to a suite of fisheries and/or aquaculture management tools, whose principle outputs will be easily comprehended by decision-makers because the outputs will frequently be in graphical, tabular and mapping formats. Though GIS and remote sensing technologies are mainly associated with developed countries, this paper has shown that the situation is rapidly changing. Because GIS is extremely flexible with respect to its degree of sophistication, developing countries will have numerous options to benefit from systems that are designed to match their needs or capacities. It is, therefore, incumbent upon the GIS users to make certain that this unique technology is promoted with considerable robustness and enthusiasm.

[316] It can be envisaged that relatively suitable GIS-based work would be addressing questions, such as "Where can aquaculture facilities best function?"; "Where is fish protein most urgently needed?"; "How accessible is expertise or extension facilities?"; "Where might processing or markets be located?"

14. Glossary

This glossary presents the definitions for some of the main terms used in this publication. Additional definitions of terms can be found in the sources listed at the end of this glossary.

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Attribute. An attribute is a set or collection of data that describe the characteristics of real world entities or conditions. Attribute data are usually alphanumeric. Small amounts of attribute data are frequently used to describe the graphic representation of an entity on a map as a label, e.g., a polygon label. Large amounts of attribute data are usually maintained as separate attribute data sets, related to a map by names or codes.

Bayesian network. Probabilistic graphical model (a type of statistical model). A Bayesian network can incorporate factors of a qualitative or probabilistic nature. For example, factors that influence farmers' perceptions about a particular aquaculture technology. The outcome of the Bayesian modelling would be a reading of the probability of farmers' positive perception of the target technology, which indicates the likelihood that they will adopt it.

Cartesian coordinates. A two dimensional, planar coordinate system in which x measures horizontal distance and y measures vertical distance. Each point on the plane is defined by an x,y coordinate. Relative measures of distance, area and direction are constant throughout the Cartesian coordinate plane.

Cell. The smallest unit of information in raster data, usually square in shape. In a map or GIS data set, each cell represents a portion of the earth, such as a square meter or square mile, and usually has an attribute value associated with it, such as soil type or vegetation class.

Classification. When image pixels are the same colour, or nearly the same colour, an image "classification" computer program can recognize this and group such pixels together. Such a grouping is called a "class" and the process of doing the grouping is called "classification". The remote sensing researcher then has the challenge of identifying exactly what each "class" represents in the real environment.

Contiguity analysis. Concerned with adjacency relationships between any given polygon and its neighbors. Typically this involves summarizing and relating the attributes of neighboring polygons to the polygon being examined.

Coordinate systems. A particular kind of reference frame or system, such as plane rectangular coordinates or spherical coordinates, which use linear or angular quantities to designate the position of points within that particular reference frame or system.

Cost-benefit analysis. Assessment of the direct or indirect economic and social costs and benefits of a proposed project for the purpose of project or programme selection. The cost-benefit ratio is determined by dividing the projected benefits of the programme by the projected costs. A programme having a high benefit-cost ratio may take priority over others with lower ratios.

Data transformation. Converting the coordinates of a map or an image from one system to another, typically by shifting, rotating, scaling, skewing, or projecting them. Also known as rectification, the conversion process requires resampling of values.

Database management system (DBMS). Software that allows a systematic approach to maintaining, accessing and manipulating database files. A DBMS may consist of a single program or a collection of task-specific programs.

Digital elevation models (DEMs). DEMs are data files that contain the elevation of the terrain over a specified area, usually at a fixed grid interval over the surface of the earth. The intervals between each of the grid points will always be referenced to some geographical coordinate system. This is usually either latitude-longitude or UTM (Universal Transverse Mercator) coordinate systems.

Digital orthophotograph. This is a "scale corrected" aerial image, depicting ground features in their exact ground positions, in which distortion caused by camera and flight characteristics and relief displacement have been removed using photogrammetric techniques.

Disequilibrium. Also referred to in this technical paper as spatial disequilibrium. Natural or man-made integrated features or processes may become out of balance such that their prevailing local distribution leads to a break-down or collapse of the eco-system, i.e. such that a system would then be functioning in an unsustainable manner.

Electromagnetic spectrum. The range of energy which contains parts or "bands" such as the visible, infrared, ultraviolet, microwave (radar), gamma ray, x-ray, radio, and which travels at the speed of light. Different parts of the electromagnetic spectrum have different wavelengths and frequencies.

Fuzzy classification. Any method for classifying data that allows attributes to apply to objects by membership values, so that an object may be considered a partial member of a class. Class membership is usually defined on a continuous scale from zero to one, where zero is non membership and one is full membership. Fuzzy classification may also be applied to geographic objects themselves, so that an object's boundary is treated as a gradated area rather than an exact line. In GIS, fuzzy classification has been used in the analysis of soil, vegetation, and other phenomena that tend to change gradually in their physical composition and for which attributes are often partly qualitative in nature.

Generalization. The process of selecting and representing information on a map in a way that adapts to the scale of the display medium of the map. So, cartographers must decide and then adjust the content within their maps to create a suitable and useful map that conveys geospatial information within their representation of the world. In making these decisions maps are simplifying the real world, with only the more important elements being shown.

Geodatabase. A database or file structure used primarily to store, query, and manipulate spatial data. Geodatabases store geometry, a spatial reference system, attributes, and behavioral rules for data. Various types of geographic data sets can be collected within a geodatabase, including feature classes, attribute tables, raster data sets, network data sets, topologies, and many others. Geodatabases can be stored in IBM DB2, IBM Informix, Oracle, Microsoft Access, Microsoft SQL Server, and PostgreSQL relational database management systems, or in a system of files, such as a file geodatabase.

Geographic information systems (GIS). An integrated collection of computer hardware, software and data used to view and manage information about geographic places, analyse spatial relationships, and model spatial processes. A GIS provides a framework for gathering and organizing spatial data and related information so that it can be displayed and analysed.

Georeference system. An (x,y) or (x,y,z) coordinate system that locates points on the surface of the earth as a reference to points on a map. Systems include latitude-longitude, Universal Transverse Mercator, and State Plane Coordinates.

Geostatistics. The branch of applied statistics that focuses on mathematical description and analysis of spatially-based data.

Geotechnology. The application of scientific methods and engineering techniques to the exploitation and utilization of natural resources (such as mineral resources). GIS requires access to techniques and geo-equipment such as GPS, remote sensing, computer associated hardware, data loggers, mobile communications, etc. These technologies may be referred to as "parallel technologies" (to GIS).

Global positioning system (GPS). A system of radio-emitting and -receiving satellites used for determining positions on the earth. The orbiting satellites transmit signals that allow a GPS receiver anywhere on earth to calculate its own location through trilateration. Developed and operated by the U.S. Department of Defense, the system is used in navigation, mapping, surveying, and other applications in which precise positioning is necessary.

Ground truthing. Remote sensing analysts must be sure that their image analysis is accurate. This is done in the field where analysts go out to the actual places shown in the images and confirm that what they think they see on the image is actually true.

Image processing. Encompasses all the various operations which can be applied to photographic or image data. These include, but are not limited to, image compression, image restoration, image enhancement, preprocessing, quantization, spatial filtering and other image pattern recognition techniques.

Keyhole markup language. XML grammar and file format for modelling and storing geographic features such as points, lines, images, polygons, and models for display in Google Earth. A KML file is processed by Google Earth in a similar way that HTML and XML files are processed by web browsers. Like HTML, KML has a tag-based structure with names and attributes used for specific display purposes. Thus, Google Earth acts as a browser of KML files.

Landsat. A series of US polar orbiting satellites, first launched in 1972 by NASA (National Aeronautics and Space Administration), which carry both the multispectral scanner and thematic mapper sensors.

Landscape ecology. The science of studying and improving relationships between ecological processes in the environment and particular ecosystems. This is done within a variety of landscape scales, development spatial patterns, and organizational levels of research and policy.

Map projection. A method by which the curved surface of the earth is portrayed on a flat surface. This generally requires a systematic mathematical transformation of the earth's graticule of lines of longitude and latitude onto a plane. Every map projection distorts distance, area, shape, direction, or some combination thereof.

Metadata. Information that describes the content, quality, condition, origin, and other characteristics of data or other pieces of information. Metadata for spatial data may describe and document its subject matter; how, when, where, and by whom the data was collected; availability and distribution information; its projection, scale, resolution, and accuracy; and its reliability with regard to some standard. Metadata consists of properties and documentation. Properties are derived from the data source (for example, the coordinate system and projection of the data), while documentation is entered by a person (for example, keywords used to describe the data).

Modelling. The representation of a system by a mathematical analogue, obeying certain specified conditions, whose behaviour is used to simulate and interpret a physical or biological system.

Multi-criteria evaluation (MCE). Decision support tool for Multi-Criteria Evaluation. A decision is a choice between alternatives (such as alternative actions, land allocations, etc.). The basis for a decision is known as a criterion. In a Multi-Criteria Evaluation, an attempt is made to combine a set of criteria to achieve a single composite basis for a decision according to a specific objective. For example, a decision may need to be made about what areas are the most suitable for industrial development. Criteria might include proximity to roads, slope gradient, exclusion of reserved lands, and so on. Through a Multi-Criteria Evaluation, these criteria images representing suitability may be combined to form a single suitability map from which the final choice will be made.

Network analysis. Analytical techniques concerned with the relationships between locations on a network, such as the calculation of optimal routes through road networks, capacities of network systems, best location for facilities along networks, etc.

Pixel (picture element). In a digitized image, the area on the ground represented by each digital number. The spatial variable defines the size (resolution) of the cell, the spectral variable defines the intensity of the spectral response.

Raster. A spatial data model that defines space as an array of equally sized cells arranged in rows and columns, and composed of single or multiple bands. Each cell contains an attribute value and location coordinates. Unlike a vector structure, which stores coordinates explicitly, raster coordinates are contained in the ordering of the matrix. Groups of cells that share the same value represent the same type of geographic feature.

Remote sensing. Collecting and interpreting information about the environment and the surface of the earth from a distance, primarily by sensing radiation that is naturally emitted or reflected by the earth's surface or from the atmosphere, or by sensing signals transmitted from a device and reflected back to it. Examples of remote-sensing methods include aerial photography, radar, and satellite imaging.

Resolution. The detail with which a map depicts the location and shape of geographic features. The larger the map scale, the higher the possible resolution. As scale decreases, resolution diminishes. The dimensions represented by each cell or pixel in a raster.

Scale. The ratio or relationship between a distance or area on a map and the corresponding distance or area on the ground, commonly expressed as a fraction or ratio. A map scale of 1/100 000 or 1:100 000 means that one unit of measure on the map equals 100 000 of the same unit on the earth.

Shapefile. A vector data storage format for storing the location, shape, and attributes of geographic features. A shapefile is stored in a set of related files and contains one feature class.

Spatial domain. The geographic concept of area that usually pertains to the two dimensional (x, y) extent of an area or to the extent of a particular surface feature.

Structured query language (SQL). A Syntax for defining and manipulating data from a relational database. Developed by IBM in 1970 s, it has become an industry standard for query languages in most relational database management systems.

System's (or computer) architecture. Refers to the configuration of hardware used that allows for the success of the system (in this case GIS). The architecture can vary from the very basic, which is essentially just the GIS software loaded to a computer that is also connected to a screen and a printer (called a Personal Area Network), to a complex integrated system of information technologies that may be world-wide and which will definitely include the Internet (called a Wide Area Network).

Systeme Probatoire d'Observation de la Terre (SPOT). A French multispectral satellite with pointable sensors first operational in 1986. There are two kinds of SPOT images - one with 10 meter ground resolution in a single panchromatic spectral region; the other with 20 meter resolution in the three spectral regions used for color-infrared maps. SPOT satellites may be pointed at an angle off-axis or off-nadir to collect forward and rearward images, a technique that yields stereoscopic image pairs from which accurate elevation rasters can be computed.

Topographic mapping. A topographic map is a two-dimensional representation of a three-dimensional land surface. Thus it usually shows relief and man-made features of a portion of a land surface distinguished by portrayal of position, relation, size, shape, and elevation of the features. Topographic maps are typically produced by the national mapping agencies of the country represented by the map.

Topology or vector topology. A description of the relationship between node, line, and polygon elements in a vector object.

Triangulated irregular networks (TINs). A TIN is a digital data structure used in a GIS for the representation of a surface. A TIN is a vector-based representation of the physical land surface or sea bottom, made up of irregularly distributed nodes and lines with three-dimensional coordinates (x, y, and z) that are arranged in a network of non-overlapping triangles.

Vector. A coordinate-based data model that represents geographic features as points, lines, and polygons. Each point feature is represented as a single coordinate pair, while line and polygon features are represented as ordered lists of vertices. Attributes are associated with each vector feature, as opposed to a raster data model, which associates attributes with grid cells.

Visualization. The act or process of interpreting in visual terms. The usage in this technical paper refers to the process of perceiving data or information that has been presented in a mapped format.

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Code of conduct for responsible fisheries. FAO-formulated code, which sets out principles and international standards of behaviour for responsible aquaculture and fisheries practices with a view to ensuring the effective conservation, management and development of living aquatic resources, with due respect for the ecosystem and biodiversity.

Complementary conservation. This is a means of conservation in which more than one approach will be taken towards trying to ensure the sustainability of a species. For instance, because a particular fish species has different environmental needs for spawning, feeding and for resting, it will be necessary that a range of in-stream habitats are conserved in order that the species can survive.

Economic surface. The division of an area into cells or units according to the value of any specified resource that can be supplied from that unit area.

Ecosystem. An organizational unit consisting of an aggregation of plants, animals (including humans) and micro-organisms, along with the non-living components of the environment.

Ecosystem approach to aquaculture (EAA). A strategy for the integration of the activity within the wider ecosystem such that it promotes sustainable development, equity, and resilience of interlinked social-ecological systems.

Ecosystem approach to fisheries (EAF). An approach to fisheries management and development that strives to balance diverse societal objectives, by taking into account the knowledge and uncertainties about biotic, abiotic and human components of ecosystems and their interactions and applying an integrated approach to fisheries within ecologically meaningful boundaries. The purpose of EAF is to plan, develop and manage fisheries in a manner that addresses the multiple needs and desires of societies, without jeopardizing the options for future generations to benefit from the full range of goods and services provided by marine ecosystems.

Essential fish habitats (EFH). Areas designated as EFHs contain habitat essential to the long-term survival and health of a fishery. Thus, certain properties of the water column such as temperature, nutrients, or salinity are essential to various species, but other species may be more dependent on certain bottom types such as sandy or rocky bottoms, vegetation such as seagrasses or kelp, or structurally complex coral or oyster reefs.

Gap analysis. An assessment of the protection status of biodiversity in a specified region which looks for gaps in the representation of species or ecosystems in areas where the species might be expected to be present. It is thus a formal means to identify and correct gaps between desired presence and actual presence of a species or ecosystem.

Integrated multi-trophic aquaculture (IMTA). Practice which combines, in the appropriate proportions, the cultivation of fed aquaculture species (e.g. finfish/shrimp) with organic extractive aquaculture species (e.g. shellfish/herbivorous fish) and inorganic extractive aquaculture species (e.g. seaweed) to create balanced systems for environmental sustainability (biomitigation), economic stability (product diversification and risk reduction) and social acceptability (better management practices).

Large marine ecosystem. Large area of ocean space of approximately 200 000 km^2 or greater, adjacent to the continents in coastal waters, that has distinct bathymetry, hydrography, productivity and trophically dependent populations.

Mariculture. Cultivation, management and harvesting of marine organisms in their natural habitat or in specially constructed rearing units, e.g. ponds, cages, pens, enclosures or tanks. For the purpose of FAO statistics, mariculture refers to cultivation of the end product in seawater even though earlier stages in the life cycle of the concerned aquatic organisms may be cultured in brackish water or freshwater.

Marine protected area (MPA). A protected marine intertidal or subtidal area, within territorial waters, EEZs or in the high seas, set aside by law or other effective means, together with the overlying water and associated flora, fauna, historical and cultural features. It provides degrees of preservation and protection for important marine biodiversity and resources; a particular habitat (e.g. a mangrove or a reef) or species, or sub-population (e.g. spawners or juveniles) depending on the degree of use permitted. The use of MPAs for scientific, educational, recreational, extractive and other purposes including fishing is strictly regulated and could be prohibited.

Marine spatial planning (MSP). A process of analysing and allocating parts of three-dimensional marine spaces to specific uses, to achieve ecological, economic, and social objectives that are usually specified through the political process; the MSP process usually results in a comprehensive plan or vision for a marine region. MSP is an element of sea use management.

Morphoedaphic index. This index measures the total dissolved solids (in mg/litre divided by mean depth in metres) in lakes or reservoirs. It was originally developed by Richard A. Ryder in the mid-1960s as an estimator of potential fish yield in lakes, and it can be used to predict both fish harvest and standing crop in freshwater bodies.

Multisectoral development. Many sectors of the government or the economic system may be involved in the planning and development of aquaculture, i.e. aquaculture can be considered as a "cross-sectoral" activity.

Parameter-specific suitability functions. This is a score allocated to any production function (at a given site) that is important to aquaculture production, with the score varying between 0 and 1 according to the relative importance of that function to the production process.

Production function. Those factors or variables that, in various combinations, influence the success of the production activity. Most factors affecting the success of fisheries or aquaculture will be physical inputs such as various aspects of water quality or water quantity, though a range of economic (cost) factors will also be important. It is likely that in the future, i.e. under EAA, EAF and MSP principles, social factors will additionally become a major consideration.

Riparian zones. Riparian buffer zones are vegetated areas along both sides of water bodies that generally consist of trees, shrubs and grasses and are transitional boundaries between land and water environments.

Stakeholder. Any person or group with a legitimate interest in the conservation and management of the resources being managed. Generally speaking, the categories of interested parties will often be the same for many fisheries, and should include contrasting interests: commercial/recreational, conservation/exploitation, artisanal/industrial, fisher/buyer-processor-trader as well as governments (local/state/national). The public, the consumers and the scientists could also be considered as interested parties in some circumstances.

Strategic planning. A systematic, formally documented process for deciding what are the key decisions that an organisation, or local or national government must get right in order to thrive over the next few years. The process results in the production of a strategic plan.

Trophic level. Position in food chain determined by the number of energy-transfer steps to that level. Plant producers constitute the lowest level, followed by herbivores and a series of carnivores at the higher levels. The various levels represent a trophic chain.

TROPOMOD. Particle tracking model used for predicting output, movement and deposition of particulate waste material (with resuspension) and the associated benthic impact of fish farms.

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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 latter part is available in this CD–ROM.