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Geographic information systems, remote sensing and mapping for the development and management of marine aquaculture

Cover photo:
The images are meant to convey the various kinds of GIS, remote sensing and mapping applications that address issues in the development and management of marine aquaculture. They include, from left to right, site selection and zoning, harmful algal blooms, impacts of aquaculture on the environment, competition between aquaculture and fisheries, development of seaweed farming, and strategic planning for offshore aquaculture. The background photo taken on 22 February 2004 (Courtesy of Fernando Jara) shows a high-tech 2 000 tonnes Atlantic salmon farm in the Reloncaví estuary, 41° Lat. S y 72° Lon. W. Chile's interior southern sea, within its intricate system of protected fjords and channels, provides prime conditions for aquaculture. Mild temperatures and abundant regular freshwater inputs represent competitive advantages for raising alien species, such as salmon and trout, making Chile one of the world's top producers of farmed salmon.

Geographic information systems, remote sensing and mapping for the development and management of marine aquaculture

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by

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Preparation of this document

The main purpose of this document is to promote the use of Geographic Information Systems (GIS), remote sensing and mapping to improve the sustainability of marine aquaculture. Focusing on developing countries, our emphasis is on implementation of GIS at the least cost and the use of data that are freely available via download from the Internet. Our approach is to demonstrate the utility and limitations of GIS, remote sensing and mapping through selected examples of a variety of applications of these tools.

This is one of the products in a long line of technical activities undertaken by the FAO Aquaculture Management and Conservation Service that deals with spatial tools to improve the sustainability of aquaculture and inland fisheries. The intended audience for this publication consists of professionals in the fisheries sector at managerial and technical levels in government service, in international organizations and in the aquaculture industry.

Dr. J.M. Kapetsky is a former FAO Senior Fishery Resources Officer.

Abstract

Geographic Information Systems (GIS), remote sensing and mapping have a role to play in all geographic and spatial aspects of the development and management of marine aquaculture. Satellite, airborne, ground and undersea sensors acquire much of the related data, especially data on temperature, current velocity, wave height, chlorophyll concentration and land and water use. GIS is used to manipulate and analyze spatial and attribute data from all sources. It is also used to produce reports in map, database and text format to facilitate decision-making.

The objective of this document is to illustrate the ways in which Geographic Information Systems, remote sensing and mapping can play a role in the development and management of marine aquaculture *per se* and in relation to competing and conflicting uses. The perspective is global. The approach is to employ example applications that have been aimed at resolving many of the important issues in marine aquaculture. The focus is on the ways tools have been employed for problem solving, not on the tools and technologies themselves. In this regard, we consider GISFish, the UN Food and Agriculture Organization (FAO) Internet gateway to GIS, remote sensing and mapping as applied to aquaculture and inland fisheries, as a complementary resource to this technical paper.

The underlying purpose is to stimulate the interest of individuals in the government, industry and educational sectors of marine aquaculture to make more effective use of these tools. A brief introduction to spatial tools and their use in the marine fisheries sector precedes the example applications. The most recent applications have been selected to be indicative of the state of the art, allowing readers to make their own assessments of the benefits and limitations of use of these tools in their own disciplines. Other applications have been selected in order to illustrate the evolution of the development of the tools.

The main emphasis is on GIS. Remote sensing is viewed as an essential tool for the capture of data subsequently to be incorporated into a GIS and for real time monitoring of environmental conditions for operational management of aquaculture facilities. Maps usually are one of the outputs of a GIS, but can be effective tools for spatial communication in their own right. Thus, examples of mapping for aquaculture are included.

The applications are organized issue-wise along the main streams of marine aquaculture: culture of fishes in cages, culture of shellfishes and culture of marine plants. Both the recent and historical applications are summarized in tables. Because data availability is one of the prime issues in the use of spatial tools in marine aquaculture, a case study is included that illustrates how freely downloadable data can be used to estimate marine aquaculture potential and a section is devoted to describing various kinds of data. Because the ultimate purpose of GIS is to aid decision-making, a section on decision support tools is included.

Finally, we summarize our findings and reach some conclusions on the state of the application of GIS, remote sensing and mapping for the development and management of marine aquaculture.

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Acronyms and abbreviations

AMA	Aquaculture Management Area
ASCS	Acoustic Seabed Classification Systems
AquaGIS	The Newfoundland and Labrador Aquaculture Geographic Information System
AATSR	Advanced Along Track Scanning Radiometer
CCRF	Code of Conduct for Responsible Fisheries
COC	Department of Aquaculture of the Spanish Oceanographic Centre in Tenerife
EEZ	Exclusive Economic Zone
ESRI	Environmental Systems Research Institute
ETOPO	2-Minute Gridded Global Relief Data
FOSS	Free and Open Source Software
GIS	Geographic Information Systems
GISFish	Global Gateway to Geographic Information Systems, Remote Sensing and mapping for aquaculture and Inland Fisheries
IOCCG	International Ocean Color Coordinating Group
IMS	Internet Map Server
KML	Keyhole Markup Language
MCE	Multi-Criteria Evaluation
MERIS	Medium Resolution Imaging Spectrometer
MODIS	Moderate Resolution Imaging Spectroradiometer
MPA	Marine Protected Areas
NOAA	National Oceanic and Atmospheric Administration
PAR	Photosynthetically Active Radiation
SAV	Submerged Aquatic Vegetation
SQL	System Query Language
SSMP	Site Suitability Modelling Process
SST	Sea Surface Temperature
HAB	Harmful Algal Bloom
UNEP	United Nations Environment Programme
WFP	World Food Programme
WVS	World Vector Shoreline

1. Introduction

1.1 OBJECTIVES AND OVERVIEW

The main purpose of this document is to promote the use of Geographic Information Systems (GIS), remote sensing and mapping as one means to assist the development and management of sustainable marine aquaculture. The perspective is global and developing countries are the focus. Because of our focus, our emphasis is on the implementation of GIS at the least cost based on data that are freely available via download from the Internet. Using a case study in the United States of America as an example, we show that a first approximation of marine aquaculture potential can be made for the Exclusive Economic Zone of any country of interest. Our review of selected applications of GIS, remote sensing and mapping applications to marine aquaculture is indicative of the state of the art, allowing the reader to make their own assessment of the benefits and limitations of these tools. This document is closely linked to GISFish, an FAO Internet gateway that makes available much of the accumulated experience on the application of GIS, remote sensing and mapping to aquaculture and inland fisheries through searchable literature data bases from Aquatic Sciences and Fisheries Abstracts, and in many cases, full papers and reports. GISFish is described more fully in Section 2.3.2.

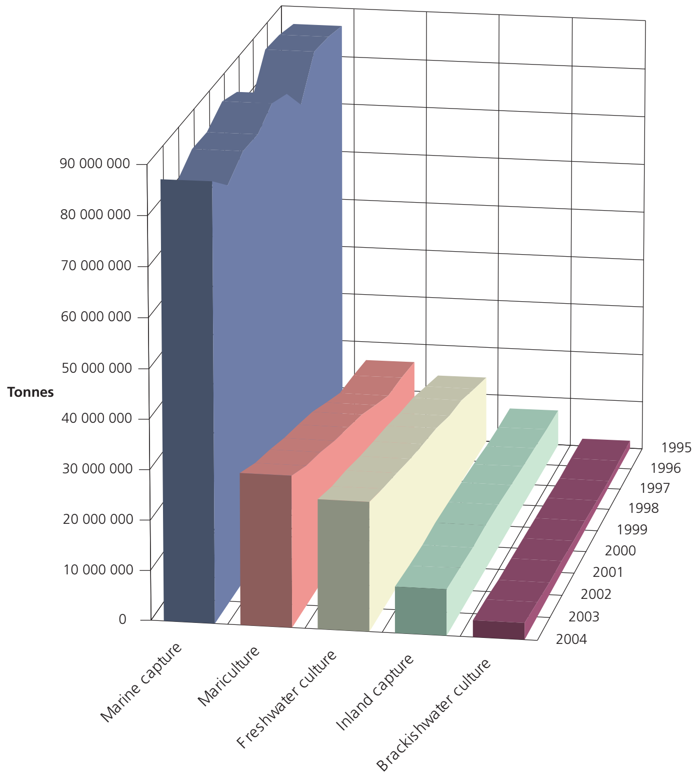
Our main emphasis is on GIS. Remote sensing is viewed as an essential tool for the capture of data subsequently to be incorporated into a GIS and for real time monitoring of environmental conditions for operational management of aquaculture facilities. Maps usually are one of the outputs of a GIS, but can be effective tools for spatial communication in their own right. Thus, examples of mapping for aquaculture are included.

Applications of these tools are best illuminated against some background. First, the importance of marine aquaculture is established with the fisheries sector. Then, GIS, remote sensing and mapping are viewed within two kinds of frameworks: the first is broad and encompasses the issues that shape present and future of aquaculture development; the second is more specific and condenses selected experiences on the applications of these tools in a review format that encompasses the purpose (research, operational development and management), target species, environment (terrestrial, near shore, open ocean), culture system, geographic scope, the factors and constraints analyzed, models, and methods employed for decision-making. Data availability for GIS and modelling and decision-making are addressed in separate chapters.

As indicated, our focus here is on how the applications of the tools have been employed to address important issues in marine aquaculture, not on the tools and technologies themselves. However, as an aid to understanding the underlying technical aspects of the applications, a Glossary section is provided in this publication with links to the relevant terminology. More detailed technical information as well as links to free and commercial software can be obtained by visiting GISFish.

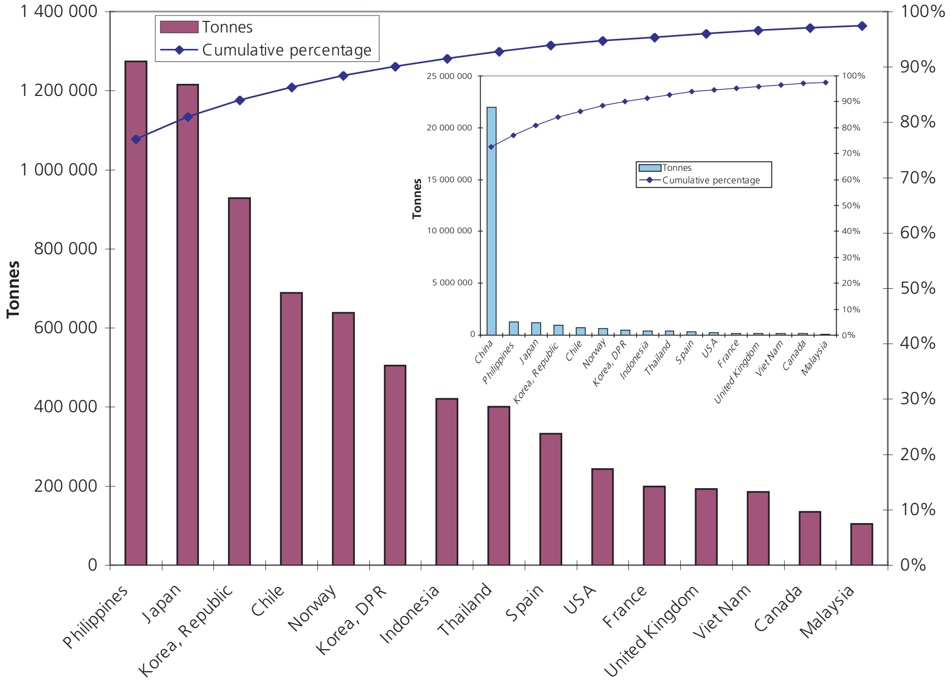
Finally, we comment on the state of the application of GIS, remote sensing and mapping for the development and management of marine aquaculture and make some recommendations for improved implementations.

FIGURE 1.1
Production trends by environment in the fisheries sector 1995-2004



Source: FAO (2006a)

FIGURE 1.2
Mariculture production and cumulative production in 2004 excluding China



Source: FAO (2006a)

1.2 THE IMPORTANCE OF MARINE AQUACULTURE

1.2.1 Production and trends in marine aquaculture in the fisheries sector

In 2004 total production from the fisheries sector reached nearly 156 million tonnes. Regarding environments and sources, marine capture accounted for 87 million tonnes and inland capture nine million tonnes, mariculture 30 million tonnes, freshwater culture 27 million tonnes, and the reminder, three million tonnes, was from brackishwater culture (FAO, 2006a).

Mariculture production is growing rapidly. Over the last decade, mariculture increased from 13 to 19% of the total production, freshwater culture increased from 11 to 17% while marine capture decreased from 69 to 56% and brackishwater culture increased from 1% to 2%. Inland capture remained stationary in relative importance at 6% of the total production (Figure 1.1).

1.2.2 Important countries in mariculture

Of the world's 186 countries with seacoasts, 86 countries reported mariculture production to FAO in 2004. Of these, China reported nearly 22 million tonnes, almost 73% of the global total. The Philippines and Japan each exceeded one million tonnes and there were 13 other countries whose mariculture production was more than 100 000 tonnes. Together, these top producers accounted for 97% of global mariculture production (Figure1.2).

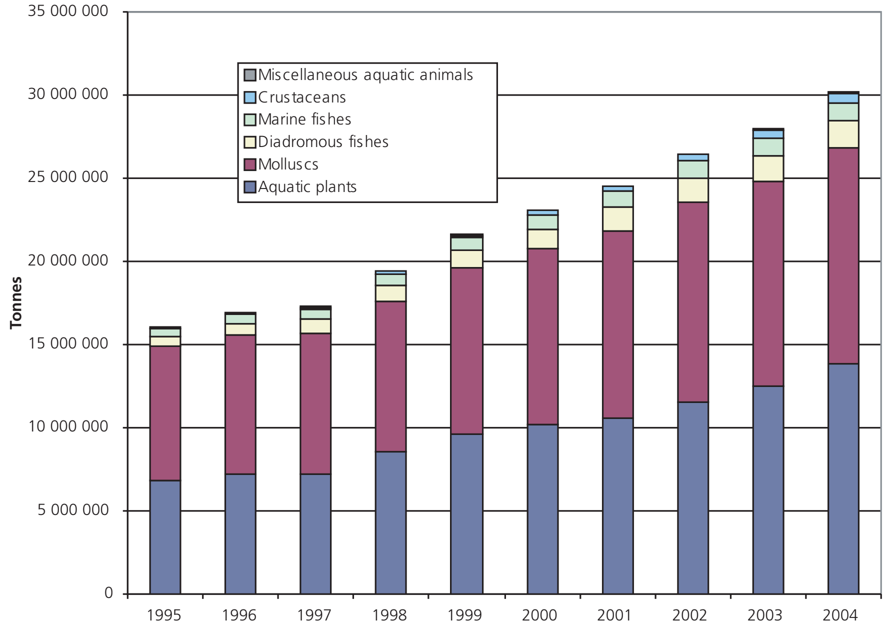
1.2.3 Important groups of aquatic species in mariculture

Considered by production weight in broad groups in 2004, mariculture production was dominated by aquatic plants (46%) and mollusks (43%) while diadromous fishes (mainly salmonids) accounted for 5% and marine fishes for 4%. Crustaceans at 2% were the least important. The relative proportions have remained similar over the last decade (Figure 1.3). The total value of the mariculture products in 2004 was US$ 27.8 billion.

1.2.4 Importance by Exclusive Economic Zone area

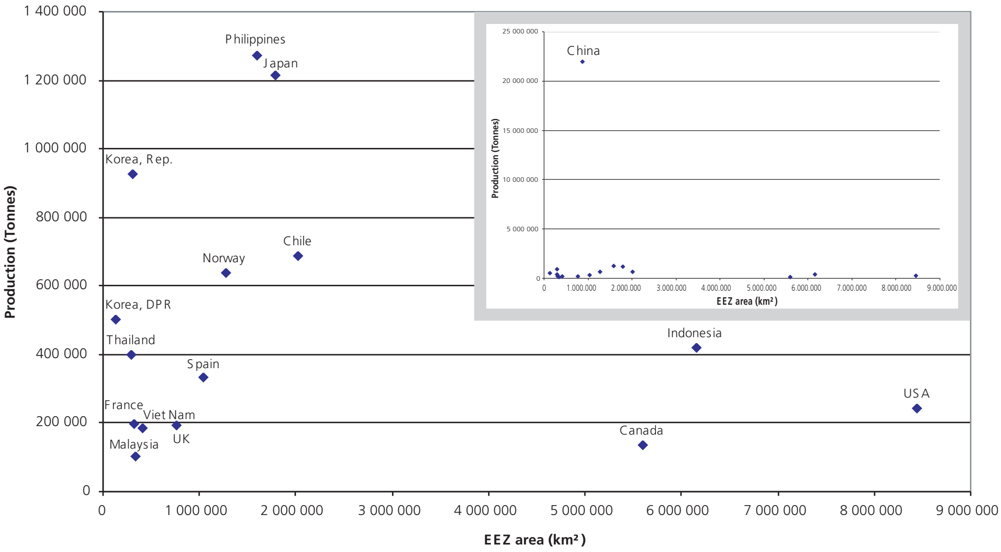
An Exclusive Economic Zone (EEZ) is the area under national jurisdiction (370 km or up to 200-nautical miles wide) declared in line with the provisions of 1982 United Nations Convention of the Law of the Sea. Within the EEZ the coastal State has the right to explore and exploit, and the responsibility to conserve and manage, the living and non-living resources found there. EEZs are the main areas in which marine aquaculture can expand from the present day near shore operations to offshore or to the open ocean. Most countries have enormous EEZs associated with their home territories and many countries have large additional EEZ areas associated with their overseas possessions. At first glance, opportunities for the expansion of marine aquaculture into EEZs appear to be boundless; however, at present constraints on technologies related to depth and sea conditions as well as competing uses reduce the available area. Nevertheless, there does not appear to be any relationship between EEZ home territory areas of the top mariculture producers and their production in 2004 (Figure 1.4). Production per square kilometre of EEZ area ranges from a high of nearly 25 tonnes for China to 0.02 tonnes for Canada.

FIGURE 1.3
Mariculture production trends by ISCAAP group



Source: FAO (2006a)

FIGURE 1.4
Mariculture production in 2004 and EEZ area (excluding China)



Source: FAO (2006a)

1.2.5 DEVELOPMENT AND MANAGEMENT OF MARINE AQUACULTURE

There is a vast literature on the development and management of marine aquaculture that covers technical, social, economic, and particularly the environmental aspects in the context of integrated coastal management (e.g., GESAMP, 2001). However, the Code of Conduct for Responsible Fisheries (CCRF) (FAO, 1995) offers the best starting point to understand broad aquaculture issues and potential solutions within international and national frameworks. The FAO Technical Guidelines for Responsible Fisheries (FAO, 1997) supplement the CCRF by addressing Article 9, Aquaculture Development, of the Code. The Bangkok Declaration and Strategy, based on the Conference on Aquaculture in the Third Millennium (Subasinghe *et al*., 2000), provides a strategy for development with a two-decade time horizon.

Some symposia and subsequent proceedings have emphasized applied research on marine aquaculture techniques and species (e.g., Seafarming Today and Tomorrow; Basurco and Sarologia, 2002), but others such as Open Ocean Aquaculture, From Research to Commercial Reality (Bridger and Costa-Pierce, 2003), Farming the Deep Blue (Ryan, 2004),The Future of Mariculture: A Regional Approach for Responsible Development of Mariculture in the Asia-Pacific Region (FAO/NACA, in press), and Offshore Mariculture 2006 (http://www.offshoremariculture.com) have dealt with important developmental aspects such as policy, institutions, socio-economics, engineering, environment, candidate species and logistics and operations.

Differences in the pace of development of marine aquaculture are reflected in the greatly varying production outputs among countries (Section 1.2.2). In this regard, an important consideration is that, although many of the issues are the same or similar from country to country, the solutions and pace of development have a national character. Another important consideration, the rationale for the deployment of GIS, remote sensing and mapping, is that many of the developmental and managerial issues of marine aquaculture have underlying geographic or spatial contexts.

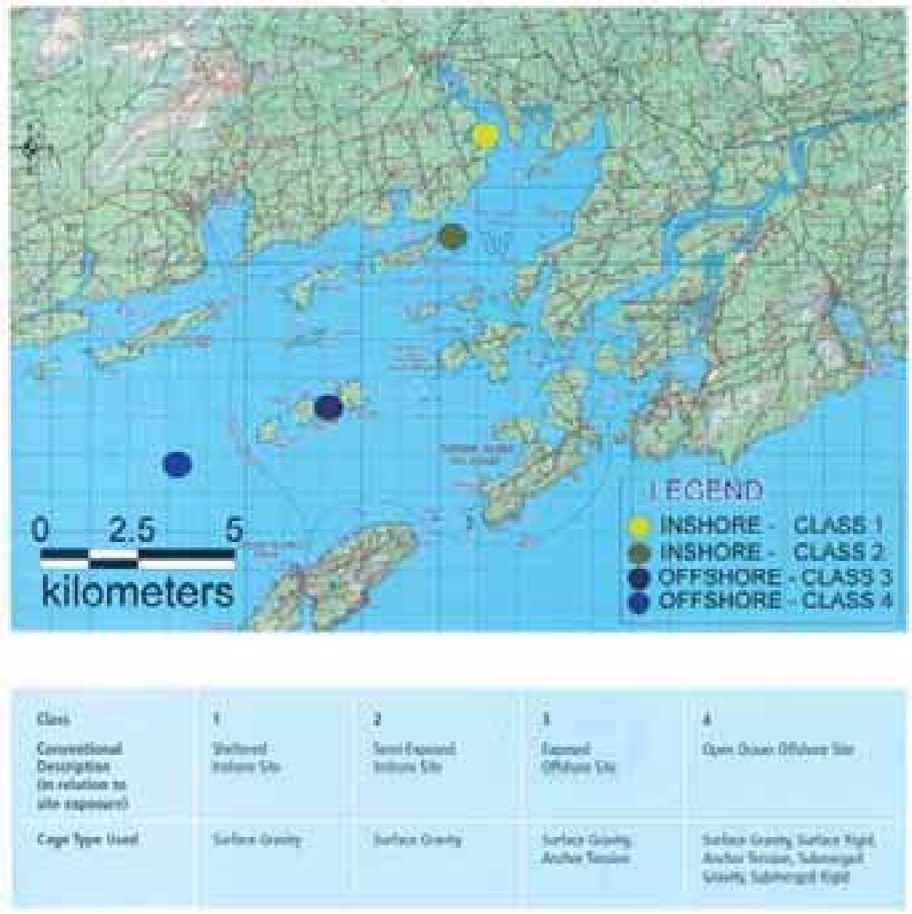
1.3 SPATIAL CONTEXT OF NEAR SHORE AND OFFSHORE ISSUES SHAPING MARINE AQUACULTURE

1.3.1 Near shore and offshore realms

In dealing with marine aquaculture, two environmental realms are evident: near shore and offshore, or the open ocean. Each realm has its own set of issues that differ mainly in relative importance. Ryan (2004) views “offshore” as related to distance from shore that is attendant with increased wave energy and a lack of shelter; however, he notes that a refined definition has yet to be made. Relating specifically to characteristics of cages, Ryan (*op cit.*) pictures four classes of locations, two of which are the offshore type that are contrasted with inshore types (Figure 1.5).

Similarly, Bridger *et al.* (2003) recognize four classes of marine aquaculture sites according to degree of exposure: (1) land-based facility, (2) coastal environments (protected bays and fjords), (3) exposed sites and (4) offshore sites. Muir (2004) contrasts coastal (inshore) aquaculture with offshore aquaculture based on four criteria that include location/hydrography, environment, access, and operation (Table 1.1) while noting that it is necessary to place emphasis on the amount of exposure and the operational conditions. Booth and Wood (2004) provide a more generalized description that considers the coastal zone as being areas visible from land (e.g., inter-tidal zone, bays and estuaries) while offshore areas are out of sight of land. From a conceptual viewpoint “nearshore” and “offshore” are broadly indicative of water space for marine aquaculture, but using spatial analysis allows us to define much more accurately and precisely where aquaculture can be developed as well as to forecast management needs. In fact, it is the requirements of the cultured organisms, the culture structure, shore support installation, and access that together define the potential for marine aquaculture. In this regard, nearshore and offshore have little meaning.

FIGURE 1.5
Cage types likely to be found in sites of classes 1 to 4



Class	1	2	3	4
Conventional Description (in relation to site exposure)	Sheltered Inshore Site	Semi-Exposed Inshore Site	Exposed Offshore Site	Open Ocean Offshore Site
Cage Type Used	Surface Gravity	Surface Gravity	Surface Gravity, Anchor Tension	Surface Gravity, Surface Rigid, Anchor Tension, Submerged Gravity, Submerged Rigid

Source: Ryan (2004)

TABLE 1.1
Characteristics of coastal and offshore aquaculture

Characteristics	Coastal (inshore)	Offshore aquaculture
Location/hydrography	05-3km, 10-50m depth; within sight, usually at least semi-sheltered	2+ km, generally within continental shelf zones, possibly open-ocean
Environment	Hs <= 3-4m, usually <= 1m; short period winds, localized coastal currents, possibly strong tidal streams	Hs 5m or more, regularly 2-3m, oceanic swells, variable wind periods, possibly less localized current effect
Access	>= 95% accessible on at least once daily basis, landing usually possible	usually > 80% accessible, landing may be possible, periodic, e.g. every 3-10days
Operation	regular, manual involvement, feeding, monitoring, etc	remote operations, automated feeding, distance monitoring, system function

Terminology: Hs = significant wave height - a standard oceanographic term, approximately equal to the average of the highest one-third of the waves.

Source: Muir (2004)

1.3.2 Near shore and offshore issues

Issues related to marine aquaculture in general (Marine Aquaculture Task Force, 2007) and to open ocean aquaculture in particular (Stickney *et al.*, 2006) have been covered in recent reviews.

We believe that the most fruitful approach to implementing GIS, remote sensing and mapping for the development and management of marine aquaculture is to first assess the issues and then to gauge the extent to which these tools can address the issues. A categorical framework of issues that relate to aquaculture was proposed by Kapetsky and Aguilar-Manjarrez (2004) and used by them to assess progress in implementing GIS. The main categories of issues are: (1) development, (2) aquaculture practice and management, and (3), multisectoral development and management that includes aquaculture.

Considering the offshore and coastal environments, the issues differ not so much in kind but rather in degree. This is reflected in the well known rationale for moving aquaculture to offshore areas. Basically, it is to lessen or resolve the most pressing problems encountered near shore (Table 1.2). Among the most important considerations are reducing the impacts of aquaculture on the near coastal environment (Table 1.3), the need for more space to accommodate large aquaculture operations that can better realize economies of scale offshore, lessening of competition and reducing conflicts from other uses, elimination of visual impacts, and improvement of water quality. With regard to the latter, Ryan (2004) mentions greater water exchange than experienced in near shore areas that is brought about by wind and wave action and tidal currents that also disperse aquaculture wastes and lessen the incidence of ecto-parasitic infections. Another husbandry-type of advantage is less extreme and more stable water temperatures offshore. The disadvantages of going offshore become important issues. Among them are the need for all weather culture structures due to the lack of shelter, greater distances and costs for the transport of feed, to service, maintain and monitor the offshore installations, and to make them secure.

Viewed at in another way, spatial issues near shore deal more with historical and actual problems arising from existing aquaculture while those offshore, because offshore aquaculture is in its infancy, are perceived or potential issues. Many types of near shore aquaculture, mainly of shellfish, cannot be easily moved offshore with present technologies. Therefore, near shore issues will have to be confronted if marine aquaculture is to expand there.

Both the realization of the advantages and the avoidance of the disadvantages require detailed advanced planning and attention to satisfying siting criteria.

1.3.3 Advanced planning for marine aquaculture

Cicin-Sain *et al.* (2001), in the course of developing a policy framework of offshore aquaculture in US waters, found that one of the major problems in all of the nations studied involved conflicts between the siting of fish farms and other uses of coastal waters such as maritime traffic, capture fisheries, tourism, and the protection of natural areas. It appeared to be important, then, to develop a set of siting criteria for aquaculture to minimize the chances of such conflicts emerging later. In several nations (such as in Chile and Norway), a formal process of determining "areas suitable for aquaculture" was undertaken early in the regulatory process.

Building on their earlier work, Cicin-Sain *et al.* (2005) devised an operational framework for the development of offshore aquaculture in US federal waters. They emphasize that the development and operation of an offshore farm requires an investment running to millions of dollars and they note that siting decisions based on insufficient or faulty information can create costly delays, environmental degradation, reduced production, leasing issues, licensing and other regulatory requirements, or ultimately, project failure. In this regard, they recommend comprehensive mapping of offshore areas be conducted to identify areas suitable for the offshore aquaculture industry as well as other uses and to further the development of a detailed, map-based marine zoning plan.

These authors foresee the need for a number of options for offshore aquaculture siting that, in turn, will require differing levels of effort and detail for their geographic definition. The options include:

- site specific lease or easement for aquaculture;
- designated or pre-approval area for aquaculture;
- zoned areas for multiple uses; and
- marine aquaculture parks.

Seven levels of aquaculture zoning are anticipated that range from those with few use restrictions (e.g., all reasonable commercial uses including aquaculture, shipping, and trawling, but with mining and oil drilling prohibited) to those with an increasing number of restrictions with the most restrictive a zone that is set aside for preservation in an undisturbed state.

TABLE 1.2

Comparison of marine aquaculture strategies as categorized by degree of exposure of the operation to natural oceanographic and storm events (from Bridger *et al*. (2003) Table 1, with modifications based on personal communications from M. Beveridge and D. Soto)

Location	Advantages	Disadvantages
Land-based Facility	- Control water quality - Isolation of operation from populated areas not required - Complete protection from storm surges	- Limited space - Expensive capital investment
Coastal Environments (protected bays and fjords)	- Less capital investment - Protected from much of the natural elements - Surveillance possible with minimal investment	- Possible self-pollution - Limited space for expansion - Isolation more desirable to be free of anthropogenic coastal pollution - User conflicts exist close to shore
Exposed Sites	- Utilizing environment previously unexploited - Consistent and high quantity water supply - Visual protection still possible form near by land - Decreased environmental impacts (Soto)	- Exposed to destructive natural elements - Limited space near shore - User conflicts exists close to shore - Increased infrastructure necessary with increased exposure - Rely more on automation
Offshore Sites	- Decreasing user conflicts with increasing distance from shore - Very consistent water supply -Improved current regime producing better quality fish (Beveridge) -Lesser incidence of harmful algal blooms (HABs) and more rapid pass through of HABs due to higher current regime (Beveridge) - Large potential for industry expansion	- Truly exposed with no protection from either side - Increased capital costs associated with increased technology and mechanization - The need for better trained (and more expensive) staff, including divers and those able to use larger, more sophisticated boats (Beveridge) - FCRs may be poorer if currents are strong, but flesh quality (i.e. lower lipid levels) may be improved, securing better prices (Beveridge) - Large investments require to ensure economic feasibility - Complete isolation from shore bases with no land in sight - Higher risk of escapees (Soto)

TABLE 1.3
Key environmental issues associated with aquaculture

Issue area	Key features
waste and nutrient loadings	outputs of solids, N.P, vitamins, minerals, husbandry/disease chemicals, antibiotics; impacts of waste materials on the adjacent benthos and the water column; on species/community diversity, quality indices, possible stimulation of blooms;
water exchange	flushing through cages, enclosures or other structures; quantities required, effects of abstraction, dilution with "low grade" wastes, at concentrations sufficient to diminish measured quality, but too low for simple treatment.
escaped stocks	from damaged systems, or through flooding, damaged or ineffective discharge screens; risks of competition with/ genetic contamination of local stocks, disease transmission, directly or indirectly reduced biodiversity
predation by conservation-sensitive species	causing damage, loss, stress-related disease to farmed stock, requiring controls without compromising conservation interests;
increasing demand for pre-emptive control	requiring a precautionary or even "zero-tolerance" approach to existing and intended development, implying anticipatory understanding of processes and risks, and provision for even very low areas of environmental risk.

Source: Muir (2004)

1.4 INTRODUCTION TO GEOGRAPHIC INFORMATION SYSTEMS, REMOTE SENSING AND MAPPING

1.4.1 Marine aquaculture development and management from a spatial perspective

Geographic Information Systems, remote sensing and mapping have a role to play in all geographic and spatial aspects of the development and management of marine aquaculture. Remote sensing, using satellite, airborne, ground and undersea sensors, is used to acquire much of the near shore and offshore data, especially data on temperature, current velocity, wave height, chlorophyll concentration and land and water use. In essence, GIS is used to assess the suitability for aquaculture development and to organize a framework for aquaculture management. "Suitability for development" and "Framework for management" can be seen at two levels. The first level concerns only the requirements to conduct aquaculture *per se*. The second level is aquaculture in the context of other uses of land and water. For both of these development and management tasks, spatial and attribute data from all sources relating to specific criteria are manipulated and analyzed within a GIS platform to facilitate decision making. Outputs are reports in database, map, and text formats.

From a geographic perspective, three broad classes of information are essential for planning the development and management of marine aquaculture: (1) suitability of the environment for the plants and animals to be cultured; (2) suitability of the environment for the culture structure and; (3) access. Of these, access is the broadest and most complex. Access has to consider the administrative jurisdictions and the competing uses of the sub-bottom, bottom, water column, water surface and land (the latter for the siting of onshore support facilities or land-based marine culture). It also examines the cost of supporting culture sites (in time and distance) and the geography of the markets for cultured products.

GIS is not divorced from economics. On the contrary, GIS-based studies will provide the most useful results when they are designed with participation by economists and outputs that that can be interpreted in economic terms.

2. Geographic Information Systems, remote sensing and mapping in the marine environment and fisheries sector – an overview

The purpose of this section is to provide a brief review of the evolution of GIS and its use in the marine environment in general, and specifically in the fisheries sector. As pointed out in more detail below, these disciplines are relevant because GIS aimed at aquaculture depends heavily on the data and techniques applied for other purposes. Furthermore, these overviews provide the background to more detailed reviews of applications that address specific issues in marine aquaculture in Section 3.

2.1 HISTORY OF GEOGRAPHIC INFORMATION SYSTEMS

The geographic roots of GIS go back some 2 500 years and have their basis in geographic exploration, research and theory building. In the early 1960s the assembled geographic knowledge began to be formalized as computer tools functioning to input, store, edit, retrieve, analyze and output natural resources information. The first GIS was the Canada Geographic Information System and it marked the inception of world wide efforts to formalize and automate geographic principles to solve spatial problems. After more than 40 years of development, GIS is now a mainstay for addressing geographic problems in a wide variety fields apart from natural resources (DeMers, 2003).

2.2 GEOGRAPHIC INFORMATION SYSTEMS IN THE MARINE ENVIRONMENT

Works on GIS in the marine environment have been mainly promotional and aimed at demonstrating a variety of applications. For example, conceptual, technical and institutional issues as well as a variety of applications are presented by Wright and Bartlett (2000) in an edited volume. Wright (2002) deals with the coastal and open ocean environments focusing on broad applications of GIS including mapping and visualization, electronic navigational charting, and the delivery of maps and data via the Internet. Breman (2002) has assembled a collection of chapters to demonstrate the progress in the use of GIS in a variety of marine sciences. Applications are organized by ocean area. One chapter deals with fisheries assessment and management. Another of the chapters in Bremen (2002) importantly deals with the inception of the ArcGIS Marine Data Model (Bremen, Wright, and Halpin, 2002). The goal of the model is to provide a structured framework that accurately represents the dynamic nature of water processes. The marine data model is covered more thoroughly in Section 6, Decision-making and modelling tools in GIS.

2.3 GEOGRAPHIC INFORMATION SYSTEMS, REMOTE SENSING, AND MAPPING PUBLICATIONS IN THE FISHERIES SECTOR

GIS, remote sensing and mapping as applied to fisheries are important for marine aquaculture for two reasons: (1) much of the data are of common interest and use (e.g., environment, and species that are both fished and cultured), and analytical techniques may be the same or similar and therefore useful for aquaculture. For example, the procedures and data used to spatially establish essential fish habitat are similar to those that are used to locate optimal aquaculture "habitat". (2) GIS implemented for management solely for aquaculture or solely for fisheries may not be efficient in the same geographic or administrative scope and, in fact, would negate one of the important advantages of GIS that is to promote cross-disciplinary understanding and cooperation. Therefore, the evolution of GIS and remote sensing applications in both fisheries and aquaculture is presented in chronological order as milestones.

In order to call attention to different kinds of information, one section deals with syntheses of experience in the form of reviews and manuals. In order to portray the breadth of experience, another section deals with symposia, workshops and an Internet site.

2.3.1 Reviews and manuals

Recognizing the need for mapping of fisheries and fishery resources in the context of coastal area management and in relation to multiple uses in Exclusive Economic Zones, Butler *et al.* (1987) produced an FAO manual containing practical guidelines and principles of cartography that was aimed mainly at personnel in developing countries. Seeing the potential of remote sensing to assist fishermen, fishery scientists and fishery managers and commercial fishing entities, Butler *et al.* (1988) prepared an introductory manual on the application of remote sensing technology to marine fisheries. Simpson (1994) dealt in great detail with the capabilities of remote sensing and GIS in marine fisheries and set the stage for the direction of future applications. In order to better understand and plan for increasing rates of changes of ocean use, infrastructure and socio-economic spatial patterns, particularly with respect to fishery resources and fisheries, the FAO Fisheries Management and Conservation Service produced a review of GIS applications in marine fisheries (Meaden and Do Chi, 1996). With the goal of promoting the use of GIS and remote sensing in aquaculture and inland fisheries in developing countries, the FAO Aquaculture Management and Conservation Service produced a lengthy review by Meaden and Kapetsky (1991) with the purpose of maintaining a balance between the technologies and the applications. Nath *et al.* (2000), in the context of applications in aquaculture, identified constraints on the implementation of GIS and proposed a seven-stage, user-driven framework to develop a GIS including personnel, activities and analytical procedures. Valvanis (2002) reviewed GIS in oceanography and fisheries from a global viewpoint, first by presenting the conceptual, methodological and institutional issues in applying GIS to marine environments. He then treated GIS in oceanography and fisheries separately. In the fisheries chapter, GIS applications in aquaculture, mainly relating to aquaculture potential and to site selection, were briefly covered.

Identifying a need for a "do-it-yourself" field manual aimed at the fisheries personnel with no formal training in GIS, the FAO Aquaculture Management and Conservation Service produced a manual by De Graaf, *et al.* (2003) based on ArcView 3.x that presents the basics along with application case studies dealing both with inland and marine fisheries.

Fisher and Rahel (2004) are the editors of "Geographic Information Systems in Fisheries" that is noteworthy in several ways: (1) one chapter thoroughly covers intellectual and theoretical challenges to the deployment of GIS in aquatic environments (Meaden, 2004) (see below), and in that it treats GIS both for inland and marine fisheries applications with chapters that are organized by fisheries environment (e.g., lakes, offshore). Additionally, one chapter is devoted to GIS applications in aquaculture in an issues-based framework (Kapetsky, 2004).

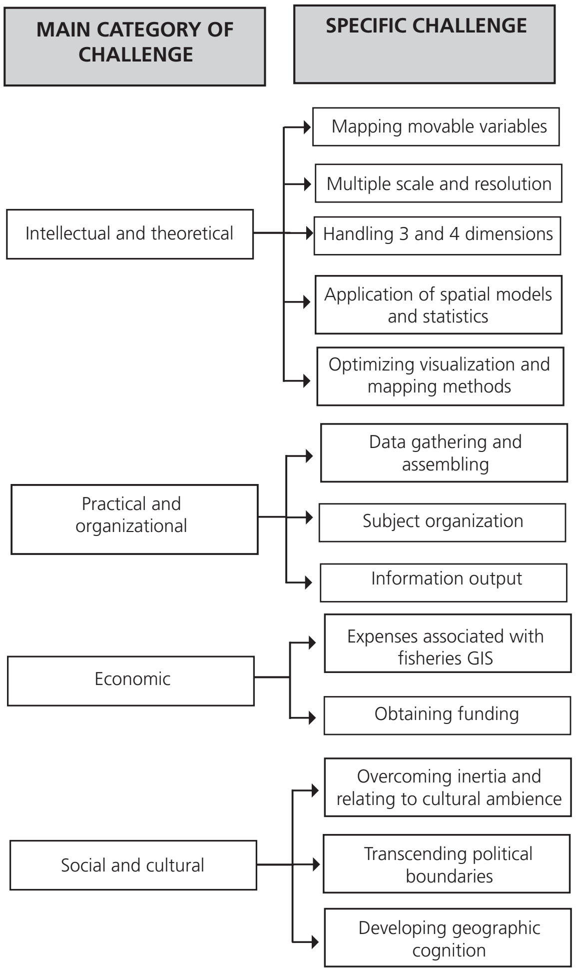
The operational challenges facing fisheries GIS that inhibit problem solving as perceived by Meaden (2004) are in four main categories including (1) intellectual and theoretical, (2) practical and organizational, (3) economic, and (4) social and cultural. The associated specific challenges are summarized in Figure 2.1.

According to Meaden (*op cit.*), the expansion of GIS in fisheries will depend on advancement towards or achieving the following:

- reduction in data costs (more widely and easily accessed data);
- a proliferation of data-gathering technologies;
- better organization of practitioners at an international level;
- networking among institutions;
- conferences at regional levels;
- examples of applications in “recognized” publications;
- projects as examples that illustrate analytical and presentational features;
- international standardization of data gathering formats;
- progress in 3-D and 4-D GIS along with data storage and modelling structures; and
- more easily accessible marine information sources.

FIGURE 2.1

Categories of challenge facing fisheries GIS



Source: Meaden (2004)

Statistical analysis is undisputedly an essential part of the geography of marine aquaculture. Meaden (2004) deals briefly with spatial statistics, spatial modelling and modelling. He sees GIS as the software platform or activity surface upon which numerical models are conceived, evaluated, or tested. According to Meaden (*op cit.*) there are at least two major mathematical challenges to modelling fisheries data, one of which is spatial autocorrelation and the other of which is securing of statistical significance.

Booth (2004) reviews at length the foundations and applications of spatial statistics in aquatic sciences and the relationship between GIS for scientific research in fisheries and spatial statistics.

Booth and Wood (2004) review GIS applications in offshore marine fisheries and in doing so they summarize the techniques that are available for analysis while providing an overview of applications to fisheries research and management.

Fisher (in press) reviews the ways in which GIS was applied in fisheries as reported in papers appearing in refereed scientific journals. He concluded that the use of GIS is becoming more complex and sophisticated; however, the applications are aimed mainly at habitats and organisms while the human dimension has received relatively little attention.

2.3.2 Symposia, workshops and the Internet

Proceedings of GIS-based symposia and reports of workshops are valuable sources of example applications that relate directly or indirectly to marine aquaculture. In the course of reviewing trends in fisheries GIS, Fisher (in press) found that 35 of the 100 peer reviewed papers published after 1999 came from the proceedings of one symposium.

A wide variety of fisheries GIS, remote sensing and mapping experience has been made available through the initiative of the Fishery GIS Research Group who have organized three symposia and published the proceedings on two of symposia with the third in preparation (Nishida, Kailola and Hollingworth, 2001; 2004; in press). Unfortunately, aquaculture applications have been rather poorly represented at these symposia.

Taconet and Bensch (2000) reviewed 16 papers and 11 other contributions to a workshop that documents the ways in which GIS has been applied to the management of Mediterranean fisheries. They found that GIS was useful in terms of mapping outputs that are used for communication, portraying the dynamics of the marine the environment, resource location, monitoring fishing, and spatial modelling of fishing effort.

Kapetsky and Aguilar-Manjarrez (2004) inventoried and quantified the use of GIS in aquaculture development and management from the perspectives of geography, environments, organisms and issues for the period 1985 to 2002. They, like Nath *et al.* (2000), concluded that, despite the many spatially-related issues affecting the sustainability of aquaculture, GIS was not being deployed systematically and synoptically to address them. They categorized 157 GIS endeavors from 1985 to 2002 in an issues-based framework and found that most of the applications related to the development of aquaculture and to aquaculture practice and management. However, within these main categories, two important sub-categories of endeavors, anticipating the consequences of aquaculture, and determining the impacts of aquaculture, received little attention. A third major category, integration of aquaculture with fisheries and aquaculture as a part of multi-sectoral development, was poorly represented. The present count on the distribution of applications among major issues and their sub-categories, as of the publication of this document, is shown in Table 2.1. The relative proportions of the applications among issues remain essentially the same at present as in the past.

TABLE 2.1
Aquaculture main issues from GISFish database (prototype version of 17 January 2007)

Aquaculture main issues from Database Number of Literature Records	No.
GIS aimed at the development of aquaculture	
Suitability of site and zoning	91
Strategic planning for development	49
Anticipating the consequences of aquaculture	11
Economics	2
GIS for aquaculture practice and management	
Inventory and monitoring of aquaculture and the environment	63
Environmental Impacts of aquaculture	16
Restoration of aquaculture habitats	7
Web-Based Aquaculture information system	2
GIS for multisectoral development and management that includes aquaculture	
Management of aquaculture together with fisheries	3
Planning for aquaculture among other uses of land and water	7
Total	294

Source: GISFish

Kapetsky and Aguilar-Manjarrez (2004) also compared GIS applications with aquaculture production by environment and found that most of the applications were in brackishwater – coastal environments, the environment with the least aquaculture production, while GIS applications in the relatively high production freshwater and marine environments were relatively few. Likewise, the authors found that there was a skewed geographical distribution of GIS applications among countries compared with the relative importance of aquaculture production at national levels. In all, there were only 33 countries with GIS endeavors in aquaculture, about one-third of the number of countries with an aquaculture production exceeding 1 000 tonnes. The United States of America accounted 36% of the total. Similarly, in analyzing trends in GIS applied to fisheries (excluding aquaculture), Fisher (in press) found that 47% of the papers pertained to the United States of America and in total only 31 countries were represented.

The results of these analyses alerted Kapetsky and Aguilar-Manjarrez (2004) to a key need that was for comprehensive information on GIS, remote sensing and mapping as applied to aquaculture and inland fisheries. A corresponding requirement was that the information should be easily accessible in a variety of ways. Two audiences were identified, one of which was potential practitioners who would require information on the benefits of the tools. The other audience was GIS users who needed easy access to the accumulated world wide experience on applications. As a follow-up activity, the FAO Aquaculture Management and Conservation Service created GISFish. GISFish is a "one stop" Internet site from which to obtain the depth and breadth of the global experience on GIS, remote sensing and mapping as applied to aquaculture and inland fisheries (Figure 2.2).The addition of marine fisheries is envisioned.

GISFish was created to satisfy the needs outlined above, basically to: (1) promote the use of GIS, remote sensing and mapping; and (2) facilitate the use of these tools through easy access to comprehensive information on applications and training opportunities. GISFish sets out the issues in aquaculture and inland fisheries, and demonstrates the benefits of using GIS, remote sensing and mapping to resolve them. The global experience provided by GISFish is captured in several ways. One way is via databases of literature references with abstracts from ASFA (Aquatic Sciences and Fisheries Abstracts), and, in many cases, links are provided to full technical reports and papers. Another way is through a Web resources database with links to training opportunities,

FIGURE 2.2

GISFish home page (prototype version of 17 January 2007)

Global Gateway to Geographic Information Systems (GIS), Remote Sensing and Mapping for Aquaculture and Inland Fisheries

GISFish is a "one stop" site from which to obtain the global experience on **Geographic Information Systems (GIS)**, **Remote Sensing** and **Mapping** as applied to Aquaculture and Inland fisheries.

GISFish sets out the issues in aquaculture and inland fisheries, 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**.

Development of GISFish is a work in progress being carried out under the guidance of the Aquaculture Management and Conservation Service (FIMA) of the Food and Agriculture Organization of the United Nations (FAO). **Information about GISFish...**

August 25, 2008: Fourth International Symposium on GIS/Spatial Analyses in Fisheries and Aquatic Sciences

March 05, 2007: Coastal GeoTools '07

freeware, data and example applications. GISFish also provides access to case studies to: (1) call attention to a wide variety of applications that have contributed significantly to solving important sustainability issues, and (2) provide important 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. Many of the papers reviewed herein are GISFish case studies. Finally, GISFish also promotes communication among workers by including descriptions of ongoing projects, activities, news and links. GISFish will be released in 2007 on the Internet, and eventually also as a CD-ROM.

3. Review of selected applications

Our purpose in this section is to provide an overview of the breadth of applications of mapping, remote sensing and GIS to marine aquaculture based on selected historical and current applications that are organized within the framework of issues presented in Table 2.1, it is not our purpose to review all of the applications. Inland aquaculture GIS applications up to 2003, including shrimp farming in ponds, have been broadly covered by Kapetsky (2004). Thus, we focus on those applications not already covered by him and we emphasize those that we believe will provide the most helpful examples. Additionally, GISFish, as mentioned above, makes available abstracts and many complete papers and reports not cited herein.

The review format includes a statement about why the application is noteworthy, a description of the environment, the issues or problems addressed, the spatial criteria used for the evaluation, the results obtained and comments on improvements to the approach, if suggested by the authors. Mapping, including mapping information systems, is presented first. Then, remote sensing applications are dealt with as a background for GIS, and finally marine aquaculture GIS applications are presented.

3.1 MAPPING APPLICATIONS IN MARINE AQUACULTURE

3.1.1 Introduction to mapping

Maps are the traditional method of storing and displaying geographic information. A map is a graphic representation of the physical features (natural, artificial, or both) of a part or the whole of the Earth's surface, by means of signs and symbols or photographic imagery, at an established scale, on a specified projection, and with the means of orientation indicated (FAO, 2006b). A map portrays three kinds of information about geographic features:

- location and extent of the feature;
- attributes (characteristics) of the feature; and
- relationship of the feature to other features.

In this regard mapping is the most straightforward way to visualize spatial relationships involved with the development and management of aquaculture and one of the easiest ways to communicate the two-dimensional needs of aquaculture for space among technical people and to the public in general.

There is a broad range of sophistication in mapping related to its purpose. The objective here is to provide some examples illustrating each range. Mapping for marine aquaculture development and management is considered in three categories: (1) Maps to delineate aquaculture sites and zones usually as accompaniments to technical reports, (2) Maps and varied attribute information accessed via the Internet that are aimed at a broad audience of government, commercial and private users involved with aquaculture development and management. These are, in fact, aquaculture information systems. AquaGIS is the prime example. (3) Interactive Internet mapping usually aimed at broad audiences that is accomplished by Internet map servers in which there is a choice of layers to view, layer attributes and descriptions and various functions such as zoom and pan. An important additional function at some sites is the capability to download selected GIS layers in various file formats. The applications are summarized in Table 3.1.

TABLE 3.1
Summary of mapping applications for marine aquaculture organized by main issues

Authors	Year	Main thrust or issue	Country	Species
Mapping aimed at the development of aquaculture				
Tiensongrussme, Pontjoprawiro and Mintarjo	1988	Strategic planning for development	Indonesia	Finfish; cockles, pearl oysters, sea cucumbers; seaweeds, mussels, and oysters.
Auckland Regional Council	2002	Strategic planning for development	New Zealand	Mussel and oyster
Macias-Rivero, Castillo y Rey, and Zurita	2003	Strategic planning for development	Spain	Species not named
Environment Bay of Plenty	2006	Strategic planning for development	New Zealand	Species not named
Mapping for aquaculture practice and management				
Scottish Executive	2000	Environmental impacts of aquaculture	Scotland	Salmon
Marine Policy Center, Woods Hole Oceanographic Institution	2003	Web-based aquaculture information system	USA	Marine mammals, whales.
Jordana	2004	Web-based fisheries and aquaculture information system	Spain	Species not named
AquaGIS, Government of Newfoundland and Labrador	2006	Web-based aquaculture information system	Canada	Atlantic Cod ; Atlantic Salmon; Blue Mussels; Rainbow Trout; Other Species

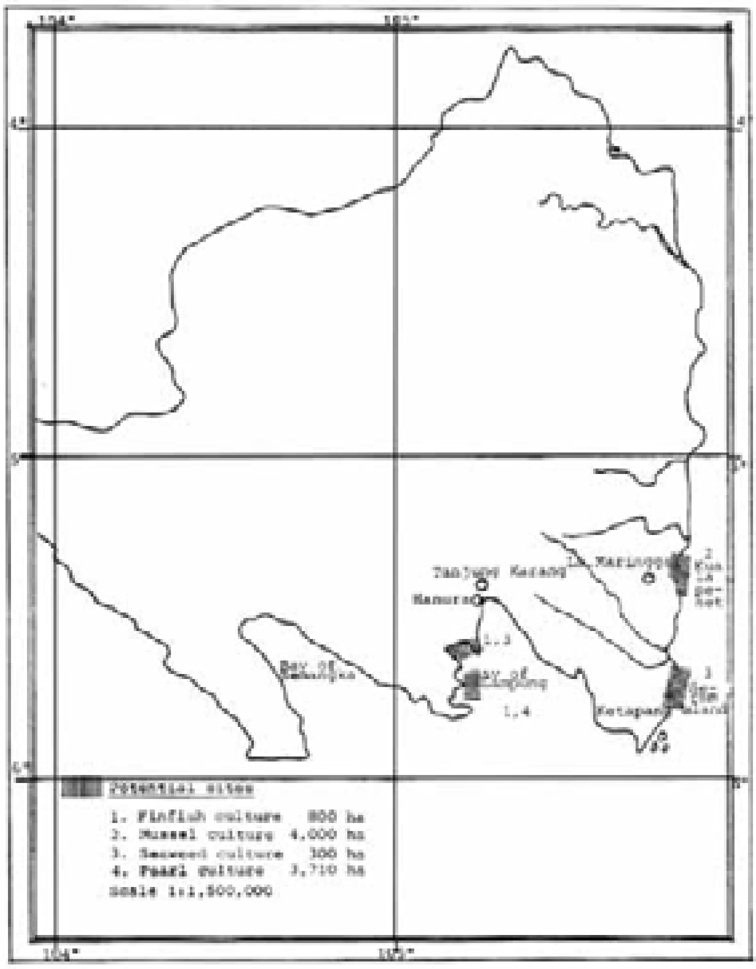
3.1.2 Mapping aimed at the development of aquaculture

The objective in this section is to illustrate an evolution in approaches to mapping for aquaculture that was facilitated by underlying advances in software and data availability. All of the examples in this section relate to the issues of strategic planning and development.

Tiensongrussmee, Pontjoprawiro and Mintarjo (1988) report on an activity to map seafarming potential throughout Indonesia's coastal waters. This study is noteworthy for the geographic scale of the operation, for the number and variety of species and culture methods included and for the use of satellite remote sensing to aid the mapping effort. The study was conducted at a time when the government policy was to take pressure off of fishery resources and to stimulate the development of aquaculture at commercial scales and also as small enterprises for low income groups. In overview, mainly biophysical siting criteria were developed for farming finfish in floating cages, on-bottom culture of cockles, pearl oysters, sea cucumbers and the seaweed, *Eucheuma*, suspended culture of mussels, and oyster culture on stakes and from rafts. Pollution sources and competing uses also were considered. Potential sites were identified by government fisheries officers, interviews with fishermen and in the literature. One positive siting criterion was the presence of naturally occurring populations of species intended for culture suggesting that the environment was suitable for them. Site selections were verified by visits over the course of five years. Mapping was based on topographic maps, nautical charts and Landsat-5 satellite images. The resulting maps are shoreline tracings with potential sites clearly shown in a diagrammatic way; however, many of the maps show latitude and longitude and some of them include the scale and a few show depth contours (Figure 3.1). Based on the results it was recommended that about 15% of the total 5.8 million km^2 of Indonesia's coastal waters should be set aside for seafarming.

Mapping of proposed aquaculture management areas has been carried out in Scotland in relation to fish health, particularly with regard to the spread of Infectious Salmon Anemia (Scottish Executive, 2000). The limits of the individual areas were hydrodynamically defined using estimated tidal excursion as the criterion in relation to

FIGURE 3.1
Potential sites for seafarming development in Lampung



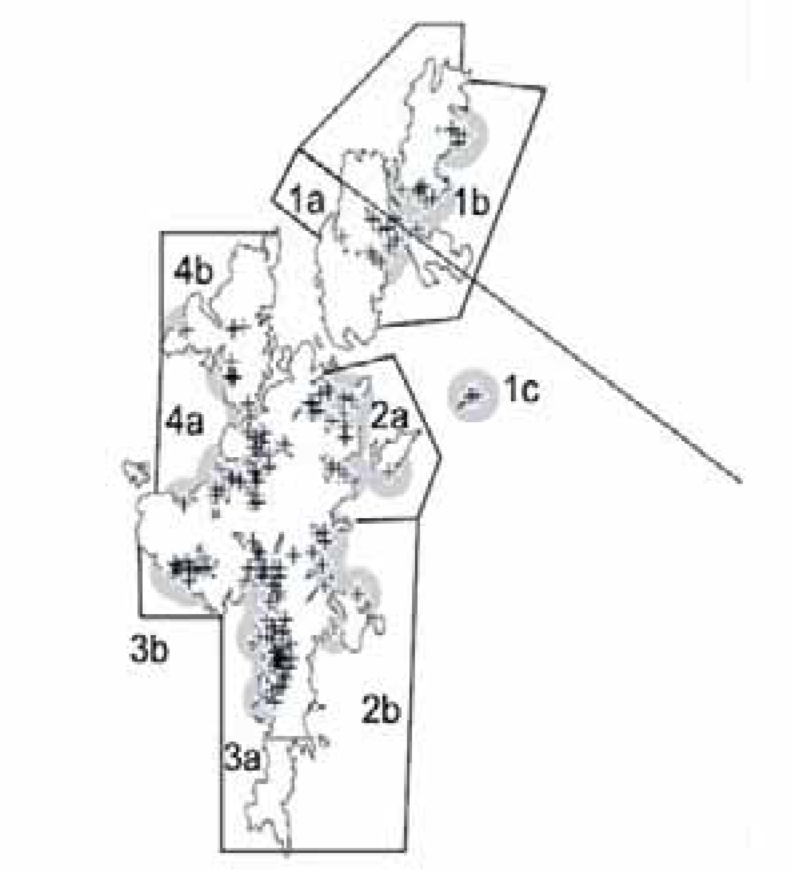
Source: Tiensongrussmee, Pontjoprawiro and Mintarjo (1988)

existing fish farms. Tidal excursion is the horizontal distance along the estuary or tidal river that a particle moves during one tidal cycle of ebb and flow. The procedure was to digitize tidal current maps to produce a 1 km x 1 km map layer. Each map shows the location of every salmon farm in the area, and indicates the tidal excursion around each farm (Figure 3.2).

Management areas are proposed based on the overlap between tidal excursions. In general, where the tidal excursions of adjacent farms overlap, the farms are assigned to the same Management Area. Where there is a break in the overlap, a new Management Area is created. This method minimizes the likelihood of rapid spread of disease, and possibly sea lice, between Management Areas. These maps have been employed for implementing the Code of Good Practice for Scottish Finfish Aquaculture (Scottish Salmon Producers Organization, 2005).

The need for Aquaculture Management Areas (AMA) in the Bay of Plenty, northeast New Zealand, arose during an overwhelming increase in the demand for space for marine farms during the late 1990s (Environment Bay of Plenty, 2006) http://www.ebop.govt.nz/Coast/AMA-project.asp). In effect, the AMAs are zones set aside for aquaculture. The demand for coastal space exposed gaps in the legislation and policy managing aquaculture activities. As a result parliament put in place a moratorium on

FIGURE 3.2
Proposed Management Areas for the aquaculture industry in the coastal waters of the Shetland Isles.



Note: Registered salmon farm sites are identified (+) and the area around each sites with a radius of one tidal excursion is shaded. Labels refer to each Management Area.

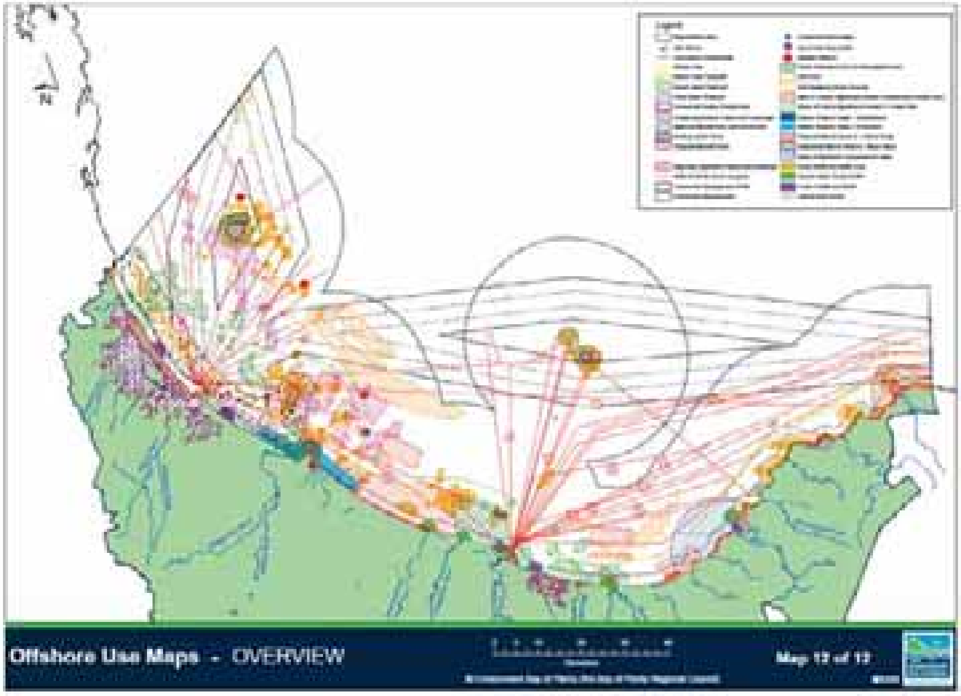
Source: Scottish Executive (2000)

new marine farming applications and the AMA project was begun by the Environment Bay of Plenty Regional Council in 2002 with the objective to identify AMAs in the bay. The project is executed in two steps. The first step is the production of offshore use maps. These maps show all the uses and values associated with the Bay of Plenty offshore environment that may limit where marine farming can take place:

- Map 1 Marine Farms in the Bay of Plenty
- Map 2 Navigation
- Map 3 Areas of Cultural Significance
- Map 4 Ecological Values
- Map 5 Marine Mammal Protection Buffer
- Map 6 Landscape/Amenity Features
- Map 7 Commercial Fishing Effort – Bottom Trawl
- Map 8 Commercial Fishing Effort – Danish Seine
- Map 9 Commercial Fishing Effort – Purse Seine
- Map 10 Bay of Plenty Fisheries – Overview
- Map 11 Recreational Fishing
- Map 12 Bay of Plenty Overview

The small scale overview map of the bay clearly shows the many uses and claims on marine areas. (Figure 3.3). One of the important uses of these maps is to stimulate

FIGURE 3.3
Overview map 12



Source: http://www.ebop.govt.nz/Coast/Offshore-Use-Maps-consultation.asp

public involvement in the aquaculture planning process and to obtain additions and corrections to the draft maps. This is accomplished by soliciting comments through questionnaires and through public meetings.

A second stage, the Offshore Science Project, is working towards determining the productivity and sustainability of aquaculture in the Bay of Plenty through investigating biophysical parameters and effects of aquaculture on the environment.

Mapping activities with the same purpose but different approach to those in the Bay of Plenty have been completed for the Auckland, Region in the north central area of New Zealand by the Auckland Regional Council (2002; no year). The first stage identified and mapped available information on constraints to future marine farming activities across the super-regional study area. Three classes of areas were identified: (1) 'absolutely constrained' areas where marine farming is considered inappropriate, (2) 'limited opportunity' areas for expansion or movement of current marine farming activities, and (3) areas of 'opportunity', apparently exhibiting low presence of constraints and therefore deserving of more detailed investigation (Stage 2 study areas).

As an example, the Stage 1 process concluded by identifying the Kaipara Harbour as an area worthy of further study. (Figure 3.4a) shows the distribution of constraints within the Kaipara Harbour as identified by the Stage 1 Assessment.

The report indicates the need for more detailed Stage 2 studies because the information was collected at a super-regional scale and may not be accurate at larger scales. Further, some Stage 1 information was qualitative rather than quantitative, and some information was missing. However, a finding was that the Stage 1 mapping results (Figure 3.4b) show that there is no overlap in the proposed AMAs with any broadly identified constraints with the exception of the visual amenity buffer. Accordingly, a Stage 2 investigation was initiated to collect more information on constraints

FIGURE 3.4A
Proposed AMAs shown against a background of marine farming constraints identified during the stage 1 assessment process

Source: Auckland Regional Council (no year)

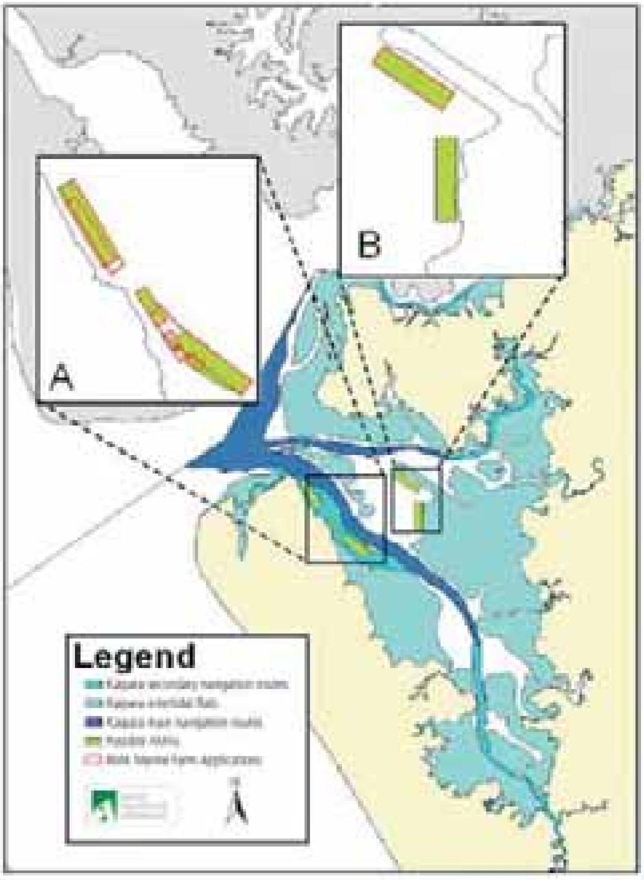
and opportunities and to verify initial Stage 1 findings in more detail. Specifically, suitability for mussel and oyster farming was evaluated, taking into account physical and ecological requirements and constraints, navigational and safety requirements, and natural character (visual amenity component).

Seeking orderly and sustainable development of marine aquaculture in the Andalucia Region of Spain, the Fisheries and Aquaculture Directorate conducted a GIS-based study to identify suitable zones for aquaculture along the nearly 900 km long coast (Macias-Rivero, Castillo y Rey, and Zurita (2003). The goal was to facilitate private initiatives as well as to inform involved government administrations of the state of use of the maritime space in each of the provinces of the region. The study was prompted by the rapid growth of onshore and near shore marine aquaculture along with an increasing number of applications for aquaculture sites in public domain marine waters. The approach was to identify areas with administrative jurisdictional incompatibilities. Twelve criteria were considered among the former:

- Bathymetry
- Port facilities
- Port navigation areas
- Mineral extraction areas
- Protected habitats
- Outfalls and drains
- Submarine cables
- Tourist areas
- Archeological zones

FIGURE 3.4B

Main and secondary navigational routes in the Kaipara Harbour.



Note: Inset "A"shows mussel farming application areas and areas considered further as possible AMAs. Inset "B" shows oyster farming application areas and areas considered further as possible AMAs.

Source: Auckland Regional Council (no year)

- Aquaculture installations, artificial reefs and fish traps
- Ship wrecks
- Military use zones

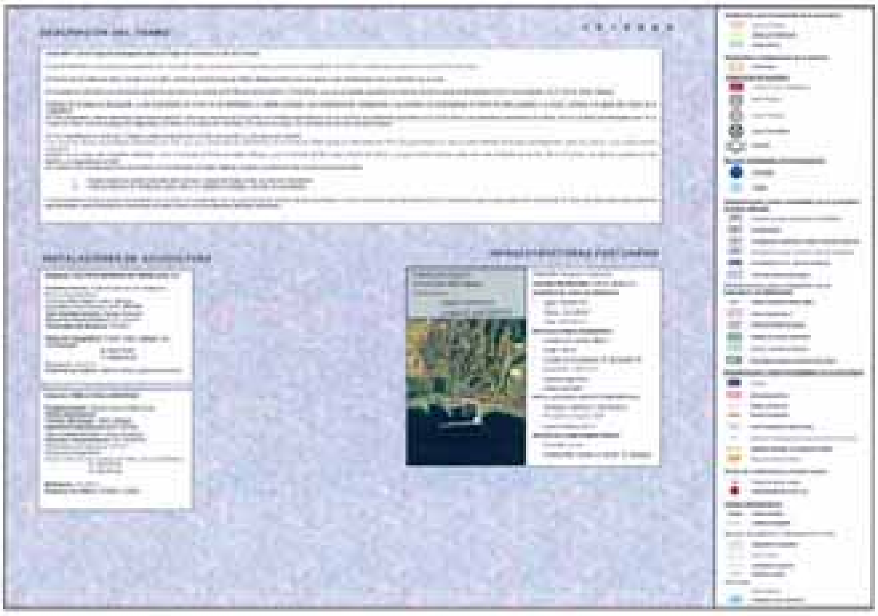
Based on the degree of compatibility among the criteria considered, three kinds of zones were demarcated: (1) suitable zones (no incompatibilities), (2) zones with limitations, and (3) exclusion zones (aquaculture incompatible with already existing uses). The result amounts to a coastal aquaculture use suitability atlas. Each province is introduced by a small scale overview map showing the coverage of the more detailed maps to follow and a page that describes the distance along the province with regard to various kinds of geologic formations (e.g., beaches) compared with the region as a whole. Each detailed map (Figure 3.5a) is accompanied by a page describing the relevant part of the coast in terms of kinds of uses. In addition, individual aquaculture installations are described in general terms as are port characteristics together with aerial photographs or plan views of the port facilities (Figure 3.5b).

In all, about 34% of the region's coast was classified as suitable for marine aquaculture from a competing use standpoint, but the authors expect this area to decrease substantially when environmental conditions also are taken into account.

FIGURE 3.5A
Site selection study to identify potential zones for coastal aquaculture development in Malaga province, Spain

Source: Macias-Rivero, Castillo y Rey and Zurita (2003)

FIGURE 3.5B
Individual aquaculture installations, aerial photograph and plan view of port facility. Malaga province, Spain



Source: Macias-Rivero, Castillo y Rey and Zurita (2003)

3.1.3 Mapping for aquaculture practice and management

The examples in this section relate to the Web-based aquaculture information systems issue. The work described by Jordana (2004) concerning the Catalonia Region of Spain is of particular interest. It deals with the integration of various kinds of data and information in order to develop a combined fisheries and marine aquaculture information system within the General Directorate of Fisheries and Maritime Affairs. Access to the maps is via a server (http://www.gencat.net/darp/c/pescamar/sigpesca/csig25.htm).

The Newfoundland and Labrador Aquaculture Geographic Information System, AquaGIS, (2006) is an Internet-based comprehensive system to collect, manage and distribute aquaculture information (http://www.aquagis.com).It was reviewed extensively by Kapetsky (2004) so only a brief overview of the background is provided here, and emphasis is placed on the functions that have evolved since then.

The project that culminated in AquaGIS commenced in 1997. With over 20 departments involved with the approval process for an aquaculture license, a system to share information was needed. Because an important part of aquaculture development is spatial, GIS became part of the system. AquaGIS integrates data from multiple government departments with the goal of easy access, low cost for users and low maintenance while providing the most up to date information held by each agency. The broad purpose is to serve regional economic, financial and environmental planning activities and its users are both the in the aquaculture industry and government agencies. Specifically, the primary focus of AquaGIS is to facilitate application processing. A secondary part of the site contains information for growers that is not restricted and does not require a username and password. AquaGIS is organized into three services: (1) Mapping, (2) Submission, and (3) Information. A portion of the Help page shows the functions within each service (Figure 3.6a).

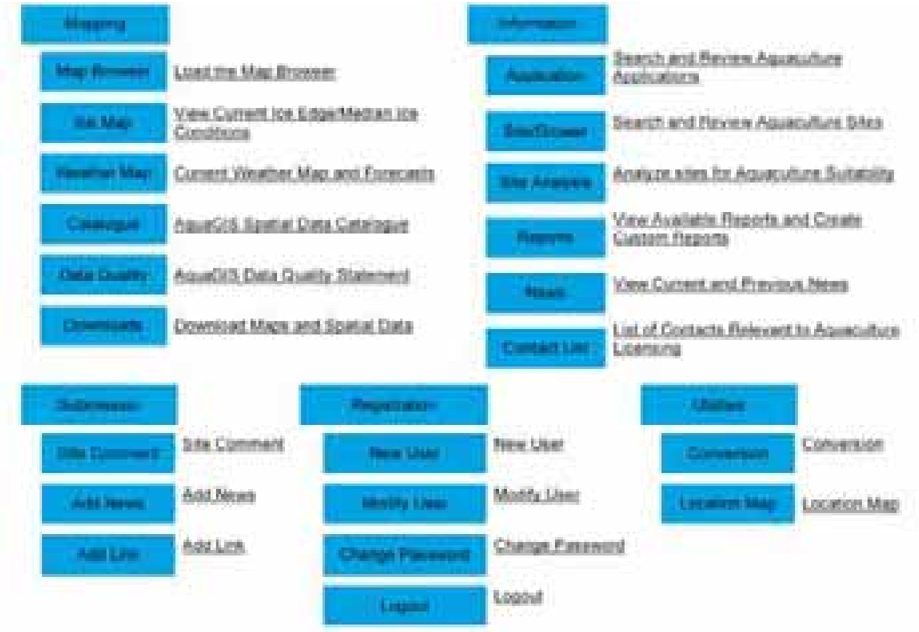
The Mapping Service contains two map browsers, one of which shows aquaculture sites, site boundaries and communities throughout the province. Sites are defined by the kind of product cultured (Figure 3.6b). Another browser is based on the South Coast Regional Aquaculture GIS. Figure 3.6c shows the layers that can be accessed in the South Coast Regional Aquaculture GIS.

The Information Service provides site profiles by species with each record containing basic information on the aquaculture enterprise along with a link to a map of the site that is rendered in the same kind of window as in the Mapping Service (Figure 3.6d). Searches also can be implemented on sites and applications for aquaculture by entering various kinds of information such as location and enterprise name. The new south coast GIS database was designed to enable current and future aquaculturists to assess site suitability and to assemble critical biophysical scientific data. This, in turn, should provide much of the extensive information requirements needed to complete an aquaculture license application. However, according to Colin Taylor (personal communication, 2006) the site analysis capability was not being used by the industry participants, was not deemed a priority and has gone by the wayside.

The Submission Service has a page to submit comments about individual aquaculture sites, news items and links.

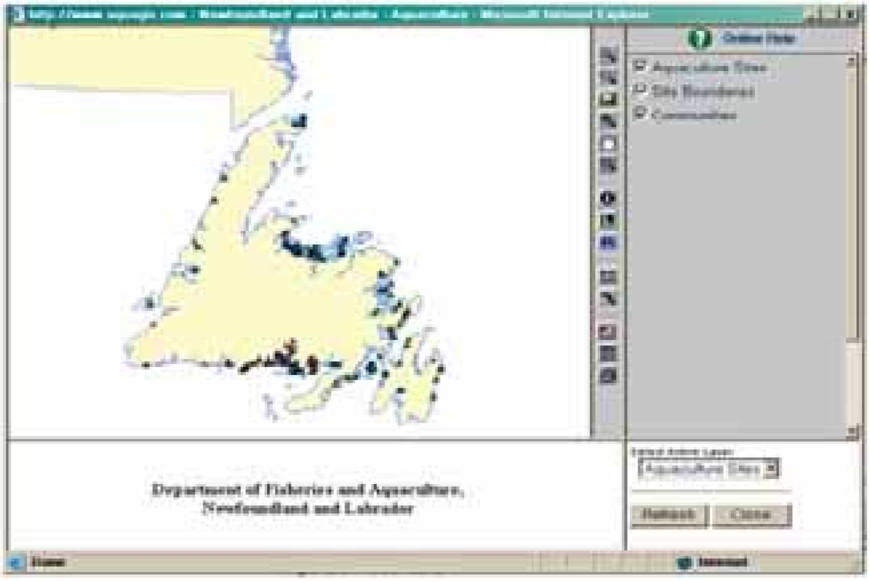
As part of the NOAA National Marine Aquaculture Initiative, the Marine Policy Center of the Woods Hole Oceanographic Institution (2003) has developed several interactive functions on the Internet. One of the interactive functions is the “Site Suitability Modelling Process” (SSMP). The SSMP can be used to compare alternative locations for aquaculture in terms of economic and environmental parameters and other uses. Data layers in the SSMP are shown in Figure 3.7. This view shows potential aquaculture site locations in relation to net revenues from commercial fishing in the adjacent areas.

FIGURE 3.6A
Overview of Available AquaGIS Services from the Help Page



Source: http://www.aquagis.com

FIGURE 3.6B
AquaGIS map browser showing aquaculture sites, site boundaries and communities



Source: http://www.aquagis.com

FIGURE 3.6C

AquaGIS map browser showing layers that can be accessed in the South Coast Regional Aquaculture GIS

Department of Fisheries and Aquaculture,
Newfoundland and Labrador

Source: http://www.aquagis.com

3.2 REMOTE SENSING APPLICATIONS IN MARINE AQUACULTURE

3.2.1 Overview of remote sensing applications

Remote sensing is the gathering and analysis of data from the study area or organism that is physically removed from the sensing equipment, e.g. sub-water surface detection instruments, aircraft or satellite (FAO 2006b).

The potential of remote sensing in fisheries and aquaculture was appreciated and promoted early on by Kapetsky and Caddy (1985), Mooneyhan, (1985) and Travaglia and Appelkamp (1985). Since then remotely sensed data have proven to have many uses in marine aquaculture development and management, but the essential nature of the data has been underemphasized because the data usually become layers in GIS-based studies. The importance and variety of remotely sensed data is covered in Section 5, Data availability. In this section a historical example is presented in which remote sensing figured prominently in site selection and other examples are highlighted in which real time remote sensing plays a vital role in marine aquaculture management.

Historically, due to the lack of digital maps, or conventional paper maps that could be digitized, data from satellite and aerial remote sensing often were used as GIS base maps for coastal aquaculture as shown by the Indonesia example in Section 3.1 on mapping. Another application was to develop land and water use and land cover and underwater layers for strategic planning and site selection (e.g., Kapetsky, McGregor and Nanne, 1987). Up-to-date inventory and monitoring of coastal aquaculture installations as a basis for management and regulation taking advantage of Synthetic Aperture Radar (SAR) satellite sensors for "all weather" observations (e.g., Travaglia *et al.* (2004)) is an application featured as a case study in GISFish. More dynamically, remote sensing also is applied to monitoring coastal water quality, particularly with regard to "red tides" that are a threat to cultured organisms, or indirectly dangerous to man through cultured animals that contain toxins (e.g., shellfish). Other "real-time" or "climatology-type" applications for site selection and zoning include surface water

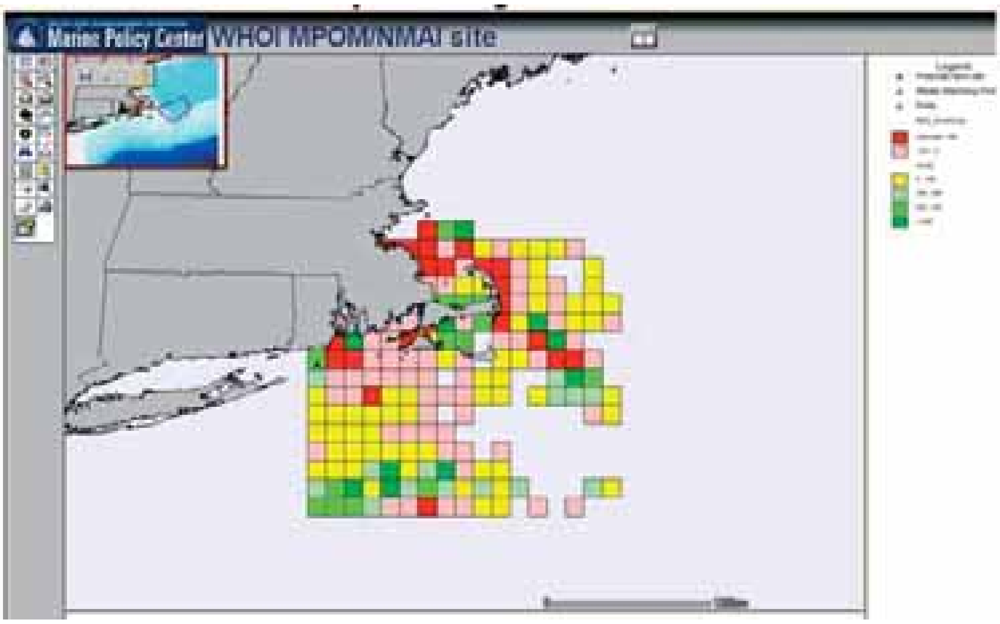
FIGURE 3.6D

Aquaculture site profile and corresponding map location from AquaGIS

Source: http://www.aquagis.com

FIGURE 3.7

Site Suitability Modelling Process



Source: http://ortelius.whoi.edu/website/NMAI01/viewer.htm temperature, wave height, and water currents. Remote sensing at acoustical wave lengths is yet another kind of application in marine aquaculture that has been used to assess build up of organic detritus under fish cages (Hughes Clark, Wildish and Duxfield, 2002).

The objective of this section is to provide an overview of the evolution of remote sensing in marine aquaculture in a variety of applications. The applications are summarized in Table 3.2.

TABLE 3.2
Summary of remote sensing applications in marine aquaculture organized by main issues

Authors	Year	Main thrust or issue	Country	Species
Remote sensing aimed at the development of aquaculture				
Cordell and Nolte	1988	Site suitability and zoning	USA	Oysters
Remote sensing for aquaculture practice and management				
Johannessen, Johannessen, and Haugan	1988	Inventory and monitoring of aquaculture and the environment	Norway and Sweden	Salmon
Travaglia *et al.*	2004	Inventory and monitoring of aquaculture and the environment	Philippines	Fish
Rodriguez-Benito, Haag, and Alvial	2004	Inventory and monitoring of aquaculture and the environment	Chile	Salmon
Van der Woerd *et al.*	2005	Inventory and monitoring of aquaculture and the environment	The Netherlands	Shellfish
National Office for Harmful Algal Blooms, Woods Hole Oceanographic Institution	2006	Inventory and monitoring of aquaculture and the environment	USA and global	Fish and shellfish

3.2.2 Remote sensing aimed at the development of aquaculture

Strategic planning for development

One of the earliest applications of remote sensing to planning for marine aquaculture was along the southeast coast of Alaska, the United States of America (Cordell and Nolte, 1988; summarized as a case study by Meaden and Kapetsky, 1991). The objective was to demonstrate that remote sensing could be cost effective in hard to reach remote areas. The study was aimed at estimating potential for oyster culture.

The authors sought information on a variety of environmental variables that included sea surface temperature, suspended sediments (turbidity), water color (plankton concentrations), sea ice, shallow water bathymetry (water clarity), sea conditions (wave directions, wave length), land use (constraints such as pollution), and sea surface vegetation (kelp).

Six sources of data were used that included satellite imagery from Landsat, SPOT, the Advanced Very High Resolution Radiometer (AVHRR), the Heat Capacity Mapping Mission, the Coastal Zone Color Scanner and infrared imagery from Alaska High Altitude Aerial Photography. The latter proved to be the most cost effective data source. Both visual and spectral analyses were used to derive the results.

Five production factors were scored at four sites within the study area (Table 3.3). The authors indicate several additional factors that should be considered that included proximity to marine wildlife habitats, sea temperatures at the sites, conflicts with existing and foreseen land uses, and proximity to freshwater outflow.

TABLE 3.3
Site selection matrix showing suitability for oyster culture

	Area Size	Mean Depth	Turbidity	Sea Ice	Shelter	Total Score
Blashke Island	3	4	3	3	3	16
Stikine Strait	2	1	1	3	1	8
Anita Bay	3	2	4	3	2	12
Jadski Cove	3	4	4	2	3	18

Factor Scoring

1. Area Size:	1 = < 1 hectare
	2 = 1 to 2 hectares
	3 = > 2 hectares
2. Mean Depth:	1 = < 5 meters or > 20 meters
	2 = 20 to 15 meters
	3 = 15 to 10 meters
	4 = 10 to 5 meters
3. Turbidity:	1 = moderate turbidity (summer)
	2 = low turbidity (summer)
	3 = slight turbidity (summer)
	4 = no turbidity (summer)
4. Sea Ice:	1 = winter sea ice
	2 = possible sea ice
	3 = no sea ice observed
5. Shelter:	1 = occasional high seas possible: two sides protected
	2 = rare high seas: three sides protected
	3 = protected on four sides

Source: Cordell and Nolte (1988)

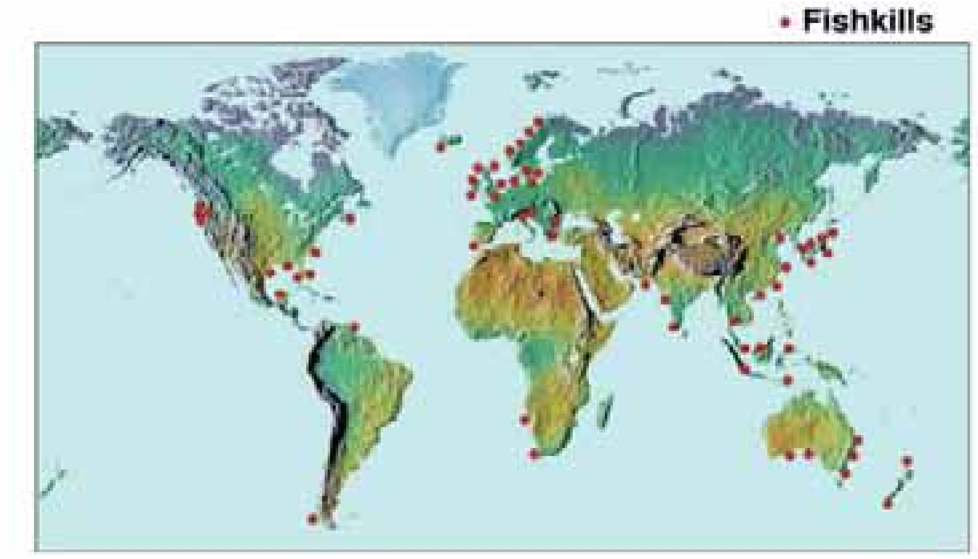
3.2.3 Remote sensing for aquaculture practice and management

Inventory and monitoring of aquaculture and the environment

A harmful algal bloom (HAB) is defined as a proliferation of algae to the extent that harmful, noxious, deleterious or mortal effects on other biota become apparent (van der Woerd *et al.* 2005). Fishes and invertebrates are directly affected by the toxins associated with some kinds of the harmful algae while others indirectly affect the aquatic organisms by oxygen depletion during the decline of a bloom. It is important to note that fishes and invertebrates are not the only organisms affected. Rather, HABs can be harmful to man through direct contact or through consumption of shellfish in which the harmful toxins have become concentrated. For example, according to Hoagland, Kite-Powell and Lin (2003) in 1987 a catastrophic harmful algal bloom, which resulted in 129 amnesiac shellfish poisonings and two deaths, caused a halt in the Prince Edward Island, eastern Canada, mussel industry for a year, and rippled through producers and processors in the entire northeastern American market. Because the economic effect of HABs is great in coastal areas that are important for recreation and tourism, impacts on humans have received more attention than effects on fisheries and marine aquaculture. Nevertheless, there are a number of activities in various parts of the world aimed at detecting and predicting HABs with direct or indirect benefit to marine aquaculture. For example, an Internet site of the National Office for Harmful Algal Blooms, Woods Hole Oceanographic Institute (USA) (2006), in cooperation with the NOAA, provides background information and mapping of occurrences of HABs, some of which pertain to fish and shellfish (http://www.whoi.edu/redtide/index.html) (Figure 3.8a and 3.8b).

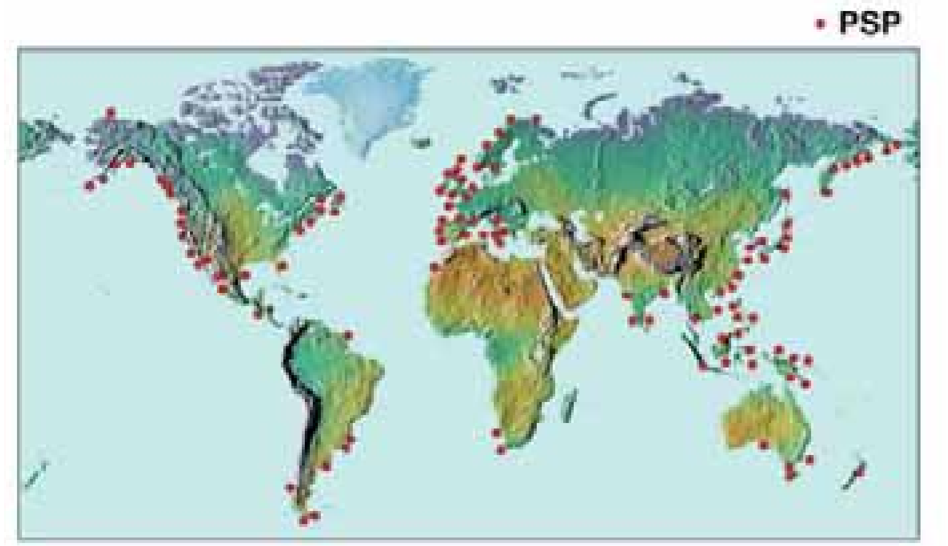
One of the earliest operational applications of airborne satellite remote sensing to marine aquaculture is described by Johannessen, Johannessen, and Haugan (1988) and also summarized as a case study by Meaden and Kapetsky (1991). A HAB was detected and monitored for four weeks as it moved from Sweden to Norway. Side Looking

FIGURE 3.8A
Fish kills



Source: http://www.whoi.edu/redtide/HABdistribution/fishkills_worldmap_2005.gif

FIGURE 3.8B
Paralytic shellfish poisoning

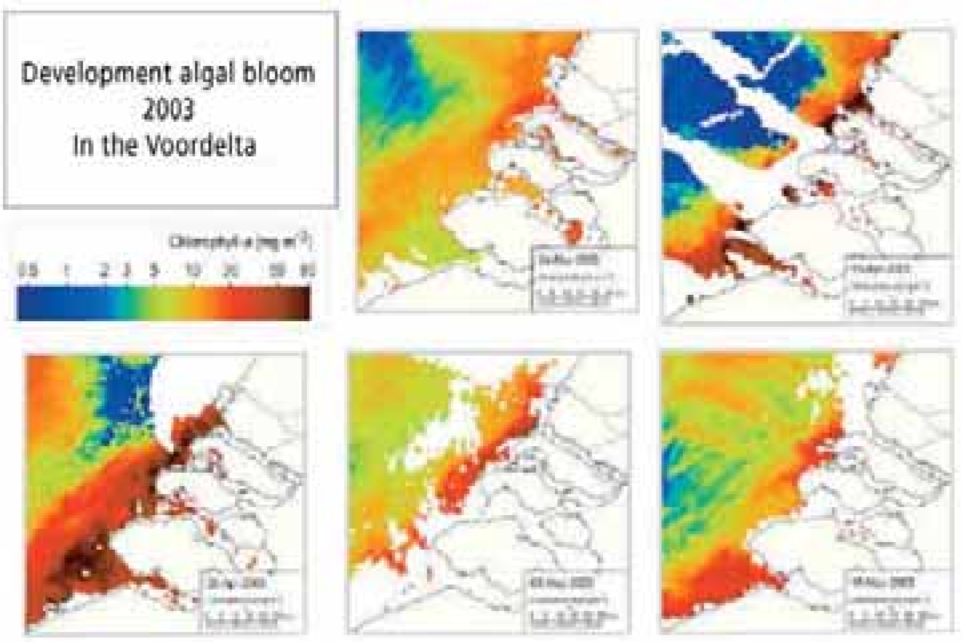


Source: http://www.whoi.edu/redtide/HABdistribution/PSP_worldmap_2005.gif

Airborne Radar on one aircraft and infrared sensors on two others were used to detect ocean fronts The fronts showed that the bloom was advancing along with warm water. AVHRR also was used to estimate sea surface temperature. Sea water sampling showed a correlation between the fronts and the advance of the HAB. The plankton could be seen from aircraft if the sea was calm. The HAB caused major fish kills of wild and farmed fish with great economic loss; however, because of periodic monitoring by remote sensing and forecasts using a water circulation model, some 200 fish farms, mainly salmon, could be evacuated to safe areas in advance of the HAB arrival.

Van der Woerd *et al*. (2005) describe a project carried out in The Netherlands

FIGURE 3.9
Development of an algal bloom in 2003.



Note: The best images for this region have been selected from MERIS REVAMP archive. White indicate land clouds or bad data.

Source: http://www.ivm.falw.vu.nl/Research_projects/index.cfm

aimed at combining information from in situ sampling, modelling and remote sensing to forecast blooms of *Phaeocystis globosa*, an alga that affects shellfish through oxygen depletion. Many harmful algal events result from algal blooms originating off-shore that are transported to near-shore areas where they can cause harm. Therefore, reliable predictions of such harmful algal events would be possible if the location of an offshore bloom can be observed with remote sensing and if a transport model can predict the transport of this bloom. The role of satellite remote sensing is for detection of elevated chlorophyll-a levels and bloom characterization (dimension, growth, transport). Although the spatial and temporal evolution of biomass can be detected, it is without explicit information on species or toxicity. The aim of the project was to fully exploit the observation of algal blooms with the MERIS (Medium Resolution Imaging Spectrometer) instrument on the European ENVISAT satellite.

The project area is the Voordelta, an area of the southern North Sea that is one of the most eutrophic marine systems in the world. High biomass algal blooms are linked to eutrophication (Figure 3.9). Large rivers such as the Rhine and Meuse and other smaller rivers discharge in a relatively shallow shelf sea, enclosed between the United Kingdom of Great Britain and Northern Ireland and continental Europe. On top of this, the projected changes in precipitation patterns in North-West Europe, as a result from climate change, will induce enhanced water and nutrient supply to the coastal area in winter. An increase in algal blooms is therefore expected as the result of increased river run-off in winter and spring. This situation places a premium on prediction of algal blooms in a region where past losses of cultured mussels due to an event in 2001 was estimated at 20 million euros.

A goal of the project was to provide the basis for a twice-weekly early warning bulletin that would summarize the alga spatial development for the previous three days and make a 5-day forecast. In this regard, the combination of remote sensing, and biophysical modelling was tested by hindcasting to 2003. The result was good agreement between the hindcasts and field observations. The authors were confident, that, if implemented, the prediction system incorporating near real time remote sensing would provide results superior to the existing system based only on field sampling.

Chile is one of the world leaders in the culture of salmon, and salmon farming is one of the most important activities in the south of the country. Since 1972 harmful algal blooms have become a growing problem resulting in economic losses. Therefore, prediction of algal blooms is seen as an important initiative to reduce losses.

Rodriguez-Benito Haag and Alvial (2004) describe a project that has been carried out with the objective to demonstrate the applicability of remote sensing to forecast phytoplankton bloom events using MERIS and Advanced Along Track Scanning Radiometer (AATSR) satellite images. Using data from these sources an algal bloom was detected that proved to be *Gymnodinium*. The bloom depressed dissolved oxygen and caused salmon mortalities.

Overall, good results were obtained from the comparison between the in situ temperature and chlorophyll measurements and the observations from the space. Correlation results were higher than 96% for the SST data and more than 86% for total phytoplankton chlorophyll.

3.3 GEOGRAPHIC INFORMATION SYSTEMS APPLICATIONS IN MARINE AQUACULTURE

Our approach is to review the applications according to the kind of organisms being cultured (shellfishes), or by the type of culture structure employed (cages) because each has its own particular spatial issues and solutions. Using this approach allows us to illustrate the evolution of GIS applications related to a particular issue and organism, and sometimes also to follow a sequence of studies within the same geographic area.

For clarity, we have standardized the terminology. Concerning criteria, there are two general kinds: (1) Production factors that are variables that enhance, or detract from, the suitability for a specific use under consideration. They are, therefore, measured on a continuous scale, and (2) Constraints, that, by contrast, serve to limit areas into two Boolean categories such as “suitable”, or “unsuitable”.

3.3.1 Introduction to Geographic Information Systems applications to marine cages

Cage aquaculture has been broadly covered by Beveridge (2004). Culture of fish in cages is important by virtue of the relatively high cost of the cultured product.

Proximity from shore determines the kinds of spatial analyses that have to be considered. From a geographic point of view several kinds of related analyses are pertinent depending on whether the location of cages is intended to be near shore or offshore. Near shore installations may have to take into account visual impacts of cage farms and may have to deal with water quality both from the viewpoints of pollutants emanating from the land and of impacts of farm wastes on the local environment. Offshore facilities are less concerned with these kinds of analyses because they usually are not within a shore-based viewshed and because of the greater volume available for water exchange offshore. In contrast, both near shore and offshore locations have the following kinds of analyses in common: (1) siting or zoning of the near shore or offshore area for a generic or specific cage design, (2) location of a shore support facility, and (3) time, distance and reliability of over-water (or air) support from the shore facility to the offshore facility.

Another criterion of importance is tethering (anchoring). Cage sites for tethered structures have to be evaluated on the basis of depth, the anchoring characteristics of various bottom materials, and on the basis of slope. Untethered cages, such as the ocean drifter foreseen by Goudey (1998), would depend largely on currents and gyres to maintain environmental conditions favorable for the cultured organisms. Thus, prediction of cage location and of the prevailing ocean conditions would become important aspects of "dynamic" cage siting.

The applications are organized into three main issues categories along with issues sub-categories as shown in Table 2.1. Table 3.4 summarizes the applications.

GIS aimed at the development of marine cage aquaculture

Suitability of the site and zoning

The applications in this section range from those narrowly focused on siting aquaculture to meet the specific needs of the organism and culture system to those in which satisfying aquaculture requirements as well as accommodating other uses plays a prominent role in zoning. The application of GIS for coastal aquaculture site selection was evaluated by Ross, Mendoza and Beveridge (1993) in a small (20 ha) bay in Scotland using salmonid cage culture as the example. They analyzed bathymetry, currents, and exposure in terms of predicted wave height. Water quality parameters, including dissolved oxygen, temperature and salinity also were considered, but the former two were not limiting at the site and not further analyzed. The point data were interpolated in various ways. A scoring system was used within each factor, but no formal weighing system among factors was applied. The total area suitable for cage culture was 1.26 ha in one portion of the bay. In comparison with the GIS results, a panel of experts suggested suitable locations in several places in the bay. The GIS results and expert opinions were broadly comparable. The authors point out a number of sources of error including inaccuracy of data, the choice of production functions (i.e., factors) selected as well as their temporal and spatial variability, the analytical approach adopted, and the restrictions imposed on the spatial model utilized. Finally, regarding the analytical approach, they show how the order of analysis of factors produces different results and thereby affects decision-making.

Site selection for rainbow trout, *Oncorhynchus mykiss*, to be raised in cages submersed from 10 to 20 m, was carried out in the Surmene Bay of the Black Sea, Turkey by Guneroglu *et al.* (2005). Selection was based on the following criteria and ranges: "If 10≤temperature≤15 and salinity≤19‰ and if 10≤current velocity≤50". A comparison was made between the Inverse Distance Weight and Kriging methods that were used to interpolate the values of field observations and no significant differences were found between them.

The wave climate of offshore installations is an important site selection factor for several reasons. The first is potential for outright destruction caused by storms and the second is normal wear and tear resulting in structural fatigue caused by the prevailing wave motion. A third consideration is the design and operation of vessels to service offshore sites. Pérez, Telfer and Ross (2003a) dealt with the former two of these in relation to siting of floating cages for seabream (*Sparus aurata*) and seabass (*Dicentrarchus labrax*) in offshore areas of Tenerife Island, Spain. GIS was used in this study in two ways: for a visual inventory of the characteristics of the wave environment as thematic maps and for the generation of suitability maps for different commercial cage systems.

The authors used data from 15 points around Tenerife to estimate average and maximum wave height, wave energy and wave direction over a five-year period. Cluster analysis was used to identify four wave zones relating to amount of exposure. Using Voronoi Tessellation techniques, average and maximum wave height maps were generated. These maps were then reclassified and combined using scoring techniques relative to the wave climate design characteristics of three types of commercial cages. The result was a wave suitability map for each kind of cage (Figure 3.10).

TABLE 3.4

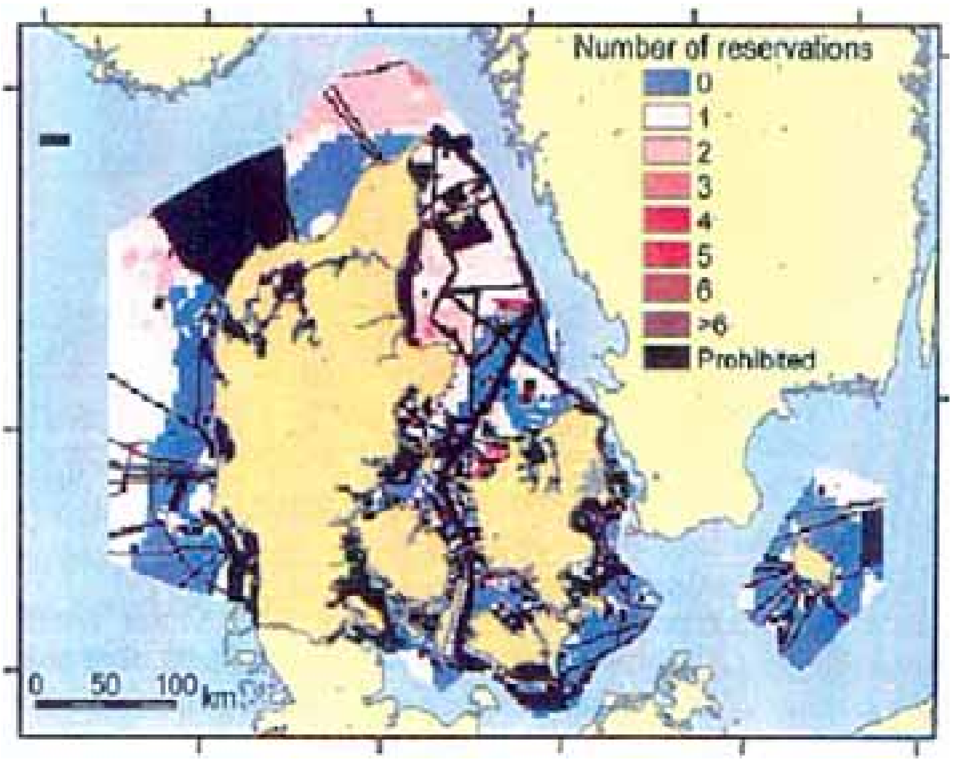
Summary of GIS applications to culture of finfishes in cages organized by main issues

Authors	Year	Main thrust or issue	Country	Species	Software	Decision support
GIS aimed at development of aquaculture						
Kapetsky, McGregor and Nanne	1987	Strategic planning for development	Costa Rica	Fishes, mussels, oysters	Earth Resources Applications Software (ELAS)	Thresholds w/o weighting, field verification
Kapetsky	1989	Strategic planning for development	Malaysia	Fishes, mussels	ERDAS (Earth Resources Data analysis System) v. 7.2	Thresholds w/o weighting, field verification
Ross, Mendoza, and Beveridge	1993	Suitability of the site and zoning	UK	Salmonids	OSU-MAP for the PC	Thresholds w/o weighting, expert verification
Servicio de Pesca y Acuicultura	2000	Suitability of the site and zoning	Spain	Fishes	Not stated	Thresholds w/o weighting
Young *et al*.	2003	Strategic planning for development	USA	Fishes	N/G	Expert opinion, thresholds and weighting
Hoagland, Kite-Powell and Lin	2003	Economics	USA	Summer flounder	N/G	N/G
Pérez, Telfer and Ross	2003a	Suitability of the site and zoning	Spain	Sea bream and sea bass	Idrisi 32, Cartalinx 1.2	Expert Opinion and MCE
Pérez, Telfer and Ross	2003b	Suitability of the site and zoning	Spain	N/A	Idrisi 32.v1.1	Expert Opinion and MCE
Geitner	2004	Suitability of the site and zoning	Denmark	Rainbow trout	ArcView 3.2, ArcView GIS 8.2, Spatial Analyst	Expert opinion, thresholds, weighting, and field verification
Guneroglu *et al*.	2005	Suitability of the site and zoning	Turkey	Rainbow trout	ArcInfo 8.0.2 and Arcview 3.2	Thresholds w/o weighting
Pérez, Telfer and Ross	2005	Suitability of the site and zoning	Spain	Sea bream and sea bass	Idrisi 32 v 1.1, ERDAS Image v 8.3.1	Expert Opinion, MCE and estimates of carrying capacity for cages
GIS for aquaculture practice and management						
Pérez *et al*.	2002	Environmental impacts of aquaculture	UK	Atlantic salmon	Idrisi 32 v. 1.1	Particulate waste distribution for Atlantic Salmon with field verification
Corner *et al*.	2006	Environmental impacts of aquaculture	UK	Atlantic salmon	Idrisi 32 plus extension	Particulate waste distribution model for Atlantic Salmon with field verification
Multisectoral planning and management including aquaculture						
Pavasovic	2004	Planning for aquaculture among other uses of land and water	Croatia	Salmonids and oysters	ArcView 3.2 with Avenue scripts	Thresholds and linear weighted modelling
Chang, Page and Hill	2005	Planning for aquaculture among other uses of land and water	Canada	Atlantic salmon	MapInfo Professional 7.0	Thresholds w/o weighting

FIGURE 3.10
Wave suitability map for (a) SeaStation, (b) Ocean Spar and (c) Corelsa cages

Source: Pérez (2003a)

FIGURE 3.11
Map on entire reservations.



Note: Dark blue shows areas with no reservations. Light blue is outside of the analyzed area. Red colours show the number of overlapping themes from one (light) to ten (dark). The number of seven to ten reservations is represented with one group. Areas where there is prohibition against the placement of mariculture are shown with black. Light yellow shows land areas of Denmark and surrounding countries.

Source: Geitner (2004)

A study aimed at the identification of areas with potential for marine aquaculture in the context of zoning for aquaculture as one aspect of coastal management was conducted for the Murcia Region of the Mediterranean coast of Spain (Servicio de Pesca y Acuicultura, 2000) where floating cage culture of fishes already had been established in nine installations. From an administrative viewpoint the study was shaped by information from entities dealing with coastal management, tourism, coastal mapping, environment and the military. The basic map data consisted of bathymetry (depths < 25 m), artificial reefs, sunken vessels, a marine reserve, ports, populated areas and existing aquaculture installations along with those in the process of approval. The first step was to map the coast relative to the concerns and criteria of each administrative entity in three classes: (1) area apt for aquaculture that is compatible with all uses, (2) aptitude requires study with eventual approval possible, and (3) areas incompatible for aquaculture development. Integration of the concerns of all of the administrative entities together resulted in zoning maps with the following categories: adequate; adequate with some reservations; inadequate for reasons of depth; incompatible from environmental or military standpoint; and areas prohibited by the military. As a conclusion the study emphasized the need for participation by all users of the coast in order to have an objective result.

The placement of net and wire cages for rainbow trout (*Oncorhyncus myksis*) culture in marine waters was reported by Geitner (2004). This study was part of a broad-based effort to clarify the future production from mariculture within the 100 000 km^2 EEZ of Denmark that was undertaken by a Mariculture Committee consisting of representatives from several ministries, angling and mariculture interest groups and consultants. The task of the committee was to promote mariculture while minimizing environmental impacts.

Data for the GIS were considered in two parts (1) those required to assess mariculture operations: bathymetry, temperature, salinity, current velocity, wave height, tide height, and (2) competing uses as restrictions (constraints) or as considerations (factors): existing mariculture, oil drilling platforms, disposal areas, potential and actual mineral extraction areas, sewage discharge, shipping routes, pipes and cables, military areas, danger areas, protected and reserved areas, biologically sensitive areas and estuaries.

The scoring system was straight-forward: numbers of restrictions and considerations were added for any given area. In all, about 75% of the entire EEZ was evaluated and about 25% of the EEZ was without either restrictions or considerations and thus suitable for cage culture (Figure 3.11).

The mariculturists in the project verified that the suitable areas identified via the GIS corresponded to their prior perceptions of suitable areas.

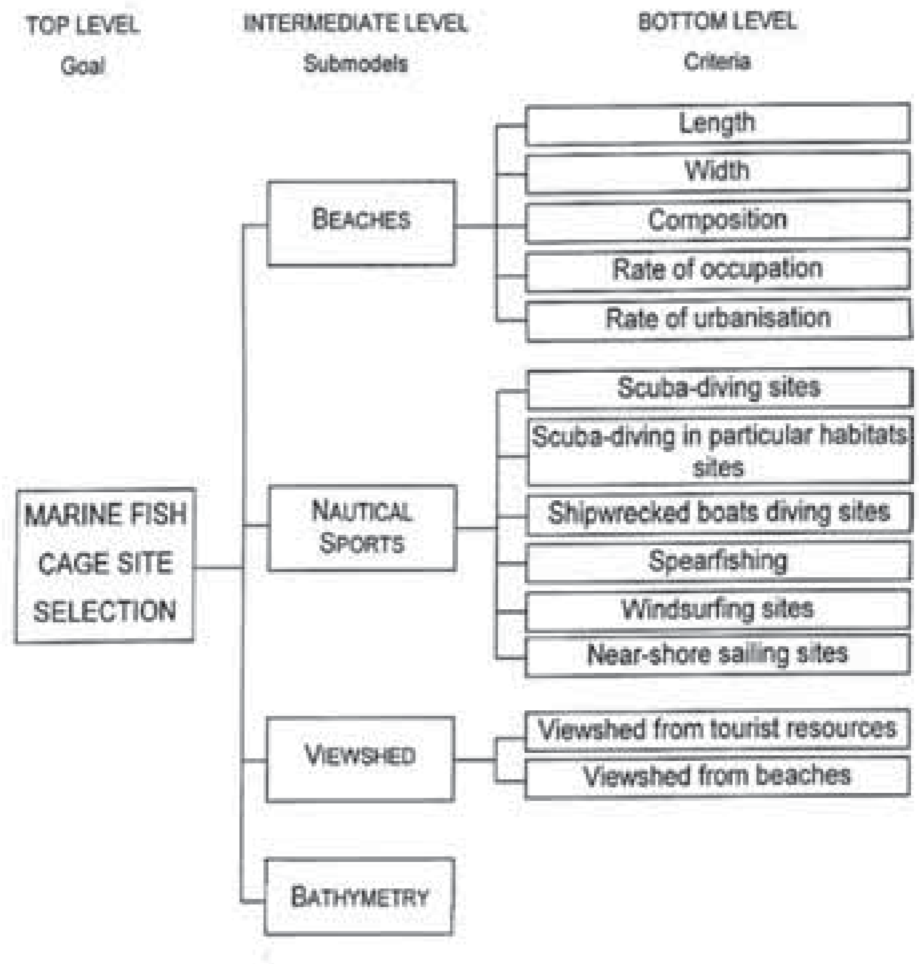
Additional criteria to improve the model included distance from a shore facility to a suitable area, as well as beach recreational areas, holiday houses, fishing areas, areas of archeological importance, and occurrence of macro algae. In order to improve analytical capabilities a more sophisticated weighting system was suggested by the author.

Tourism is the most important sector in the economy of Tenerife, Canary Islands. In this light Pérez,Telfer and Ross (2003b) evaluated the integration and coexistence of marine fish cages within the tourism industry. Tenerife has a number of advantages for marine aquaculture including a ready market, favorable temperature and good water quality, but there is a scarcity of land, and sheltered near shore areas are already dedicated to other uses.

The authors used a hierarchical process to organize their criteria into sub-models that included beaches, nautical sports and the viewshed (Figure 3.12a). Criteria within sub-models were scored and weighted using Multiple Criteria Evaluation techniques. This is a two-step process: (1) the relative importance of criteria within a sub-model is determined by pair-wise comparisons, and (2) weights are placed on each sub-model. Finally, the results are integrated for an overall assessment.

One of the most important objections to near shore cage installations is the negative impact on the view. The viewshed sub-model is of particular interest in dealing with this factor. The viewshed is based on using beaches and prominent buildings associated with tourism as the observation points. The visibility of a potential cage site was based on a distance of 2 km as determined with a digital elevation model.

FIGURE 3.12A
Conceptual structure of the suitability analysis for integration of marine fish cages within the tourism industry in Tenerife



Source: Pérez, Telfer and Ross (2003b)

Combining the sub-models, the overall result was that 46% of the available area (< 50 m) was very suitable and an additional 10% was suitable.

Subsequently, the same authors (Pérez, Telfer and Ross, 2005) expanded their study in Tenerife by considering 31 production functions for offshore floating cage culture with the objective of developing a standard methodology for cage site selection in an island environment. This application is noteworthy for the variety of production functions considered as well as for carrying on beyond siting results to estimate the actual capacity for cages.The multiple criteria approach was similar to that described for their earlier study. Decision makers in three focus groups decided on the relative importance of the production functions. Each focus group consisted of four individuals with different experience in the field. The three groups comprised (1) aquaculture researchers from the Department of Aquaculture of the Spanish Oceanographic Centre in Tenerife (COC), (2) marine fish cage farmers in Tenerife, and (3) Ph,D., and M.Sc. students at the Institute of Aquaculture, University of Stirling, the United Kingdom of Great Britain and Northern Ireland, with experience in marine aquaculture. Questionnaires were used to obtain feed-back. The production functions were organized into sub-models that included seven factors and one constraint sub-model along with the derived weights on each as summarized in Figure 3.12b. Satellite remote sensing was used to estimate sea surface temperature for the water quality sub-model.

Of the 228 km^2 of available area, 37 km^2 were deemed suitable for offshore cages. Using various assumptions about cage size and number as well as distance between cage farms, the authors calculated that Tenerife could support up to 22 farms of 12 cages each. In turn, making other assumptions on production rates per cage and the market for farmed fish, the authors estimated a total potential output from cage farms approaching 11 000 tonnes with a possible gross contribution to the island economy amounting to 0.5% of the gross domestic product.

Improvements that could be made to the study identified by the authors included the addition of bottom type in relation to kind and cost of cage anchoring systems and with regard to assimilative capacity of the environment to fish and feed waste. A particulate distribution model developed by Pérez *et al.* (2002) (Section on "Environmental impacts of aquaculture" below) was not used in this study because of a lack of data on currents.

Strategic planning for development

The three examples reviewed herein pertain to pre-siting studies, the results of which are indicative of the most promising locations for further detailed field investigations that would be undertaken by commercial developers of marine aquaculture, or by government officials responsible for zoning. In this regard, the applications can be viewed as pertaining to the issue of strategic planning for development. In contrast to the other examples that deal with culture of fish in cages, one example deals with seaweed culture. It is placed here because seaweed culture can employ structures that are suspended from rafts or longlines.

Among the earliest work, in the Gulf of Nicoya, Costa Rica (Kapetsky, McGregor and Nanne, 1987) was conducted to promote the use of GIS and it was not solely aimed at farming of fishes in cages, but included sub-tidal and intertidal shellfish culture and shrimp farming in ponds. The study took into account the need for shelter with regard to storms and the effect of wear and tear on surface cages and rafts by determining prevalent wind and storm directions and by calculating wave height based on wind speed and fetch. Security in terms of proximity, transportation infrastructure, salinity and water quality in relation to land use also were considered. In a parallel study, Jacquet (1987) analyzed Landsat imagery for water quality in the gulf.

It was concluded that the results were indicative of opportunities for aquaculture development for general planning purposes and that additional verification in the water and on the ground was required. Suggested improvements dealt with updating and adding production factors relating to infrastructure, physical and chemical environment of the water, land uses and economics.

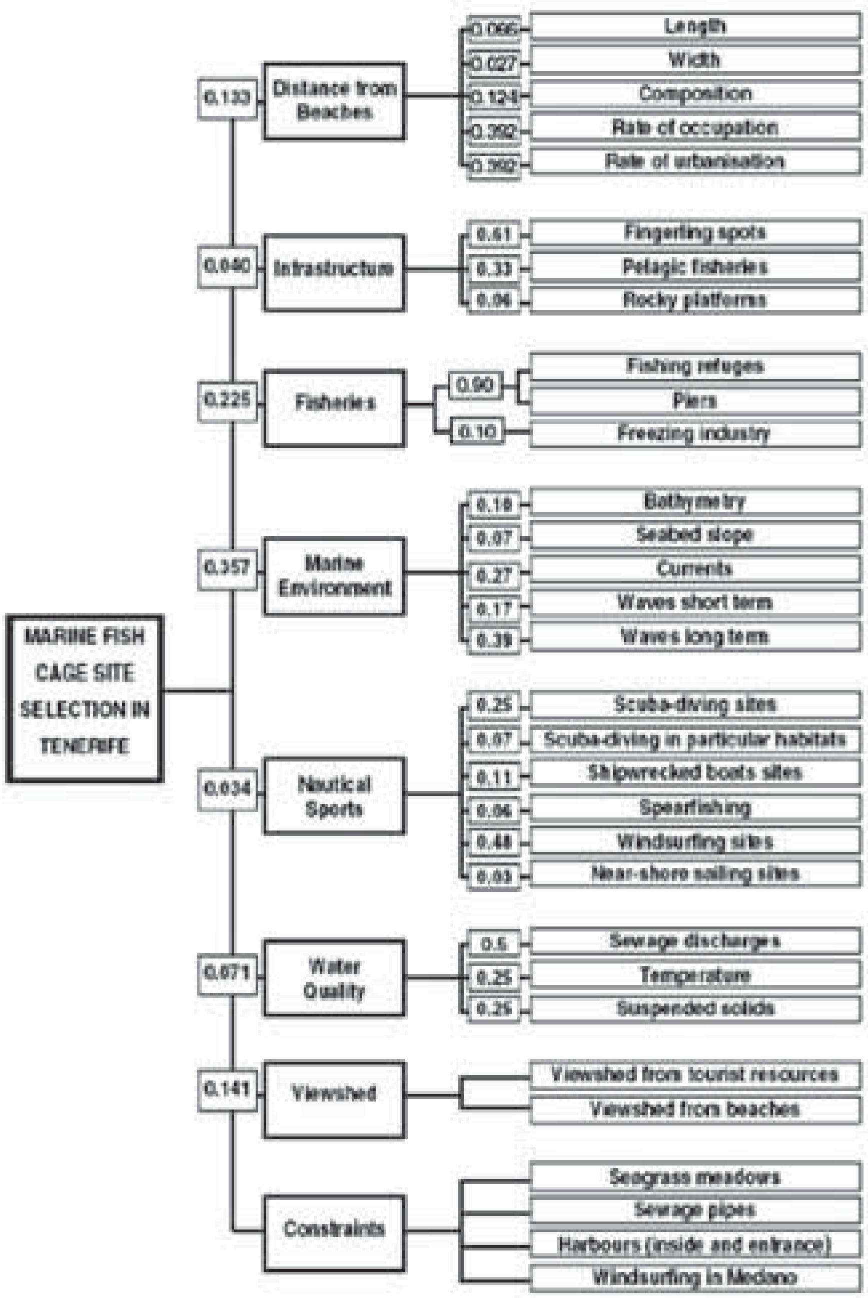
Infrastructure, water quality attributes in relation to land use, water depth, shelter, and current speed were taken into account in assessing floating fish cage potential as part of aquaculture development possibilities in the State of Johor, Malaysia (Kapetsky, 1989). This study followed a methodology similar to that of Kapetsky, McGregor and Nane (1987), but was undertaken to train government officers on the theory and practical application of GIS as well as to make a practical contribution to strategic planning.

An archipelago-based study of offshore areas suitable for consideration for open ocean cage culture was that of Young *et al.* (2003) in Hawaii, the United States of America.

This is an example of the results that can be obtained when the need to limit project costs is a constraint: only existing data were utilized, current speed and direction were modeled and no field data were collected. In turn, these constraints necessitated the

FIGURE 3.12

Conceptual structure of the suitability analysis for marine fish cage site selection in Tenerife (as a hierarchical structure) showing the weights assigned to the different factors and submodels



Source: Pérez, Telfer and Ross (2003b)

use of a model with only four general production factors that included bathymetry, restricted areas (military, harbor, and navigation), water class with respect to US Environmental Protection Agency regulations, and a 3-mile (4.8 km) boundary from shore. The possibility to vary both the importance of production factors and to scale criteria within factors was a feature in the model.

Despite the limitations, the approach was found useful for statewide aquaculture planning.

GIS for aquaculture practice and management of marine cages

Environmental impacts of aquaculture

One example of environmental impacts of aquaculture are effluents from fish cages in the form of uneaten food and excreta from the fish that affect water quality and bottom organisms in the vicinity of the cage. In practical terms, if the wastes cannot be processed in the nearby sediments, they may affect the health of the cultured fish and impact the natural adjacent environment. According to Corner *et al*. (2006), estimating the environmental impacts of cage farms through the use of particulate waste dispersion models has a number of applications that include cost-effective methods to evaluate outcomes in site selection and biomass limits in terms of local environmental capacity, setting quality standards, and aiding decision-making for environmental regulation and management by testing a variety of pre-production scenarios for given environmental conditions.

Pérez *et al*. (2002) developed GIS spatial modelling techniques for particulate waste distribution for Atlantic salmon, *Salmo salar*, raised in cages. The model was developed in three main steps: (1) quantification of the waste material (uneaten feed and faeces) using mass balance techniques, (2) calculation of the distribution of the waste components, and (3) calculation and generation of the final contour distribution diagrams using the GIS. The specific role of the GIS was to first interpolate the carbon values from the point estimates generated by the model. Then filters were used to adjust the distribution of the carbon in space relative to changing current velocities and directions. The model was tested against data collected at a salmon farm site. The result was that there was a strong correlation between the predicted and actual carbon results. The GIS output is a contour map showing the distribution and concentration of the fish wastes and uneaten feed on the substrate as carbon among 18 cages in two rows of nine cages and in the adjacent area.

The authors foresee potential applications for the model for Environmental Impact Assessment (EIA), design of monitoring programs, site selection, farm management and rapid generation of ‘what if?’ scenarios.

The work of Pérez *et al*. (*op cit.*) has been extended by Corner *et al*. (2006) so that the model is fully integrated into the GIS. The advantage over the spreadsheet and GIS combination used by Pérez *et al*. (*op cit.*) is that it ensures that there is no data loss when integrating data from various sources and the outputs from the waste dispersion module can become one of a number of layers within an integrated Coastal Zone Management (ICZM) approach to aquaculture site management. The architecture of the model is shown in Figure 3.13. The model was validated by comparing model predictions with observed deposition measured using sediment traps during three 2-week field trips at a fish farm on the west coast of Scotland.

Another innovation of this study is accounting for the effect of fish cage movement on waster dispersion (Figure 3.14). The system output is a set of raster images from which further graphical or statistical information can be generated depending upon the requirements of the particular application. The system can operate at any spatial resolution and the 1 m^2 used in this study is particularly suitable for farm level particulate dispersion modelling and with the potential to use larger scales in an assessment of complex multisite systems.

Overall accuracy of the model, 58%, was affected by observed versus predicted differences under the cages and away from the cages. Nevertheless, the authors state that there are two main applications of their dispersion model (1) providing the industry with a free-standing tool that can be tested at the farm scale, and (2) environmental management of aquaculture sites, including aspects such as carrying capacity prediction, land–water interactions and multisite effects.

From a GIS viewpoint, this study draws attention to the importance of user defined

FIGURE 3.13
Architecture of the integrated model

Source: Corner *et al.* (2006)

modules as extensions. Also, working within the GIS provides the opportunity to develop new applications.

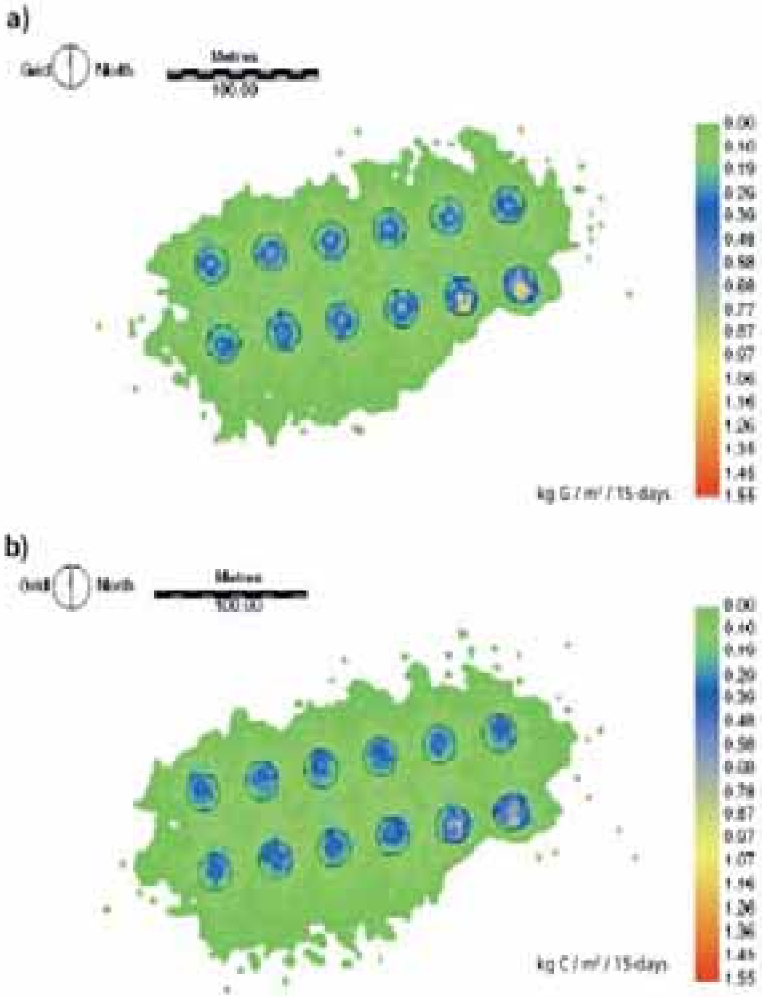
GIS for multisectoral development and management that includes marine aquaculture in cages

Planning of aquaculture among other uses of land and water

There is a scarcity of studies that are in the realm of coastal area management in which aquaculture is specifically included as one of the uses or in which aquaculture receives special attention; however, the study of Pavasovic (2004) is an exception. His investigation is noteworthy because it is couched in the broader context of coastal zone management and because the output is not a technical report or publication, but rather a tool that is designed to be used by coastal zone management personnel with only a basic knowledge of GIS. He describes an investigation on suitability for aquaculture at two locations in the Croatian portion of the Adriatic Sea. The overall project is entitled Coastal Zone Management Plan for Croatia with Particular Focus

FIGURE 3.14

Contour raster image for fish farm site showing predicted faecal carbon settlement to the sediment, using GIS dispersion model. (a) Static cages model, (b) moving cages model



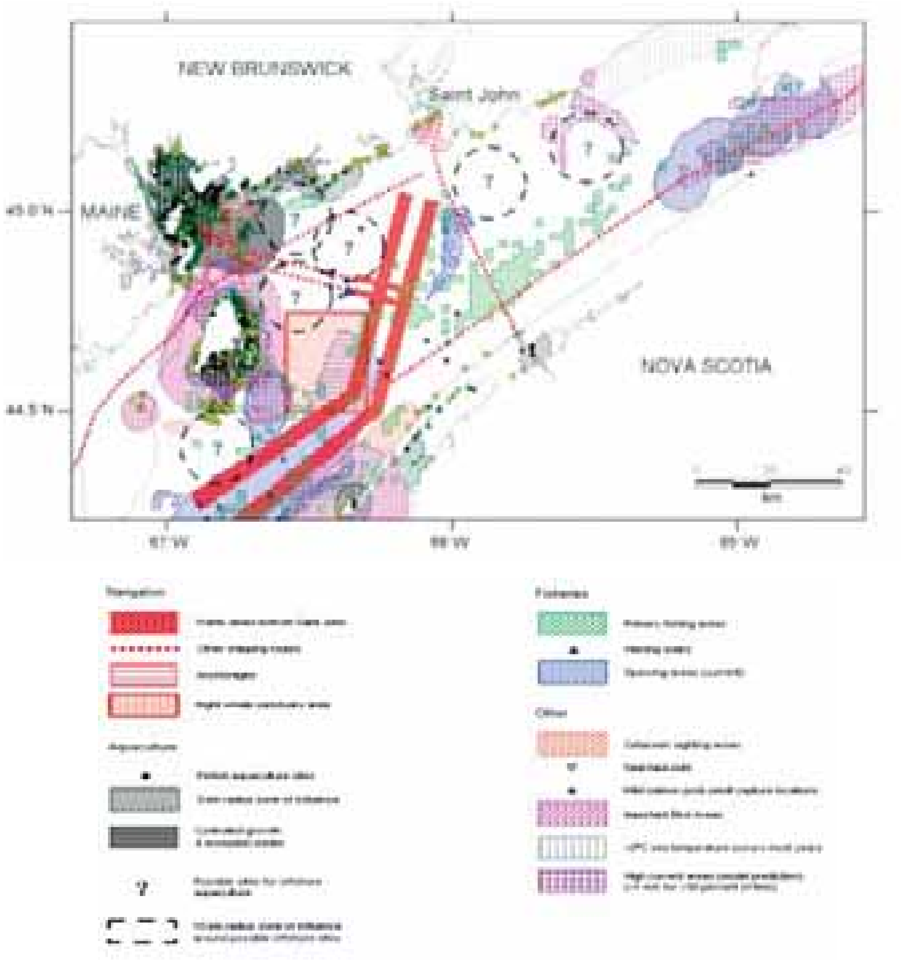
Source: Corner *et al*. (2006)

on Marine Aquaculture" with the main objective to prepare guidelines and procedures for planning, integration and monitoring of marine aquaculture in Croatia. Several Croatian ministries, scientific institutions and national and international experts participated.

The objectives of the GIS portion of the project were: (1) user-friendliness: the tool must be simple so it can be used by persons with basic knowledge of GIS software, (2) flexibility of analysis: the tool must enable testing of different scenarios, (3) transparency of the modelling process: the tool must make the "black box" between the input data and the results as transparent as possible especially with regard to understanding how certain values for some model parameter affect the final result, and (4) the tool must be versatile: it must support analyses other than for marine aquaculture based on adaptations of the database. Although the main use of the tool is suitability analysis, an underlying objective is to achieve the participatory planning potential of the tool. That is, those of the public with an economic interest in some development could use the tool to understand the objectivity of the analytical procedure and to take advantage of proposing different scenarios to achieve alternative locations.

In order to achieve these objectives, the GIS supports three modules: (1) classification

FIGURE 3.15
Open ocean aquaculture in the Bay of Fundy, Canada



Source: Chang, Page and Hill (2005)

of criteria (production factors), (2) modelling to eliminate areas not meeting criteria values proposed by the user, and (3) linear weighted modelling in which weights are assigned to the criteria. The latter two modules support five scenarios each.

The broadest study of marine aquaculture in terms of competing uses is that of Chang, Page and Hill (2005) who analyzed open ocean aquaculture in the Bay of Fundy, Canada with the objective of mapping to assist the aquaculture industry, coastal zone managers and stakeholders in their deliberations about aquaculture potential. The Canadian portion of the Bay of Fundy is 15 300 km^2 with offshore depths from 50 to 200 m and tidal ranges from 4 to more than 12 m.

An advantage to this study was the insight gained from already well established near shore cage farming of Atlantic salmon (*Salmo salar*).

The main categories of production functions they considered include the physical environment, existing marine finfish aquaculture, ship traffic, commercial fisheries, and protected or endangered species and protected areas (Figure 3.15).

The result was that there were virtually no areas of the Bay of Fundy where there were no competing uses. Thus, the authors conclude that the main challenges for management are to (1) reduce conflict within the areas of overlap to a minimum, and (2) balance potential detrimental impacts of open ocean aquaculture with its potential economic, social and environmental benefits. As an analytical approach the authors advocate proceeding by stages. The first stage is essentially a constraints map in which no aquaculture is to be allowed either for physical reasons (e.g., risk of temperatures too low for salmon) or because of competing uses (e.g., the most productive fishing areas, busiest shipping lanes). Then, a second stage would attempt to balance aquaculture suitability within areas of less compelling competing uses.

Regarding how many open ocean aquaculture sites could be allowed in any one area, the authors consider a separation distance equivalent to one tidal excursion as a criterion. Thus, the greater the tidal current speed, the larger the tidal excursion and the greater the distance between sites.

Finally, with regard to data and including additional production functions, the authors indicate that there are issues and activities for which there are no spatial data available (e.g., lobster fishing and critical habitat for wild salmon) or for which additional data are required (water currents and wave heights).

3.3.2 Introduction to Geographic Information Systems for shellfish culture

There are a variety of opportunities for GIS and remote sensing to be applied to shellfish culture, one of which is that, for the most part, shellfish culture takes place in relatively shallow near shore areas. Being near shore implies that the environment, especially water quality, diseases and competing uses are prime production factors for analysis. Additionally, near shore areas are more data dense than offshore areas and the resolution or detail of the data is usually greater there. Finally, the production by weight of shellfish is much greater than for finfish (Section 1.2.3). Thus, it is no surprise that GIS applications in shellfish culture are more numerous and diverse than for finfish culture in cages.

Some of the reviews herein deal with GIS and shellfish but not specifically with shellfish aquaculture. Nevertheless, the applications are relevant in the sense that they could be just as easily applied to culture situations.

The reviews, as in the previous section, are arranged according to the main and sub-categories of issues (Table 2.1). The applications are summarized in Table 3.5.

GIS aimed at the development of marine shellfish aquaculture

Suitability of the site and zoning

The potential for mussel (*Perna perna*) culture in the Sepetiba Bay, in the eastern part of the State of Rio de Janeiro, Brazil was examined by Scott and Ross (1998). The bay, about 544 km^2, is under considerable pressure from shoreline port and industrial development and untreated sewage from municipalities. Production function criteria grouped in sub-models included water quality (temperature, chlorophyll-a, salinity dissolved oxygen, and fecal coliform), shelter (wave height, current velocity), and infrastructure (proximity to urban centers, main roads, fishing areas, and to mussel seed sources). Thresholds were set on each criterion and they were classified into four groups ranging from ideal to inadequate. Constraints included areas of high pollution, high turbidity, possible conflicting or competing uses, areas used by the military and for navigation, shrimp trawling and port operations. In all, 10 000 ha were found to be ideal, 9 600 adequate and 1 270 marginal.

Building on the work just described, Scott, Vianna, and Mathias (2002) identified the regions and municipalities with conditions most favorable for various kinds of aquaculture development across the State of Rio de Janeiro, Brazil. The study was supported by an organization that promotes small businesses. Their work is noteworthy for being comprehensive in several ways: (1) it covers aquaculture both

TABLE 3.5

Summary of GIS applications to marine shellfish culture organized according to issues

Authors	Year	Main thrust or issue	System	Country	Species	Software	Decision support
GIS for the development of aquaculture							
Scott and Ross	1998	Suitability of the site and zoning	N/G	Brazil	Mussel	IDRISI 2.0	Expert Opinion and MCE
Scott, Vianna and Mathias	2002	Suitability of the site and zoning	Long line, lantern, off-bottom	Brazil	Oyster and mussel	ArcView 3.0, SPRING 3.5,	Expert Opinion and MCE. Estimates of capacity, productivity and field verification are included
Buitrago *et al*.	2005	Strategic planning for development	Raft	Venezuela	Oyster	MapInfo 6.0	Expert Opinion and MCE
GIS for aquaculture practice and management							
Jefferson *et al*.	1991	Inventory and monitoring of aquaculture and the environment	Bottom	USA	Oyster	ARC/INFO	Mapping and characterization of oyster reefs
Legault	1992	Inventory and monitoring of aquaculture and the environment	N/G	Canada	Check	CARIS (Computer Aided Resource Information System)	Gauges pollution effects on shellfish culture. Includes and economic viewpoint
Smith and Jordan	1993	Inventory and monitoring of aquaculture and the environment	Bottom	USA	Oyster	N/G	GIS-based oyster management information system. GIS was used for management, research and education
Smith, Jordan and Greenhawk	1994	Inventory and monitoring of aquaculture and the environment	Bottom	USA	Oyster	N/G	GIS-based oyster management information system. GIS was used for management, research and education
Durand *et al*.	1994a ; 1994b	Restoration of aquaculture habitats	Bottom	France	Oyster	ARC-INFO	Thresholds w/o weights
Jordan, Greenhawk and Smith.	1995	Inventory and monitoring of aquaculture and the environment	Bottom	USA	Oyster	N/G	GIS-based oyster management information system. GIS was used for management, research and education
Smith and Greenhawk	1996	Inventory and monitoring of aquaculture and the environment	Bottom	USA	Oyster	N/G	Characterization, inventory and mapping of oyster reefs
Smith, Greenhawk and Homer	1997	Inventory and monitoring of aquaculture and the environment	Bottom	USA	Oyster	N/G	Sub-bottom profiling and side scan sonar. Used GIS to discern sedimentation over historical oyster bars and on charged oyster reefs.
Populus *et al*.	1997	Inventory and monitoring of aquaculture and the environment	Off-bottom	France	Oyster	ArcView, Spatial Analyst	GIS, by providing a capture and edition tool, a data base, script programming and mapping functions allowed to fully take advantage of the digital form of data layers and compute indicators essential to proper management of an economically important coastal resource.

Authors	Year	Main thrust or issue	System	Country	Species	Software	Decision support
Loubersac *et al*.	1997	Inventory and monitoring of aquaculture and the environment	Off-bottom	France	Oyster	ARC/INFO v. 7 ARC/VIEW Spatial Analyst ERDAS Imagine v. 8.3 ERDAS Orthomax	GIS, by providing a capture and edition tool, a data base, script programming and mapping functions allowed to fully take advantage of the digital form of data layers and compute indicators essential to proper management of an economically important coastal resource.
Goulletquer *et al*.	1998	Inventory and monitoring of aquaculture and the environment	Off-and on bottom	France	Oyster	N/G	Production models. Carrying capacity of oyster culture.
Soletchnik *et al*.	1999	Inventory and monitoring of aquaculture and the environment	On- and off-bottom	France	Oyster	N/G	Production models. Carrying capacity of oyster culture.
Smith, Bruce and Roach	2001	Inventory and monitoring of aquaculture and the environment	Bottom	USA	Oyster	MapInfo	ASCS to assess oyster habitat
Smith *et al*.	2001	Inventory and monitoring of aquaculture and the environment	Bottom	USA	Oyster	MapInfo	ASCS to assess oyster habitat and associated bottom type
Smith, Roach and Bruce	2002	Inventory and monitoring of aquaculture and the environment	Bottom	USA	Oyster	MapInfo	Acoustic technologies and GIS to assess location, geological origin and composition of oyster bars
Bacher *et al*.	2003	Inventory and monitoring of aquaculture and the environment	Lantern nets	China	Scallop	ArcView, Avenue	Carrying capacity relative to food depletion of scallop. GIS was used to produce bay-wide maps of seston depletion and scallop growth.
Carswell, Cheeseman, and Anderson	2006	Inventory and monitoring of aquaculture and the environment	Inter-tidal bottom	Canada	Clam	ArcView (version not specified)	Inventory of clam aquaculture and the environment and estimating environmental impacts of aquaculture on bird populations.
Vincenzi *et al*.	in prep; in press; 2006	Inventory and monitoring of aquaculture and the environment	Bottom	Italy	Clam	Surfer v. 7.02	Carrying capacity of Manila clam in terms of yield potential. Habitat Suitability Models for yield estimation. Expert opinion and weights.
GIS for multisectoral development and management that includes aquaculture							
Arnold, Norris and Berrigan; Arnold and Norris; Arnold *et al*.	1996; 1998; 2000	Fisheries and other competing uses	Bottom	USA	Hard clam	ArcView, Spatial Analyst	GIS-based hard clam aquaculture lease site model. Thresholds w/o weighting.
Center for Coastal Resources Management	1999	Fisheries and other competing uses	Bottom	USA	Hard clam	N/G	Thresholds. Clam and SAV Habitat suitability models. Results were considered a starting point to identify several options for policy debate.
Dolmer and Geitner	2004	Fisheries and other competing uses	Longlines	Denmark	Mussel	N/G	Thresholds and weighting.

along the coast (mussels, oysters, shrimp) and inland (fish, frogs) and it (2) compares the results in terms of spatial capacity and productivity for aquaculture with apparent wholesale market demand for the products and in terms of self-sufficiency for the state (Table 3.6 and Figure 3.16).

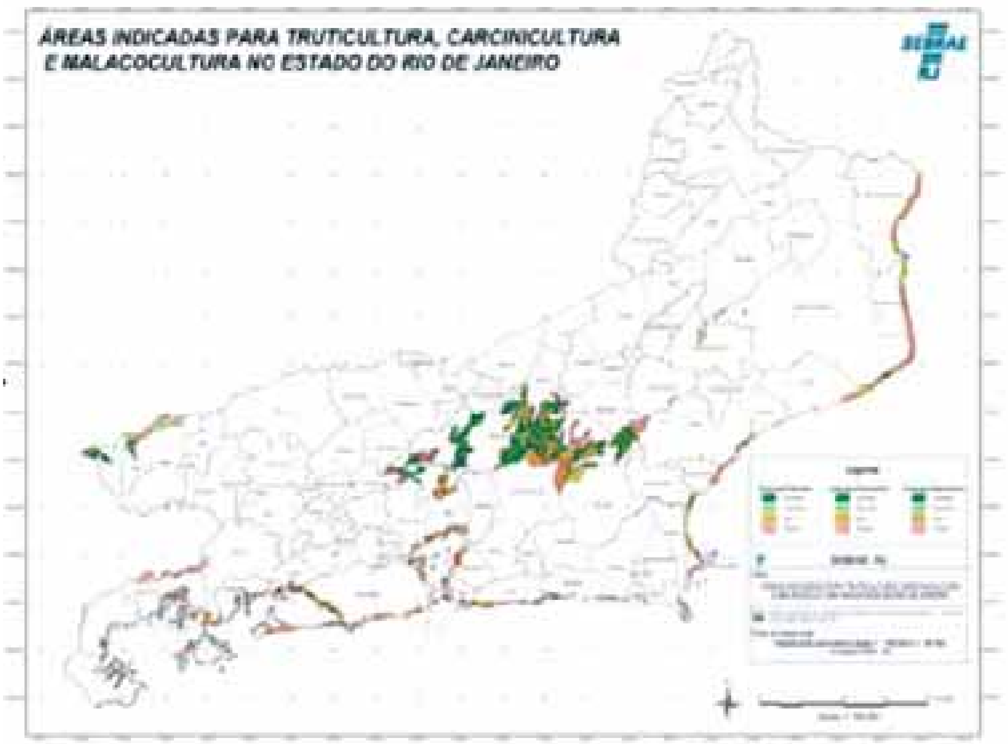
TABLE 3.6
Summary of GIS modelling results for Rio de Janeiro potential and demands

Commodity	Estimated Productivity (kg/ha/yr)	Suitable areas (ha)	Area needed to cover demand (ha)	Percent of suitable areas needed to make state self sufficient	Priority Index (PI) to cover aquaculture products in the state
Marine shrimp	2,000	47,331	264	0.5578	0.8355
Tilapia	5,700	2,060,189	29.5	0.0014	0.0933
Tropical fish	4,300	2,060,189	20.1	0.0010	0.0636
Mussel	25,000	16,448	1.9	0.0117	0.0061
Oysters	115,000	16,448	0.1	0.0008	0.0004
Scallops	60,000	16,448	0.04	0.0002	0.0001
Trout	72,000	161,115	0.3	0.0002	0.0008
Frogs	75,000	3,186,768	0.06	0.0000	0.0002

(Marine shrimp = *Litopenaeus vannamei.* Tilapia = Red varieties and hybrids of *Oreochromis niloticus*. Tropical fish = *Colossoma macropomum*, *Piaractus mesopotamicus, Colossoma brachypomum* and hybrids. Oysters = *Cassostrea rhizophorae*. Scallops = *Nodipecten nodosus*. Trout = *Oncorynchus mykiss*. Frogs = *Rana catesbiana*.

Source: Scott, Vianna and Matias (2002)

FIGURE 3.16
Suitability for shrimp, bivalve molluscs and trout farming across the State of Rio de Janeiro, Brazil



Source: Scott, Vianna and Mathias (2002)

The authors arrived at estimates of suitable areas by assigning a weight varying between 0 – 10 for each production function relating to each species. The weight was assigned on the basis of the experience of members of the group and discussion about the relative importance of each factor in relation to each species. Verification was carried out by presenting the suitability maps to experienced extension agents who then judged the results based on their own knowledge. There was good agreement between the modeled results and areas known to be of various levels of suitability.

Strategic planning for development

Buitrago *et al.* (2005) set out to evaluate oyster culture possibilities on rafts in lagoons at Isla Margarita, Venezuela and two nearby smaller islands, making an initial study area of nearly 3,900 km^2. This study is noteworthy because it is aimed at site selection for community-based aquaculture, because a large number of experts participated in decision-making and because of the use of a non-traditional approach to considering production factors. In all, 20 factors were considered. They were grouped into four main criteria: (1) those affecting the survival of the oyster (environmental intrinsic), (2) those relating to the success of the farming activity (environmental extrinsic), (3) logistic, and (4) socio-economic. Eighteen experts in fields related to mollusk aquaculture from universities, research institutions, government agencies, and private companies scored the factor checklist with the restriction that the sum of scores was to be 100. The importance of each factor was based on the average of the responses to it. Factors were then individually assigned to five suitability classes (optimum to limiting) beginning with the mean score as the highest class (Table 3.7). Then, each of the 20 factors was thematically mapped and each thematic map was cast into the same five classes as used to score the factors (Figure 3.17a).

Assignment of classes to the thematic maps was based on a variety of information including the results of earlier studies, questionnaires, interviews and the personal experience of the investigators. Constraints also were established and used to mask the relevant areas. Constraints reduced the study area to 1 274 km^2. A stepwise process was followed to combine factors for a Multi-Criteria Evaluation (MCE). First, factors within the each of the four main criteria were combined by overlay to identify high potential areas (Figure 3.17a). Then, criteria scores were combined, again identifying the optimum areas across all criteria. The outcome was that 13 sites totaling 4.1 km^2 were considered optimum for raft culture of oysters. Sites less than optimum, but still with high scores numbered 137 and occupied a total of 37.5 km^2 (Figure 3.17b). One of the problems identified by the authors was the relatively high variation among experts as to the importance of some factors (Table 3.7). Another problem was that the approach may have been overly restrictive in that a relatively large numbers of sites, as well as a relatively small area overall, were identified as having the highest potential.

GIS for shellfish aquaculture practice and management

Inventory and monitoring of aquaculture and the environment

Inventory and monitoring of aquaculture installations and operations along with investigations of the environment are among the most common applications of GIS applied to shellfishes.

Water quality and diseases related to operations are two important aspects of aquaculture and the environment. It goes without saying that good water quality is essential to sustain marine aquaculture. Water quality in terms of GIS applications can be viewed in two contexts: (1) sources external to the aquaculture operation, usually land-based, that contribute to poor water quality, and (2) enrichment of the aquaculture locale with dissolved nutrients in the water column and particulate matter in the sediments as well as the possibility of diseases within the aquaculture operation itself.

TABLE 3.7

Selected suitability criteria and factors, their optimum consideration and categorically restrictive levels

Site suitability			Judgment weights: mean ± SD (range)
Criteria and factors	**Optimum**	**Restrictive**	
Intrinsic environmental			
Temperature	22-27°C	N.A	36± 2.7 (0-10)
Bathymetry-tide	> 5 m and small tide	> 5 m or large tide	3.3 ± 3.4 (0-15)
Range	Fluctuation	Fluctuation	
Suspended solids and turbidity	Secchi depth > 3 m	N.A.	3.9 ± 2 (0-8)
Salinity	32-40 p.s.u.	N.A.	3.5 ± 2.6 (0-10)
Primary production	High but no algal blooms reported	Oligotrophic waters	7.7 ± 3.6 (0-15)
Competitors and parasites	No reports of Polydora	N.A.	4.3 ± 2.1 (0-8)
Environmental extrinsic			
Predators	Upstream from hard bottom seagrass, mangroves areas	N.A.	4.7 ± 2.3 (1-10)
Algal blooms-red tides	No red tides reported or harmful algal blooms	N.A.	4.5 ± 3.1 (1-10)
Currents	Speed 20-40 cm	N.A.	3.9 ± 2.6 (0-10)
Wave action protection	Protected from all three regional major wave incoming directions	Not protected from incoming waters	6.8 ± 3.6 (0-15)
Substrate characteristics	Away from environmentally highly sensitive communities (reefs, seagrass, hard bottom)	N.A.	3.5 ± 2.1 (0-8)
Sewage pollution	Area approved by shellfish sanitation regulations	Area might not achieve regulatory standards	8.3 ± 4.3 (3-20)
Industrial outflow	Area approved by shellfish sanitation regulations	Area might not achieve regulatory standards	6.2 ± 2.9 (2-12)
Logistic			
Site accessibility	Target communities near	No fisheries communities nearby	5.9.± 2.7 (0-10)
Services availability	All required services < 8 km	N.A.	5.22 ± 2.4 (0-10)
Facilities safety	Rafts easily supervised	N.A.	5.8 ± 3.7 (0-15)
Space and resources use conflicts	Away from protected areas, fishing grounds, and navigation channels	Nearby protected areas, or trawling or purse nets fishing grounds	7.2 ± 4.2 (0-20)
Socioeconomic			
Community organization	Community organized includes women participation in decision-making	N.A.	5.4 ± 2.9 (0-10)
Economic level	Few alternative development opportunities	N.A.	3.4 ± 2.3 (0-8)
Fisheries tradition	Long historic record of marine resources use	N.A.	3.3 ± 2.5 (0-10)

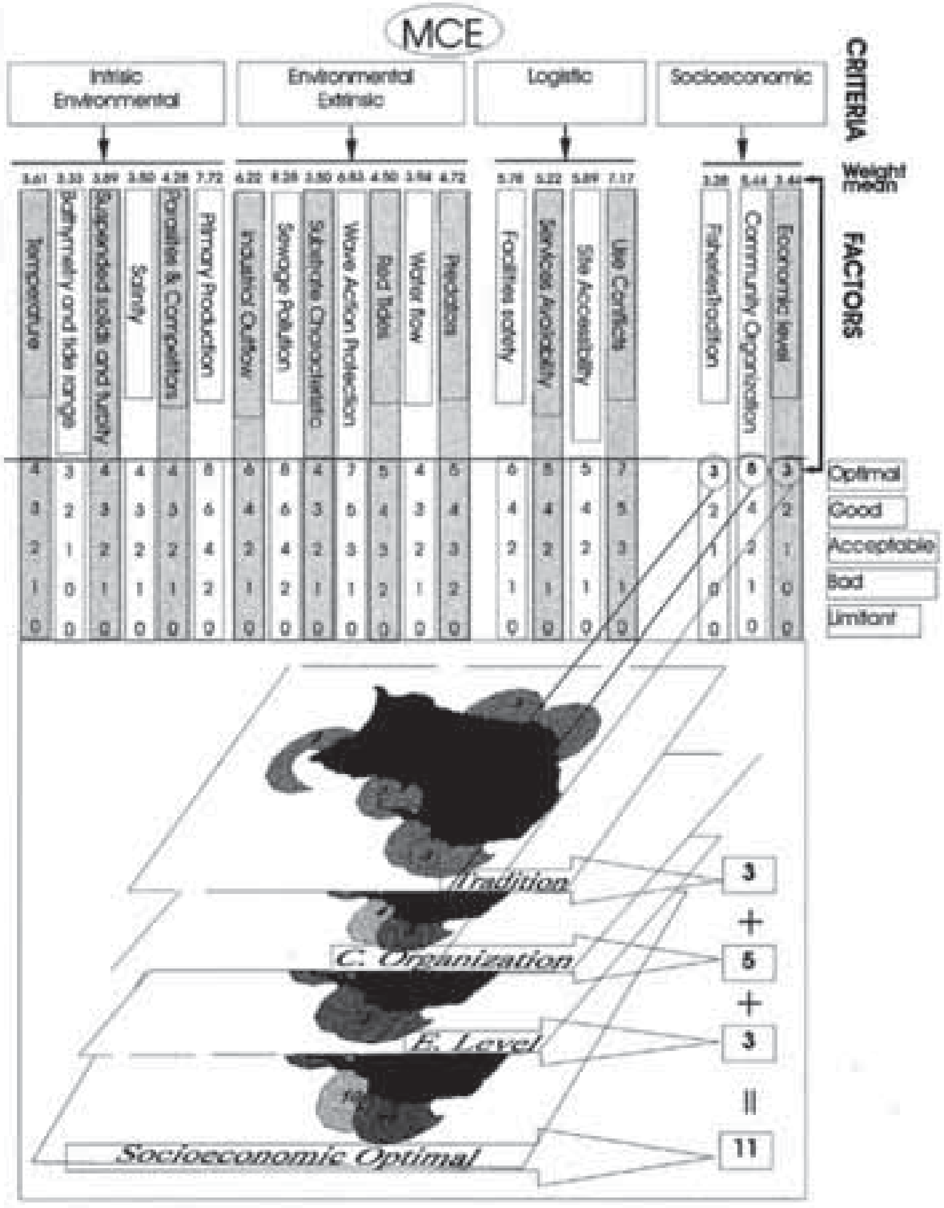
Note: Expert's judgment results, suitability factor weights, standard deviations and ranges are given. N.A. = Not applicable.

Source: Buitrago *et al.* (2005)

Jefferson *et al.* (1991) studied oyster reefs in Murrells Inlet, South Carolina, the United States of America as part of an investigation to examine the effects of urbanization on estuaries. The goal was to enhance resource management decisions. Murrells Inlet is a shallow high salinity estuary without any riverine input that is surrounded by development, except on one side that is adjacent to a park. It is heavily utilized both by commercial and recreational fishermen.

FIGURE 3.17A

Methodological framework to assess oyster culture possibilities on rafts in lagoons at Isla Margarita, Venezuela and two nearby smaller islands



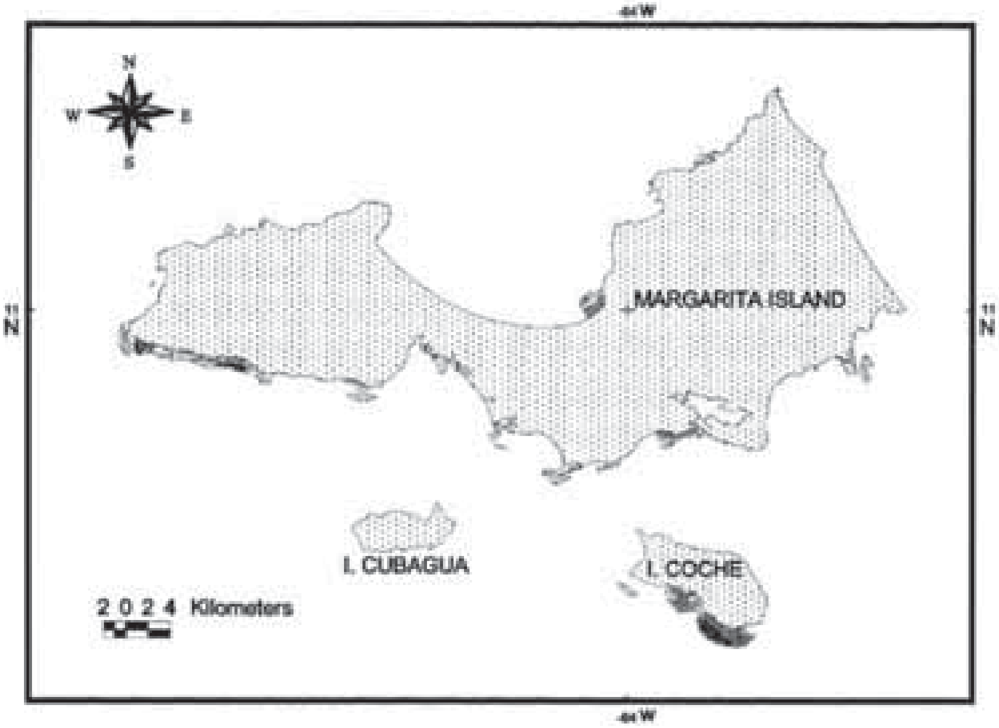
Source: Buitrago *et al.* (2005)

Oyster reefs within the intertidal zone of the estuary were mapped and characterized according to (1) live standing crop, (2) various aspects of structure and ecology and associated oyster recruitment, and (3) spat size. Other layers included land use patterns, marinas, and sites of point and non-point pollution.

In general, oyster reefs in polluted areas were located near marinas, high boat traffic, and runoff from service industries and high density housing. Reefs with high recruitment were characterized by relatively large size and generally not located in areas of high boat traffic, marinas, or highly polluted areas. As a part of the study

FIGURE 3.17B

Final map showing areas accounting for more than 80% of possible localities (■) in southern Macanao and Coche covering 4.1 km².

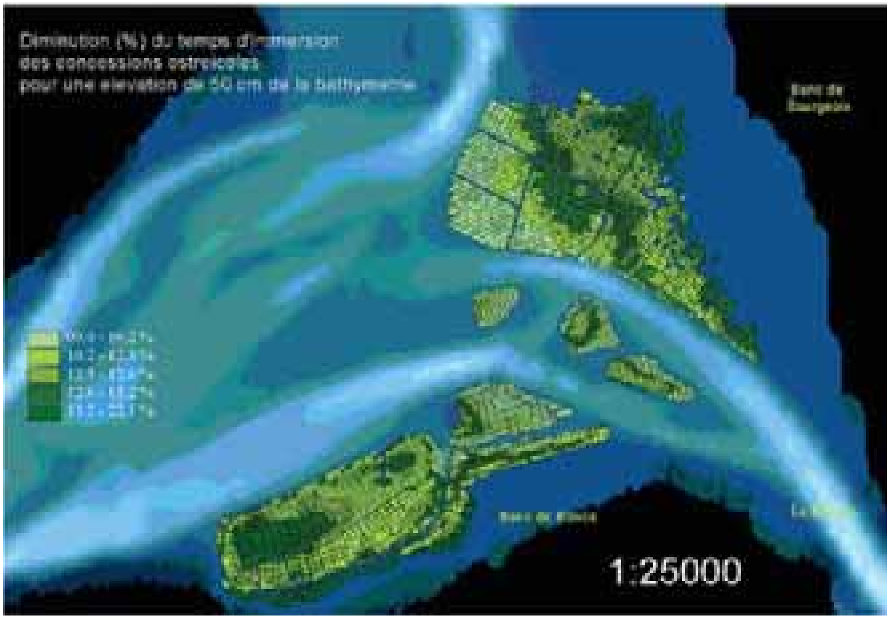


Note: It is considered that those places have the optimum conditions for oyster raft aquaculture in the Margarita Island region. Additional locations meeting 75% (■) or 70% (■) of the demanded criteria for a final suitable selection cover 137 sites encompassing 37.5 km².

Source: Buitrago *et al.* (2005)

FIGURE 3.18

Loss of duration of immersion (in %) for a theoretical siltation rate of 50 centimetres on oyster lease grounds in Bancs de Ronce and Bourgeois



Source: Populus *et al.* (1997)

spatial search and overlay were used to examine the numbers and areas of oyster reefs that could be affected by various development scenarios including dredging to maintain a marina and a boat channel.

Legault's (1992) shellfish study is noteworthy in two ways: First, as an early application of GIS to gauge pollution effects on shellfish closures, and secondly, because an economic viewpoint is included. This was a pilot study with the objective of showing the capabilities and limitations of a GIS for the evaluation of habitat impacts. The study area was on the eastern coast of Prince Edward Island, eastern Canada, where closures mainly due to coliform bacteria affect shellfish leases in two ways: the shellfishes have to be moved to new areas to depurate, and products may be suspect if harvested near to closed areas. Spatially, the GIS encompassed shellfish leases, shellfish closed and approved zones, the coastline, roads, and waste water outfalls as well as attribute data on the leases that were in the data base. Using limited data on production and value, the losses due to closed areas were estimated. Although no cause and effect studies were carried out, the locations and kinds of pollution sources were mapped.

One of the major problems encountered was the diversified and inconsistent nature of the data. Data existed, but were not readily available in useful formats. Regarding the implementation of the GIS, it was observed that the allocation of sufficient human and financial resources is essential for effective operation, and that GIS is labor and time intensive, but in the end the results, in terms of savings of time compared with non-automated alternatives and in terms of the thoroughness of data analysis, justify the expenditure.

The Bassin de Marennes-Oléron in Charente-Maritime is one of the most important areas for oyster culture in France. Goulletquer and Le Moine (2002) review the state of the management of shellfish aquaculture within the context of coastal zone management in the Marennes-Oléron Bay and Charentais Sounds. Populus *et al.* (1997)[1] and Loubersac *et al.* (1997) report on the development of a GIS to improve the management of oyster culture in the same area. They worked with 22,000 oyster leases within an area of 2,900 ha.The main management problems were overstocking of lease sites, inappropriate culture systems, sedimentation, and competition with naturally occurring oysters.

The stepwise process consisted of creating a database of the leases and their attributes, digitizing paper maps of the leases, georeferencing the leases, and allocation of leases to "banks" (administrative and management units). Mapping of the average depth of oyster culture leases was an important activity because of siltation that is thought to be due to the off-bottom culture structures called "tables". With the depths of leases mapped, it was then possible to estimate the immersion time for each lease area, a variable associated with oyster growth, and ultimately with the productivity and value of each lease (Figure 3.18). Finally, the lease location and lease-depth data proved useful to plan for dredging to ameliorate the effects of siltation.

Additional uses of the GIS foreseen by the authors included periodic georeferenced aerial photography to check on compliance with culture practices, and to estimate the biomass of oysters as well as linking the lease data to oyster population dynamics and the environment including rainfall and pollution discharges.

Goulletquer *et al.* (1998) and Soletchnik *et al.* (1999), building on the background work of Populus *et al.* (*op cit*) and Loubersac *et al.* (*op.cit*), studied the summer mortality of oysters in on-bottom and off-bottom culture in one of the banks of the Marennes-Oleron Bay described above. Although summer mortality of oysters in the area was a

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[1] A study based on a recent publication by Populus *et al.* (in press) on the geomatics of oyster leases is a case study in GISFish.

problem of some concern, the causes were not known with any certainty. Accordingly, their study acquired growth, sexual maturity survival rates and environmental data from 15 sample sites to investigate the relationship. Mortalities were related to relatively high temperatures and pre-spawning glycogen catabolism. Production models were built based on analysis of the field data and incorporated into a GIS. Geographically varying carrying capacity was demonstrated for both culture systems.

Among the acoustic remote sensing applications in shellfish aquaculture are inventories of shellfish resources and characterization of shellfish habitat using hydroacoustical remote sensing. Satellite remote sensing as a data source for GIS and for real time monitoring has an underwater counterpart in acoustics. Smith, Bruce and Roach. (2001) identify three approaches for assessment and representation of the bottom. Single beam sonar can be used to assess general surface and sub-surface characteristics, but habitat classification is subjective. Side scan sonar provides high resolution textural images of the bottom that can be mosaicked, but it is demanding of ground truthing effort. Acoustic Seabed Classification Systems (ASCS) have recently come to the fore. These classify echo returns statistically into definable habitat types using wave forms that reveal various kinds of substrate information. ASCS, too, require extensive ground truthing.

Smith, Bruce and Roach. (op cit.) describe the results of evaluations of the above-mentioned technologies to assess oyster habitat. They concluded that ASCS is well suited for the identification and charting of oyster shell as well as for distinguishing between oyster shell and fine sediments. Further, ASCS offered an excellent linkage with GIS display and analysis capability.

Although many shellfish resources may be fished and not cultured, in the case of some oyster fisheries there is an element of marine aquaculture because the substrate on which oyster spat attach and grow is supplied in the form of artificial reefs.

In some cases it is possible to follow the evolution of GIS over a relatively long period as it is applied to a variety of related problems. The Chesapeake Bay oyster (*Crassostrea virginica*) resource in Maryland, the United States of America waters provides a good example. The Chesapeake Bay is the largest US estuary with an area of 11 600 km^2. It is relatively shallow with an average depth of less than 9 m.

The use of GIS applied to oyster resource investigations and management in the Chesapeake Bay has a long history. One of the impediments to management was that the complexity of the data on populations and diseases meant that the data were not being fully utilized or were not being analyzed in a timely way. Initiation of an annual oyster survey in 1990 with GIS analysis in mind has had two results: (1) local and regional data are represented in a geographic context and (2) management oriented queries and statistical capabilities have been created (Smith and Jordan, 1993) in the form of a GIS-based oyster management information system (Smith, Jordan and Greenhawk, 1994). The system has proved especially useful in supporting the information needs of the state's Oyster Recovery Action Plan (Jordan, Greenhawk and Smith, 1995). Managers, scientists, and policy-makers have been provided with clear, graphical portrayals of oyster habitat, population and disease status, and salinity gradients. Apart from its usefulness as a management and research tool, the GIS proved to be a valuable educational tool for students and tour groups.

In the Chesapeake Bay later studies have focused on characterizing oyster reefs. As indicated above, this has important implications for management as significant costs are incurred in maintaining and restoring artificial ("charged") oyster reefs. Thus, characterization, inventory and mapping are important applications of remote sensing and GIS. Smith and Greenhawk (1996) recognized two kinds of oyster reefs in the Chesapeake Bay, fringing and patch. Rate of loss of exposed oyster shell (cultch) is related to reef type. They employed a GIS using data on charged reef boundaries, bathymetry, and bottom composition to study cultch loss from the turn of the 20th century to the 1970s, and they identified local sedimentation as one of the principal causes of habitat loss.

The marked decline of oyster populations in the Chesapeake Bay has been attributed to habitat loss due to sedimentation as shown above, over-harvest and disease. Of these, the former is the most difficult to quantify over large areas. In order to further investigate the effects of sedimentation, Smith Greenhawk and Homer (1997) employed sub-bottom profiling and side scan sonar over areas previously known to be oyster bars. They employed a GIS to integrate the data in two and three dimensions. In this way sedimentation over historical oyster bars and on charged oyster reefs could be discerned.

In a related study, Smith *et al.* (2001) created a GIS of oyster habitat and associated bottom types in Maryland's portion of the Chesapeake Bay that was based on data from various kinds of survey devices deployed between 1975 and 1983. The purpose of the survey was to reassess the extent and condition of oyster bars that were initially surveyed in 1912.The survey data were used to classify the bottom into six categories, three of which were related to oyster habitat and the remainder to non-oyster bottom. The original survey data were used only to produce maps of oyster bar boundaries on mylar sheets, but the maps were of limited use because they were not georeferenced and shorelines were not shown. Further, the original bottom classification data were not mapped. In order to take advantage of the analytical possibilities inherent in the data, the mylar sheets were digitized and integrated into a GIS along with other useful spatial data such as bathymetry and recent or planned acoustic surveys (Figure 3.19).

A combination of acoustic technologies and GIS was used by Smith, Roach and Bruce (2002) to assess the location, geological origin and composition of oyster bars in mesohaline areas of the Chesapeake Bay. Certain geological structures initially provide the basis for oyster bar formation and, when charted, provide a basis for locating oyster bars and for assessing their condition. In some locations oyster bar terraces have been covered with sediment, or sedimentation is progressing. Although harvesting practices have been blamed for the widespread reduction in oyster bar relief, the results of this study do not clearly support that idea. Rather, oyster restoration should occur only in locations where the underlying geological features can support the restoration material in areas where bottom sediments are not encroaching.

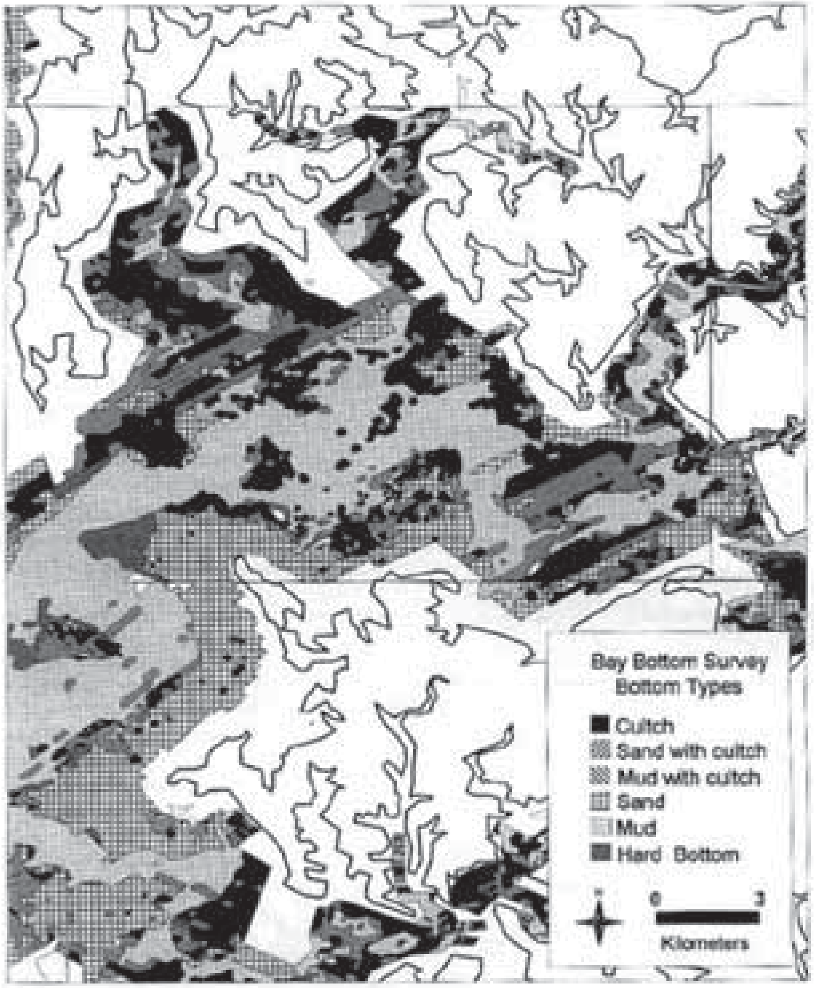
A study of shellfish aquaculture in Baynes Sound, Vancouver Island, BC Canada by Carswell, Cheesman, and Anderson (2006) addresses several issues related to aquaculture development using aerial remote sensing and GIS. The issues include inventory of clam aquaculture and the environment while at the same time estimating the environmental impacts of aquaculture on bird populations.

Baynes Sound, of about 8.6 km^2 in area, accounts for most of the shellfish production in the province and also is one of its most intensively farmed areas. The three main commercial intertidal clam species in Baynes Sound are the native littleneck clam, *Prothaca staminae*, and two introduced species, the varnish clam, *Nuttallia obscurata*, and the manila clam, *Tapes philippinarum*. Clams are cultured under protective nets. One possible environmental effect of shellfish farming is the spatial extent of clam netting as it affects the availability of prey items for two bird species.

The inventory of shellfish tenures was based on georegistered aerial photography. The photos were scanned, mosaiced and then integrated into a GIS. The outlines of the clam netting were digitized in order to estimate their areas. GIS also was used to combine clam net coverage with an existing inventory of shore types (e.g. tidal flats). Clam habitats were delineated according to elevation contours of the intertidal areas. These intertidal ranges were then intersected with the clam net coverage to determine proportions of intertidal clam habitat by substrate type covered by netting.

The results showed that although the area of lease tenures is relatively large, the area actually covered by nets is relatively small overall and small, too, according to

FIGURE 3.19
An example of the digitized rendition of the Maryland Bay Bottom Survey in the Choptank River region



Note: The shoreline and the borders of the original Mylas charts are layered upon the survey bottom themes, but are not included in the digital file. Original Mylar transparencies were 70 x 111 cm, drawn at a scale of 1:20,000 and projected in U.S. State Plane NAD27. The general North-East/South-West orientation of bottom themes depicted here is the result of radio beacon navigation.

Source: Smith *et al.* (2001)

coverage by various shore habitat types. Thus, the impact of shellfish culture area-wise is relatively little. The manila clam is the only cultured species in the sound and therefore, the only clam for which netting is deployed. Evidence suggests that the birds of concern feed to an important extent on the varnish clam so that impeding access of the birds by netting would not appear to impact their food source. The authors conclude that spatial analysis of the extent of shellfish aquaculture in Baynes Sound should prove invaluable for making informed risk assessments and resource allocation decisions.

Inglis *et al.* (2000) have reviewed carrying capacity in relation to mussel culture in New Zealand. They recognize four kinds of carrying capacity:

- physical carrying capacity – the total area of marine farms that can be accommodated in the available physical space;

- production carrying capacity – the stocking density of bivalves at which harvests are maximized;
- ecological carrying capacity – the stocking or farm density which causes unacceptable ecological impacts; and
- social carrying capacity – the level of farm development that causes unacceptable social impacts.

Investigations of carrying capacity can apply to aquaculture development if conducted before aquaculture has been implemented, or, as in the case of the following study, to aquaculture management, if conducted after aquaculture is underway. Bacher *et al.* (2003)[2] have looked into carrying capacity relative to food depletion of the scallop, *Chlamys farreri*, in Sungo Bay [place name in Chinese is *Sanggou*], one the marine areas most intensively used for aquaculture in China.

Carrying capacity is the maximum production achievable in a given ecosystem given the biological constraints and characteristics of the aquaculture activity. Food depletion was defined as the ratio of food concentration within culture areas to the concentration outside of them. Thus, selection of culture sites and determination of rearing densities are critical aspects of carrying capacity and depletion studies in relation to the sustainability of aquaculture.

Sungo Bay averages 10 m in depth and occupies 140 km^2. Due to low nutrient inputs from land, primary production originates from import of organic matter and nutrients from the sea. Kelp, *Laminaria laminaria*, and oysters, *Crassostrea gigas*, are cultured in addition to scallops.

The stepwise analytical process included (1) quantifying the relationship between the filter feeders and the environment. With regard to the filter feeders, that included food filtration, ingestion, assimilation and metabolic losses in relation to temperature, all of which affect growth. With regard to the environment, that included the concentrations of food and total suspended matter using a current model to predict food delivery. (2) defining the geographical scale of the food limitation at 1000 m within which rearing density, food concentration and hydrodynamics interact.

Simulations were developed in which hydrodynamic and food conditions were varied and GIS was used to produce bay-wide maps of seston depletion and scallop growth.

A tool (Figure 3.20) was developed to:

- compute and plot particle trajectories;
- select length scale, rearing density, site and simulate the annual scallop growth;
- map the final scallop growth or depletion factor;
- compare growth and depletion factors simulated with different densities on one site or over the bay;
- compute statistics of growth and depletion factors over the bay, such as the percentage of areas with a given depletion factor; and
- estimate the rearing density which guarantees a given depletion factor or a final scallop weight by simple arithmetics.

A series of studies by Vincenzi *et al.* (in press, 2006) deal with estimating the carrying capacity of Manila clam, *Tapes philippinarum*, culture in the sense of yield potential in the Sacca di Goro lagoon along the northern Adriatic coast of Italy. The latest study (Vincenzi *et al.* in prep) compares three variations of Habitat Suitability models for the yield estimation. The lagoon has a total area of 26 km^2 and about 10 km^2 are devoted to the intensive culture of the clam. Clam farming is agency regulated on

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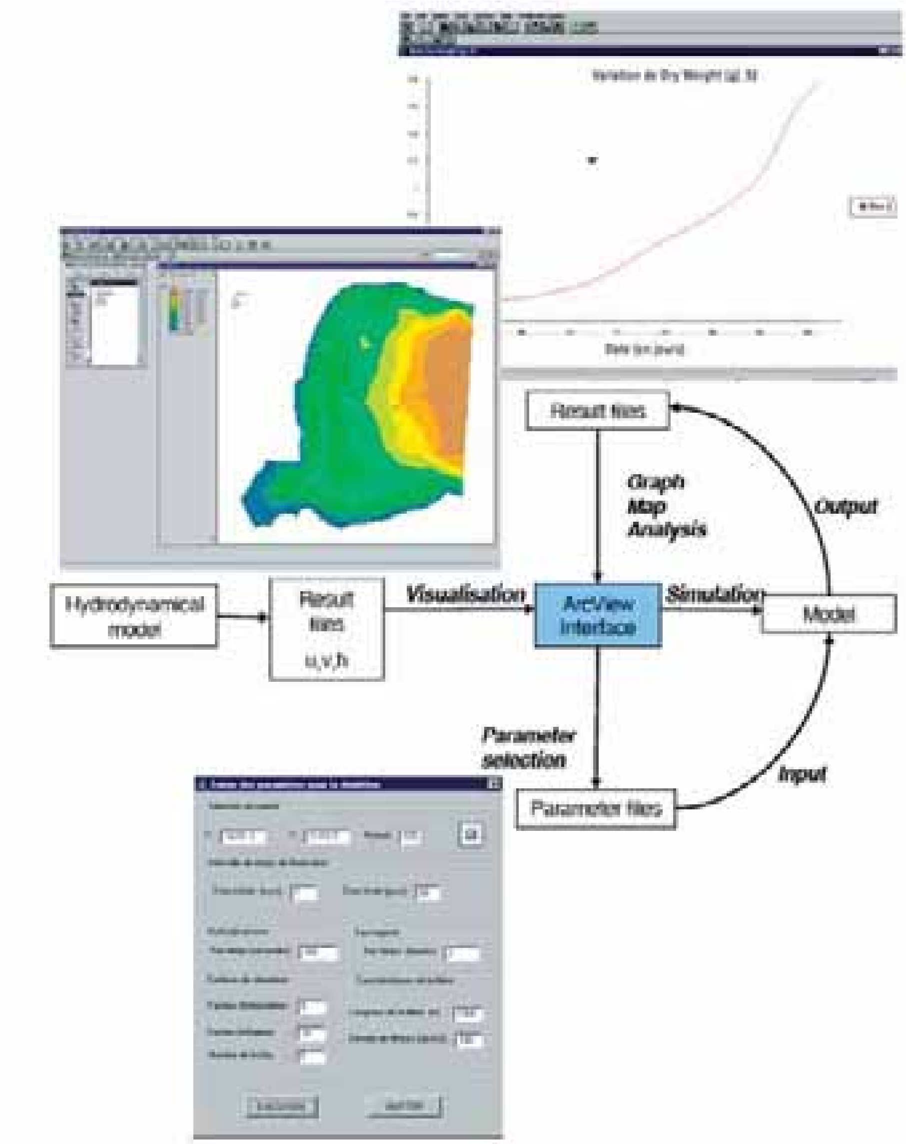
[2] This is a case study in GISFish.

FIGURE 3.20
Integration of models and GIS



Source: Bacher *et al.* (2003)

the basis of concessions. The basis of improving the concession process is a knowledge of the yield potential in spatial terms. The approach was to employ several variations of GIS-based habitat suitability models to explore the relationship between occurrence and abundance of Manila clam and key biogeochemical and hydrodynamic properties that affect its survival and growth. A condition is the environmental variables should be sampled or estimated at a fairly low-cost.

The six environmental parameters included in the models are sediment type, dissolved oxygen, salinity, hydrodynamism, water depth and chlorophyll-a. The basic Habitat Suitability Index (*HSI*) model uses parameter-specific functions based on expert opinion to transform environmental data into parameter-specific Suitability Indexes and a weighted geometric mean – with weights based on expert opinion – to estimate the overall Habitat Suitability Index (*HSI*). A scaling function derived from field observations is used to transform HS values into estimates of annual potential yield. Data were from 15 sampling sites and the results are generated as point estimates.

The role of GIS was for the interpolation of the point data and for the preparation of thematic maps.

The potential yields predicted by the models for the lagoon are more than twice as much officially reported by the fishery (Figure 3.21). This is because model estimates of potential were outside of areas currently farmed. The authors caution that their results should not be used to define the maximum sustainable Manila clam yield for the lagoon. Rather, ecological carrying capacity also has to be considered.

Restoration of aquaculture habitats

The Charente Maritime coast of central western France is the most important for oyster culture in Europe, but the high density of culture structures in the limited inter-tidal area of the Marennes-Oleron Basin causes low growth rates and high mortality of oysters that result in socio-economic problems for the culturists. One solution is to shift some production to nearby sub-tidal areas. This alternative was explored in pioneering work by Durand *et al*. (1994a) and Durand *et al*. (1994b) as a demonstration project. Apart from the importance of oyster culture, the region is the second-most visited area in the country and contains the most popular pleasure boat harbor in Europe. Thus, in addition to satisfying requirements of oysters cultured on the bottom and harvested by dredges, other competing uses were important considerations.

As criteria for oyster culture the authors considered bathymetry, slope, bottom type, current speed, water quality and interaction with inter-tidal culture. Regarding competing uses, navigation, culture of mussels and algae on longlines, fisheries, and spawning grounds and nurseries were taken into account.

A four-level scoring system was implemented with three levels relating to suitability for oyster culture and a fourth that pertained to exclusion zones (constraints); however, no weights were applied.

The result was that about 8% of the area was very favorable for sub-tidal oyster farming.

The main problems encountered were lack of spatial data and socio-economic attributes, insufficient knowledge to weight competing activities, and difficulties with thresholding continuous data in meaningful ways. The authors foresaw the need for three-dimensional and temporal data management and links to land-based GIS.

GIS for multisectoral development and management that includes marine shellfish aquaculture

Management of aquaculture together with fisheries

Spatial use conflicts in aquaculture are of many kinds. Two of the most important are reviewed here. They are direct competition for space between aquaculture and fisheries and indirect conflicts for space in which shellfish aquaculture may displace or reduce the biological productive capacity of the environment and thereby ultimately decrease fisheries productivity. These studies are noteworthy not only for the technical aspects of applications themselves, but also for the fact that GIS was employed in anticipation of use conflicts, not after the fact.

Studies by Arnold, Norris and Berrigan (1996), Arnold and Norris (1998) and Arnold *et al*. (2000)[3] in support of the development of hard clam (*Mecenaria* spp.) aquaculture in Florida, the United States of America provide a good example of GIS applied to anticipating competing uses including fisheries and other uses while dealing with factors affecting clam production and general sustainability of aquaculture

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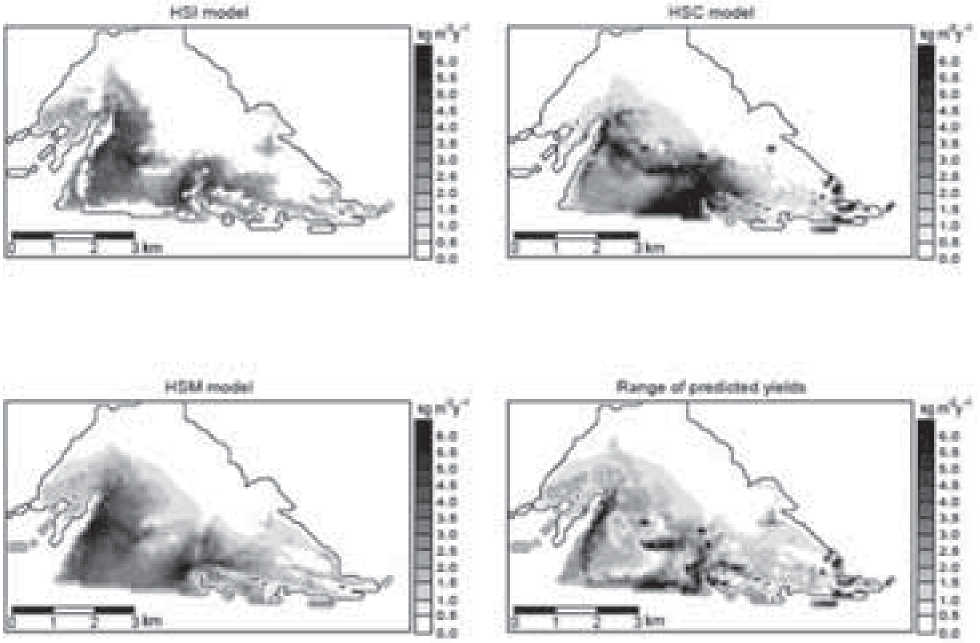
[3] GISFish case study.

FIGURE 3.21

Estimating the carrying capacity of Manila clam, Tapes philippinarum, culture in the Sacca di Goro lagoon along the northern Adriatic coast of Italy



Source: Vincenzi *et al*. (in press, 2006)

leases. The latter study is also noteworthy in demonstrating how a GIS approach designed for one area can be applied to another area at a different stage of aquaculture development.

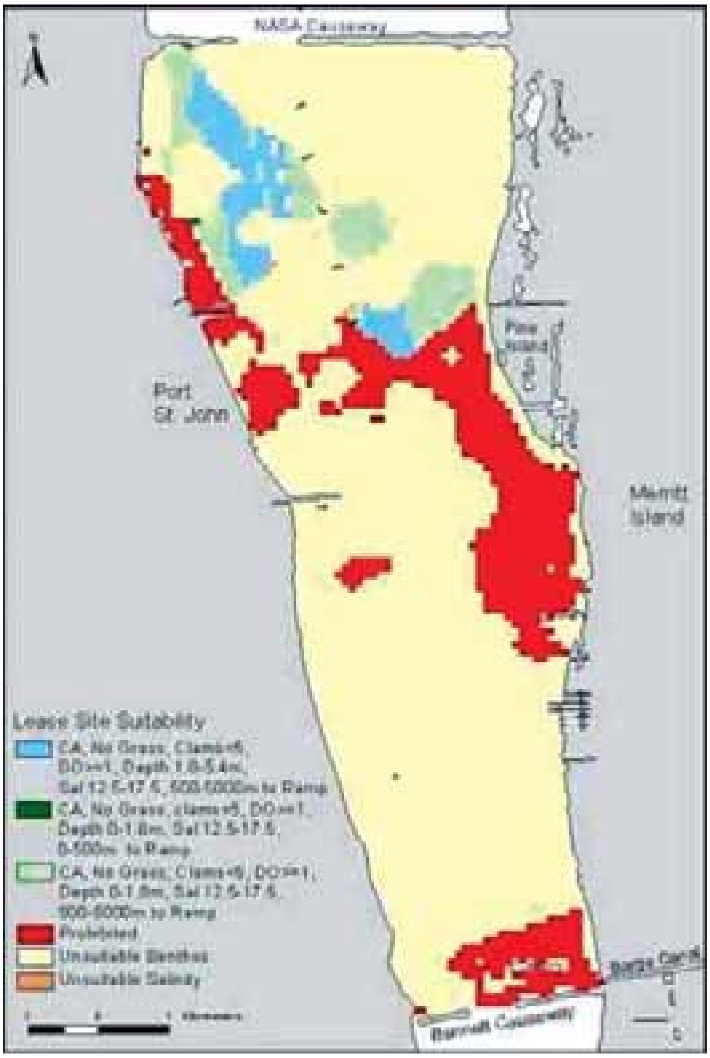
Clam aquaculture in Florida has grown at a rapid pace, but among the issues is that grow-out has to take place on publicly-owned bottom. Going along with this is the need for culture sites to support economically viable growth and survival while not directly or indirectly interfering with other functions such as primary production, navigation and fisheries, especially the fishery on clams.

The authors addressed these issues in the Indian River Lagoon on Florida's east coast by employing a set of constraints that initially excluded sea grass habitat, and areas naturally highly productive of clams, the latter to avoid conflicts with clam fishers. Other areas that were excluded were those with unfavorable salinities and dissolved oxygen conditions as well as those near navigable channels and boat ramps. Finally, several categories with relative values were considered: (1) Approved (harvest any time) and Conditionally Approved shellfish classification zones (restricted harvest), (2) distance to boat ramps (ease of access to lease sites), and (3) depth (greater difficulty in planting seed and harvesting with increasing depth) (Figure 3.22). The same criteria were applied to Charlotte Harbor on Florida's west coast and generated a new set of area estimates and locations.

The authors emphasize that the maps and data so generated should be considered as a starting point in the allocation of clam lease sites rather than as end points because many of the criteria (e.g., water quality patterns, depth, and clam density) may be subject to reconsideration or compromise. Refinements identified by the authors include determining set backs from privately held properties and accounting for varying growth patterns of clams among areas and habitats.

FIGURE 3.22

Areas suitable for hard clam aquaculture leases in Shellfish Harvesting Area C of the Indian River lagoon, Florida.



Legend, CA = Conditionally Approved shellfish harvesting area; DO = dissolved oxygen (mg/l); Sal = salinity (ppt); range in metres represents water depth (first) or distance to the nearest boat ramp (second).

Note: Areas categorized as unsuitable are not appropriate for hard clam aquaculture due to the presence of seagrass, high density clam populations recorded during our 1994 survey, low levels of dissolved oxygen recorded between 1987 and 1998, excessive water depth or the proximity of navigable channels, or low salinity conditions inimical to clam survival. Of the remaining area, those cells classified as prohibited (= Prohibited or Conditionally Restricted classification) do not meet shellfish harvesting water quality standards.

Source: Arnold *et al.* (2000)

The Center for Coastal Resources Management (1999)[4], based on the work of Kershner, describes a project designed to assess a potential conflict due to the displacement of Submerged Aquatic Vegetation (SAV) (*Zostera marina* and *Ruppia maritima*) with hard clam (*Mercenaria mercenaria*) farming in a region of current intensive aquaculture in the Virginia, the United States of America portion of the

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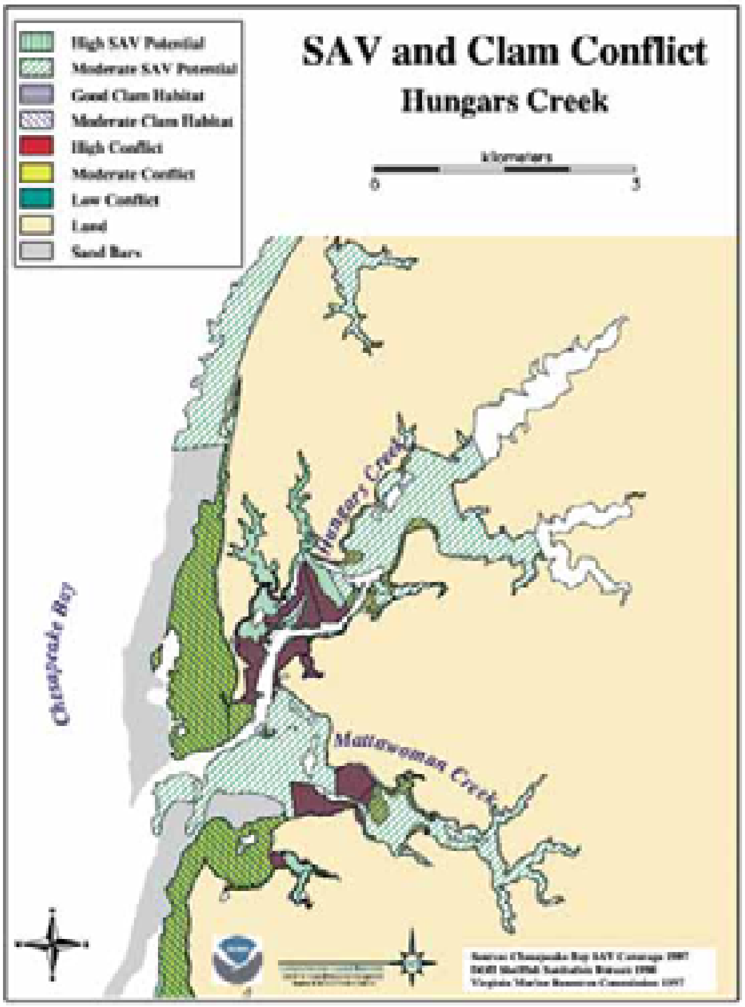
[4] GISFish case study.

FIGURE 3.23
Clam and SAV habitat suitability conflict areas



Source: Center for Coastal Resources Management (1999)

Chesapeake Bay. The potential conflict arises because SAV provides an important habitat for fishes and for the commercially important blue crab (*Callinectes sapidus*) as well as a food source for water fowl. Grow-out of the hard clam involves the use of covered trays and large nets that are anchored to the bottom to protect the clams from predators. Both the trays and nets kill existing SAV and prevent SAV from later growing in the culture areas.

A clam aquaculture habitat suitability index was developed based on production factors that included salinity, sediment type, bathymetry (depth < 1 m to allow access for cleaning nets), exposure to wind and waves, and one constraint denominated condemned areas (high fecal coliform counts). Thresholds were designated for each factor and cast into three classes (high, medium, low suitability habitat for clams). Preliminary validation of the clam model was provided by comparing the prediction of suitable aquaculture areas with the areas of current culture activity in two creeks. There was a good correspondence in one creek, but not in the other. Exposure was determined to be the problem production factor. Likewise, a SAV habitat suitability model was developed based on water quality, bathymetry and wave exposure. Water quality, in turn, was based on light attenuation. Bathymetry and wave exposure were assigned the same thresholds as for clam habitat. Similar to the clam model, there were three classes of habitat: high, medium and low. In assessing the model against actual SAV distribution, it was apparent that the depth restriction was too stringent. Overlaying the clam and SAV habitat suitability areas produced a potential conflict model (Figure 3.23).

The outcome was that at present there was little conflicting use between clam aquaculture and SAV, but about 46% of the study area would potentially be in conflict should clam aquaculture expand into areas where its potential is moderate to high that, at the same time are areas of moderate to high potential for SAV habitat.

The project was not designed to provide a definitive resolution of the potential conflicts, but rather to document the current situation and to develop and test an analytical approach. In this regard, the simple GIS models, despite the shortcomings of thresholds on some production factors, provided a good starting point to identify several options for further policy debate.

In the Limfjorden, Denmark, Dolmer and Geitner (2004) describe a GIS created as a management tool to aid an increase in the relatively recent blue mussels (*Mytilus edulis*) culture while taking into account important fisheries for mussel (80 000-100 000 tonnes/year) and for the flat oysters (*Ostrea edulus*) (850 tonnes), as well as trawl fisheries for herring and spat (no species names mentioned). Both shellfish species are fished by dredges.

The GIS data were organized in three categories (1) areas not available for mussel production (general constraints), (2) areas with culture possibilities and (3) areas specifically constrained by fisheries (Table 3.8).

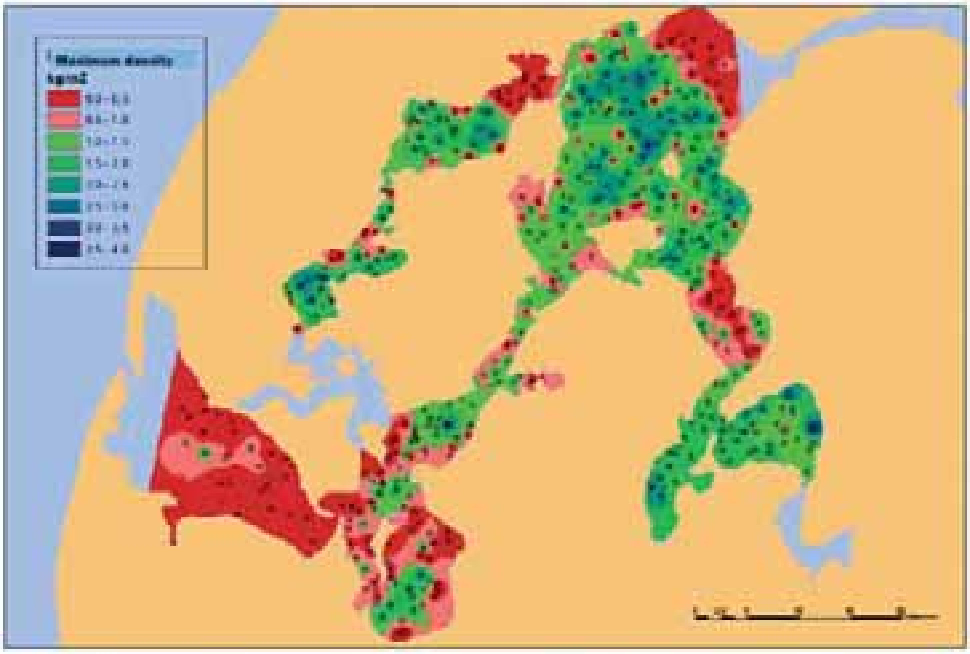
TABLE 3.8
Factors described in a GIS management tool on regulation of bivalve production in Limfjorden

Areas not available for mussel production:
Harbors
Depots of dredged sediments
Streams polluted with discharged water
Local polluted areas
Pipes and cables
Areas available for some forms of mussel production:
Areas regulated by international nature protection directives: Habitat-Ramsar-Birddirective
Areas regulated by national nature protection directives
Areas closed to mussel dredging
Areas with eel grass and macroalgae
Areas included in monitoring programme of macroalgae
Areas with stone reefs
Areas close to summerhouses
Areas close to bathing beaches
Navigational marks and corridors
Areas with extraction of sediments
Areas with fishing grounds
Blue mussels
Flat oyster
Herring/sprat

Source: Dolmer and Geitner (2004)

The categories were determined by technical experts from a number of institutions at various levels of government. Areas with culture possibilities were delimited simply by showing the number of restrictions ranging from 0 to 9 pertaining to any given area. The importance of mussel and oyster fishing areas was determined by annual

FIGURE 3.24
Maximum density of blue mussel in Lamfjorden 1993-2003.



Note: The circles indicate sampling stations.

Source: Dolmer and Geitner (2004)

FIGURE 3.25
An example of potential areas for seaweed culture in Paraíba as indicated by the GIS analysis (green areas indicate high potential whilst orange areas indicate medium potential)

Source: Soares de Souza (2003)

or biennial sampling. Areas with low densities of mussels and oysters were deemed available for mussel farming (Figure 3.24). There were no comparative data on the herring and spat trawl fishery so depth greater than 6 m was used as a surrogate criterion to establish trawlable areas.

The GIS was used both by government authorities and potential mussel farmers as a planning tool. Additional capabilities foreseen for the GIS include estimating carrying capacity in relation to the number and density of farms and identifying areas with fouling problems.

3.3.3 Introduction of Geographic Information Systems for seaweed culture

A joint FAO–Brazil project entitled "Small-scale seaweed farming in Northeast Brazil" was implemented with the general objective of supporting the social development of poor coastal communities through the promotion of sustainable aquaculture practices (Soares de Souza, 2003). The strategy proposed by this project was to test the possibility of introducing longline culture of *Gracilaria spp.*, and to evaluate its potential for expansion in five communities in three states namely Ceará, Rio Grande do Norte and Paraiba. The project duration was two years.

GIS was used in this project to (1) assess the potential of seaweed farming in the three states selected, and (2) to identify additional areas in other states in Northeast Brazil that have potential for seaweed cultivation. Coastlines, winds, currents, and bathymetry were chosen as the primary factors to determine the suitability of the sites for culture and then these selected sites were further analyzed from a economic point of view by estimating (1) distance, and (2) social characteristics within each site (i.e. culture experience, social group class, and number of families that could benefit from culture). A simple, but very comprehensive model was developed (that included System Query Language (SQL) queries) to integrate the environmental and social data described above.

The outputs derived from this model were a number of maps per state at 1:150 000 scale illustrating potential sites for seaweed culture along about 1 000 km of coastline. The results indicated that there is an enormous potential for seaweed culture; in the east coast of Ceará 2 324 ha were identified (Figure 3.25), 713 ha in the West, 1 081 ha for the North coast of Rio Grande do Norte, 930 ha in West coast of Rio Grande do Norte and 1 256 ha in Pariaba's coast.

The study is novel because it deals with seaweeds and because it takes into account important social considerations in the suitability analysis of each culture site

A follow-up to this project is a five-year Unilateral Trust Fund (UTF) project on "Coastal Communities Development" for the period 2006-2010. The UTF will collect and enter the required information in a GIS to pre-select 15 new sites per state for further analysis. The establishment of GIS for integrated mariculture and artisanal fisheries is envisioned and will include the training of the operators and the programming of the system which would also be used for monitoring of project impact (Freddi and Aguilar-Manjarrez, 2005).

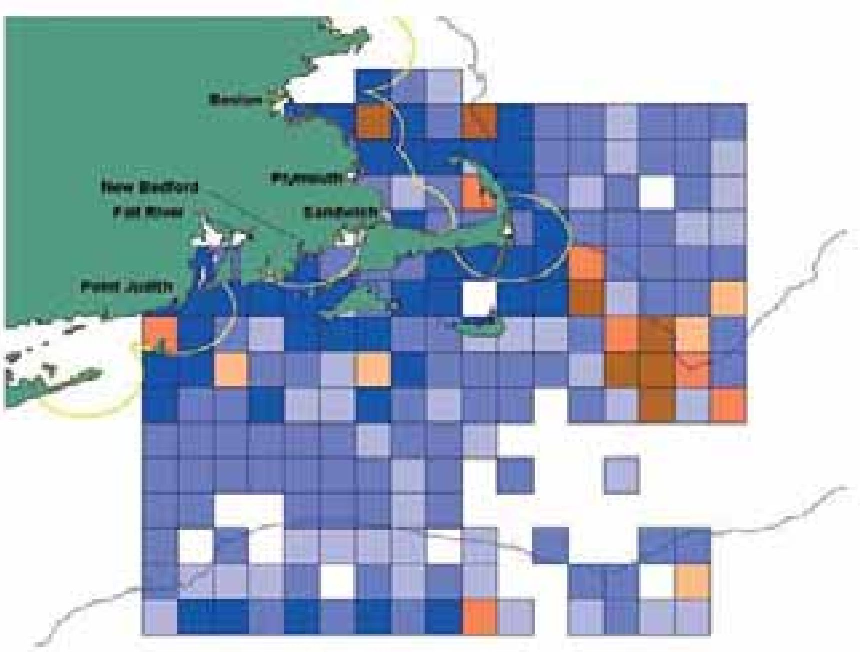
3.4 ECONOMICS, SOCIO-ECONOMICS AND GIS

This section deals both with economic and socio-economic applications of GIS. Fundamentally, all aspects of aquaculture have a basis in economics; however, there are few studies that combine the geography of aquaculture and economic considerations. For this reason, the available applications have been combined herein and they have been summarized in Tables 3.4 and 3.5.

The costs and benefits for the development and management of marine aquaculture are important as much for governments as for the commercial sector. In fact, all aspects

FIGURE 3.26

Value of commercial fishing in the New England region



Note: An overlay of economic values for ocean aquaculture and commercial fishing off the coast of Massachusetts. The boxes are geographic ten minute squares that display estimated average net revenues from commercial fishing of all types during the spring, summer, and autumn of the years 1995-97. The colors represent estimated averages during this period of the ranges of net profits or losses summed over all fishing vessels: dark blue (losses): <-$25,000; light blue (losses): -$25,000 to $0; beige (profits): $0 to $25,000; orange (profits): $25,000 to $50,000; light brown (profits): $50,000 to $100,000; dark brown (profits): >$100,000. The yellow lines delimit estimated bid-rent zones (areas of positive profits) for the growout of summer flounder (*Paralichthes dentatus*) in ocean netpens (which might take place during the spring to autumn in New England).

Source: Marine Policy Center, Woods Hole Oceanographic Institute (2003)
http://www.lib.noaa.gov/docaqua/nmaimages2001/finrepwhoi.htm

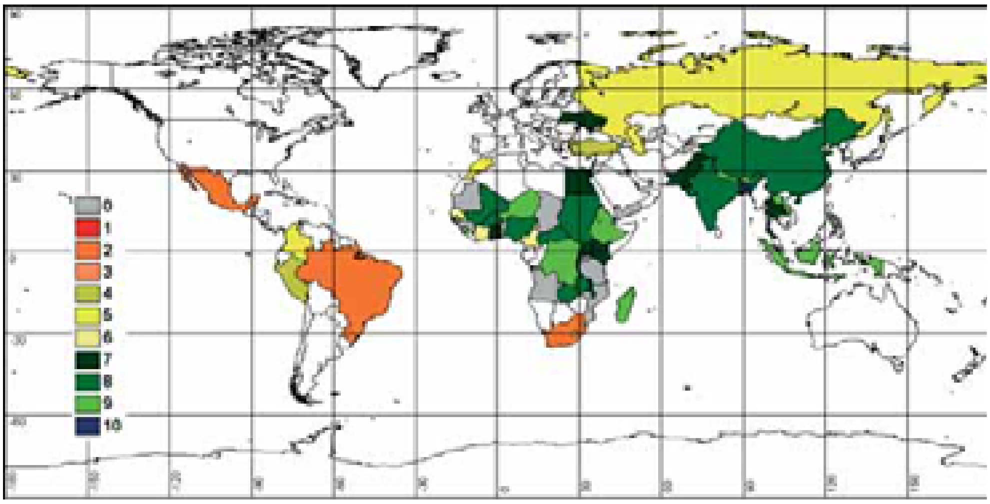
of marine aquaculture have underlying economic implications that affect sustainability. It follows then that all economic facets of marine aquaculture that are also spatial in nature have solutions that can be addressed by mapping, remote sensing or GIS. Opportunities for the use of GIS in marine aquaculture economics relate generally to zoning and site selection. Specifically, GIS analyses can be used to (1) assess time and distance cost alternatives for servicing offshore facilities from shore, (2) identify areas with physical conditions that favor the culture structure (e.g., depth, current speed, wave energy, incidence of storms), (3) integrate bioeconomic models of environmental conditions that favor growth and survival of the cultured organisms (e.g., temperature, current speed, chlorophyll-a), (4) assess alternative costs of locations of shore support and grow-out facilities (e.g., acquisition, communications, transportation of feed and cultured products), and (5) evaluate competing uses of space against potential for marine aquaculture development.

3.4.1 Economics and cage culture

Regarding the economic assessment of competing uses, Hoagland *et al.*,2003 identified and compiled data on the value of commercial fishing in the New England region. Figure 3.26 depicts both the average net value of commercial fish harvests in the coastal ocean off Massachusetts (shaded ten minute squares) and the economically feasible areas in which summer flounder might be grown out in netpens (yellow lines). GIS data layers such as this can be used to better understand the opportunity costs of allocating areas for uses other than aquaculture.

FIGURE 3.27

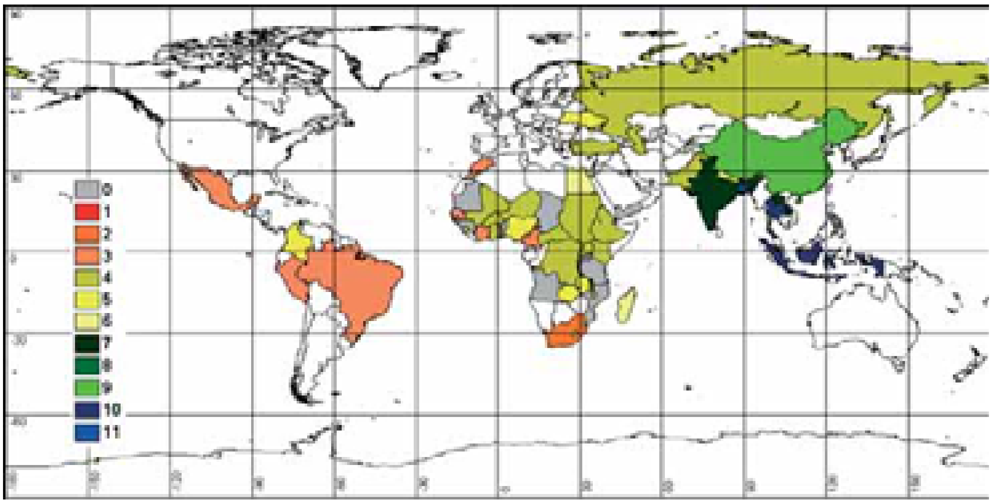
Poor countries dependent on aquaculture (directly and indirectly)



Source: Pérez, Muir and Ross (2000)

FIGURE 3.28

Countries most dependent on aquaculture which are at least moderately poor (directly and indirectly)



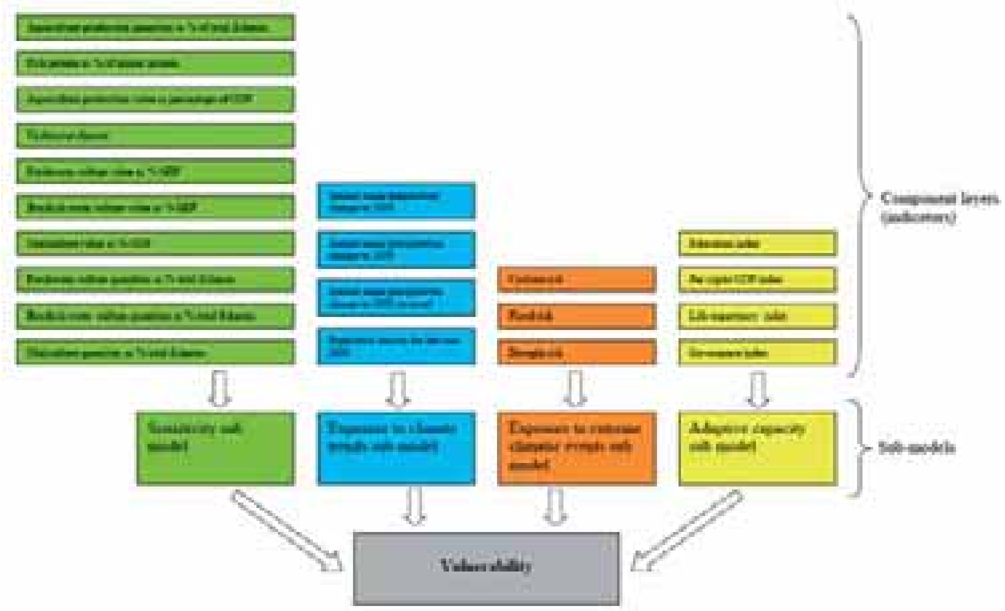
Source: Pérez, Muir and Ross (2000)

3.4.2 Economics and socio-economics of global aquaculture

The preliminary results of a global study at country level that employed spatial modelling to relate aquaculture with poverty are reported by Pérez, Muir and Ross (2000). The study is noteworthy for taking poverty into account, for its global scope and for the modelling that depended on a limited amount of comparable data that were available at the country level. The objectives of the study were to (1) identify the poorest countries where aquaculture is significant and where it might become a more important activity if improvements can be made, and (2) identify the countries which are not necessarily the poorest, but where dependence on aquaculture is high.

Basically, the authors used GIS to generate country level results as thematic maps that were scored on a 1 – 12 scale. The maps were combined in various ways using

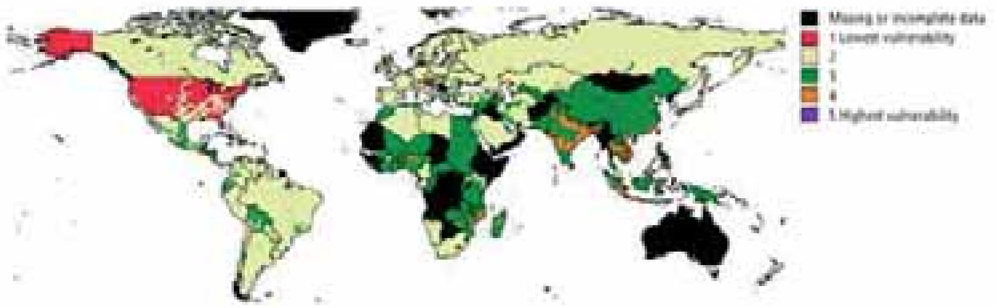
FIGURE 3.29
Schematic representation of the vulnerability assessment model



Note: The complete range of component layers (indicators) available for use in the model are shown although not all will be used at any one time. The choice of layers and weightings (significance) used in their combination will vary depending on the issues being investigated.

Source: Handisyde *et al.* (2006)

FIGURE 3.30
Vulnerability



Source: Handisyde *et al.* (2006)

models of poverty and aquaculture dependence. The first model, based on two indices, identified the poorest countries. Then GNP data were used to determine the level of poverty of each of the countries. A second model was developed to determine in which counties aquaculture was of significant importance. Importance was based on the countries' direct and indirect dependence on aquaculture. Direct dependence was gauged on the basis of internal consumption and employment generated while indirect importance was measured using aquaculture production and exports. The results were further refined by considering national-level poverty and significance of aquaculture together. Two kinds of poverty – aquaculture distinctions were made by varying the weights placed on poverty and on the importance of aquaculture: (1) the poorest countries in which aquaculture is significant (Figure 3.27), and (2) the countries which are dependent on aquaculture and which are at least moderately poor (Figure 3.28). Another combination of thematic maps identified those countries most dependent on aquaculture, irrespective of poverty level).

The authors point out several limitations of the study that include a lack of comparable country-level data for all of the countries regarding poverty indices, and the need to estimate aquaculture consumption and exports internal to the study due to the lack of published data. While the study identified countries where aquaculture potentially could benefit poor people, an improvement would be to determine where within the most needy countries aquaculture would be most suitable.

Another global GIS-based study addresses the effects of climate change on aquaculture (Handisyde *et al*., 2006). Climate change effects can be direct, e.g., changes in water availability, temperature, and damage by extreme climatic events, or indirect such as increased fishmeal costs with consequences for aquaculture feed costs. The role of GIS was to identify areas where livelihoods are vulnerable to climate change impacts on aquaculture. The model (Figure 3.29) sets vulnerability as a function of exposure and sensitivity to climate change and adaptive capacity. The analytical procedure is a familiar one: (1) each production function (layer) was reclassified so that its cells had an importance ranging from 1 to 5, (2) data layers in the sub-models and main model were combined using multi criteria evaluation (MCE) with weighted linear combination and with the weights placed on layers determined by expert opinion.

The most vulnerable areas overall were in parts of Asia, Africa and Latin America (Figure 3.30). Seven other models were run, each one emphasizing a different kind of vulnerability (e.g., vulnerability in terms of food security, vulnerability of mariculture to cyclones) with each model one identifying the regions and countries most affected.

According to the authors, a number of factors affected the results of this study. Among them are that data for the layers varied in resolution, typically with data for extreme events, population and climate having the highest resolution while social, political and economic data were at national level. Higher resolution data throughout would have been preferable, but this is difficult with global studies. Another factor was that current vulnerabilities were being compared with future changes predicted by climate change models. Nevertheless, it was concluded that current vulnerabilities are the best proxies for the future situation. It was noted that a larger focus group (there were only six individuals in the study group) would have broadened the experience and made the results more statistically robust. It was emphasized that the aim of the assessment was to highlight areas likely to be vulnerable as a way to identify those areas requiring more detailed investigation. The use of spatial data and GIS provided results superior to those that could have been achieved with a numerical index by identifying affected areas within countries as well as the geography of the issues; however, the results have to be regarded as indicative.