ISSN 0429-9345

FAO
FISHERIES
TECHNICAL
PAPER

458

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

FAO
FISHERIES
TECHNICAL
PAPER
458

by

James McDaid Kapetsky
Consultant

and

José Aguilar-Manjarrez
Fishery Resources Officer

Aquaculture Management and Conservation Service
FAO Fisheries and Aquaculture Department

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS
Rome, 2007

The mention or omission of specific companies, their products or brand names does not imply any endorsement or judgement by the Food and Agriculture Organization of the united nations.

ISBN 978-92-5-105646-2

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.

Kapetsky, J.M.; Aguilar-Manjarrez, J.
Geographic information systems, remote sensing and mapping for the development and management of marine aquaculture.
FAO Fisheries Technical Paper No. 458. Rome, FAO. 2007. 125 pp.

Acknowledgements

We would like to thank our many colleagues who kindly provided copies of their papers, articles and technical reports for review. Special thanks go to our reviewers for many valuable comments. They were, in alphabetical order: William Arnold, Malcolm Beveridge, William Fisher, Alessandro Lovatelli, James Muir, Oscar Pérez, Lindsay Ross, Philip Scott and Doris Soto. Also, we would like to thank Steve Walker for his useful contributions to Table 4.3. Tina Farmer and Françoise Schatto-Terrible proofed the document and supervised its publication. Sylviane Borghesi prepared the cover and Fabio Carocci assisted in its design. The document layout specialist was Nadia Pellicciotta.

Contents

Figures

Tables

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.

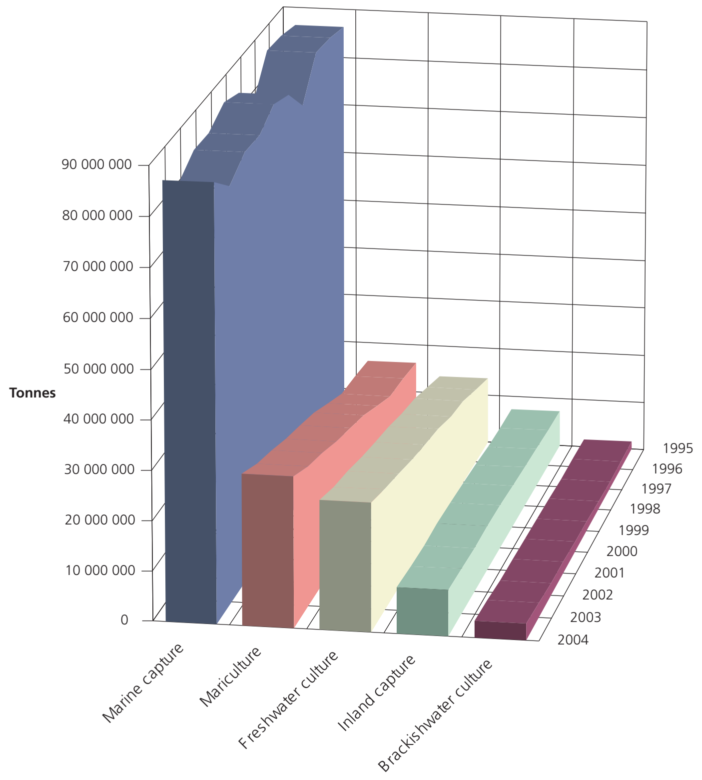
Our main emphasis is on GIS. Remote sensing is viewed as an essential tool for the capture of data subsequently to be incorporated into a GIS and for real time monitoring of environmental conditions for operational management of aquaculture facilities. Maps usually are one of the outputs of a GIS, but 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.

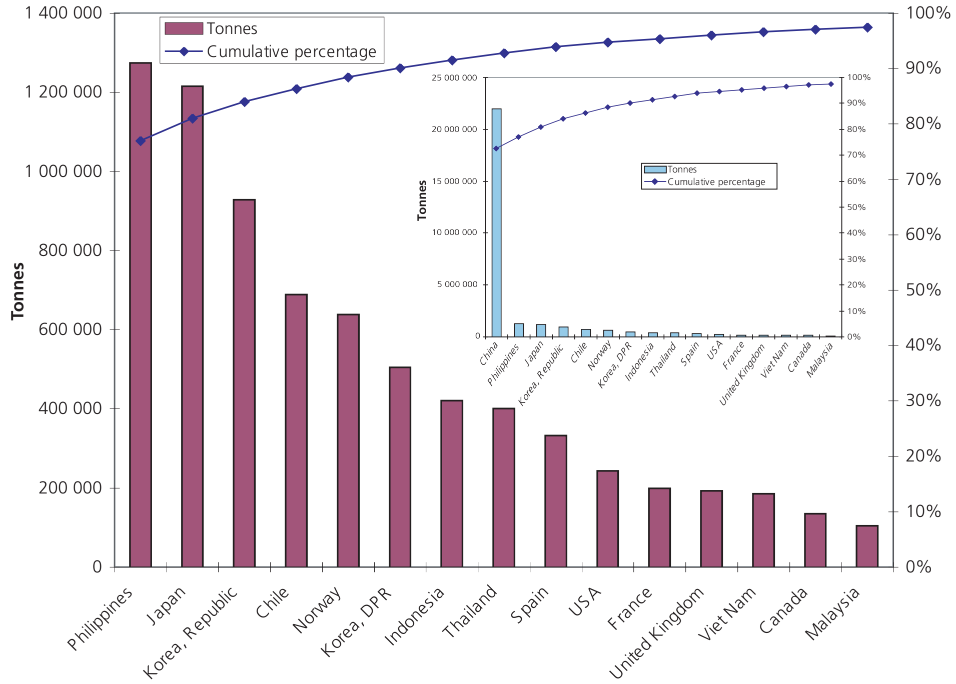
Finally, we comment on the state of the application of GIS, remote sensing and mapping for the development and management of marine aquaculture and make some recommendations for improved implementations.

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).

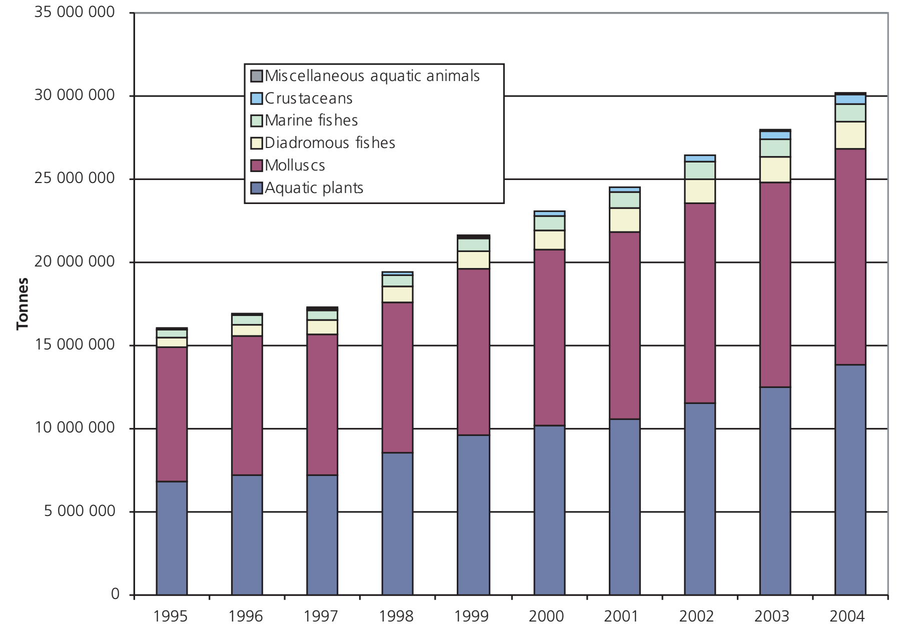
1.2.3 Important groups of aquatic species in mariculture

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

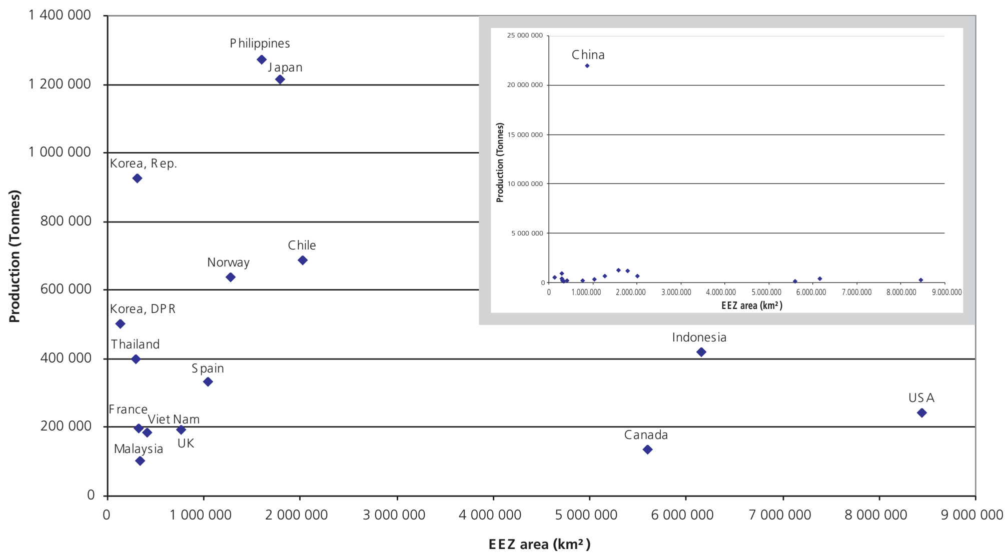
An Exclusive Economic Zone (EEZ) is the area under national jurisdiction (370 km or up to 200-nautical miles wide) declared in line with the provisions of 1982 United Nations Convention of the Law of the Sea. Within the EEZ the coastal State has the right to explore and exploit, and the responsibility 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.

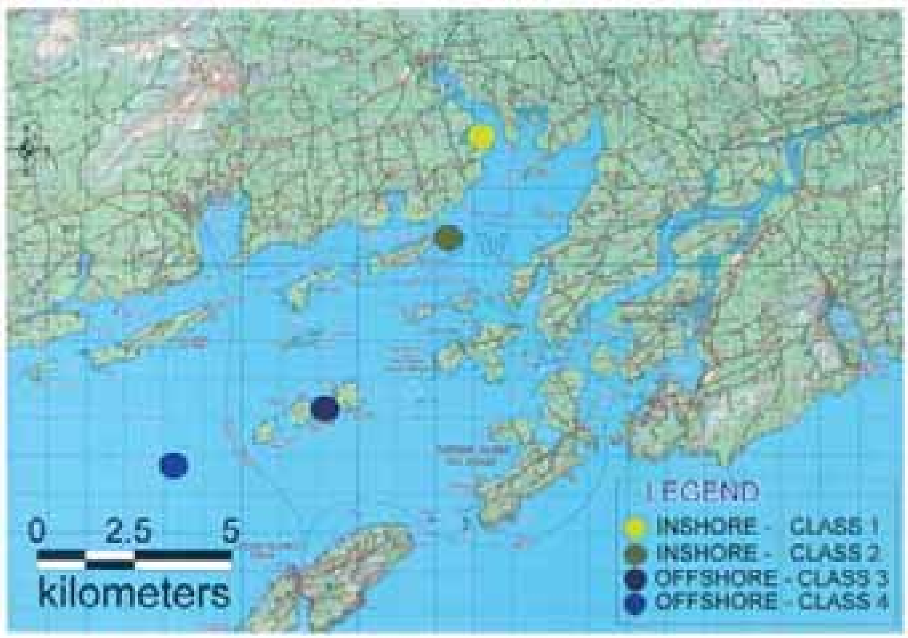
1.3 SPATIAL CONTEXT OF NEAR SHORE AND OFFSHORE ISSUES SHAPING MARINE AQUACULTURE

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).

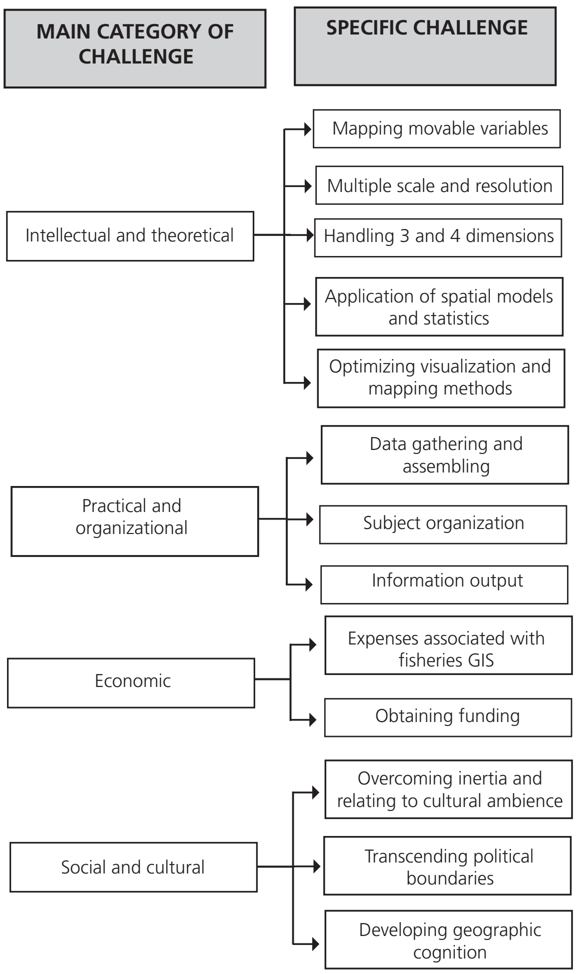
The operational challenges facing fisheries GIS that inhibit problem solving as perceived by Meaden (2004) are in four main categories including (1) intellectual and theoretical, (2) practical and organizational, (3) economic, and (4) social and cultural. The associated specific challenges are summarized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

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

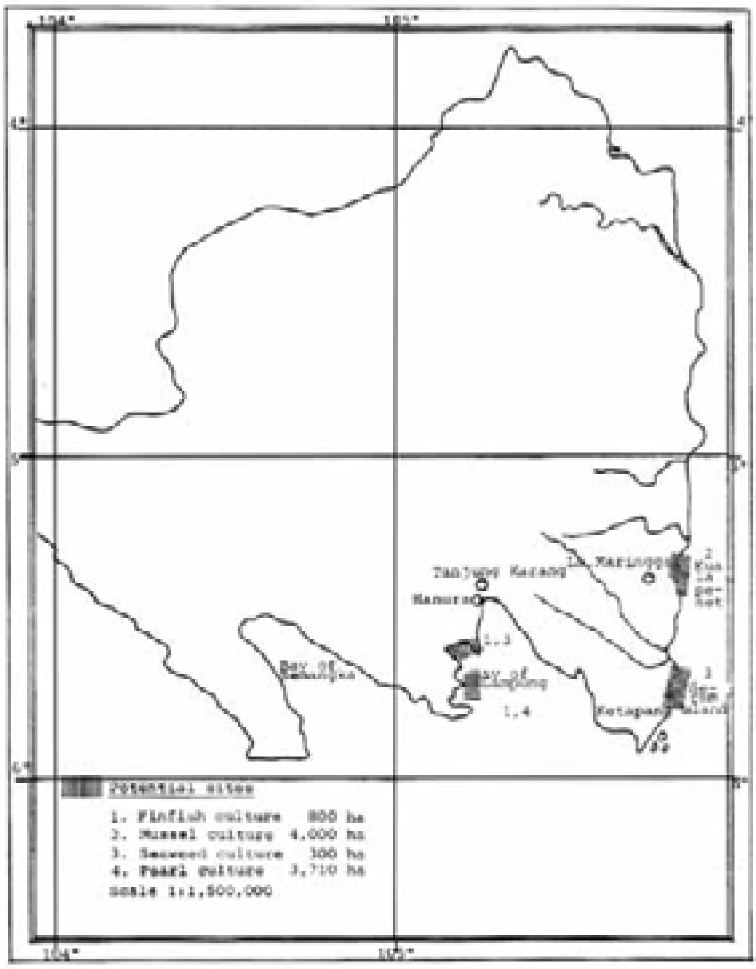
3.1.2 Mapping aimed at the development of aquaculture

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



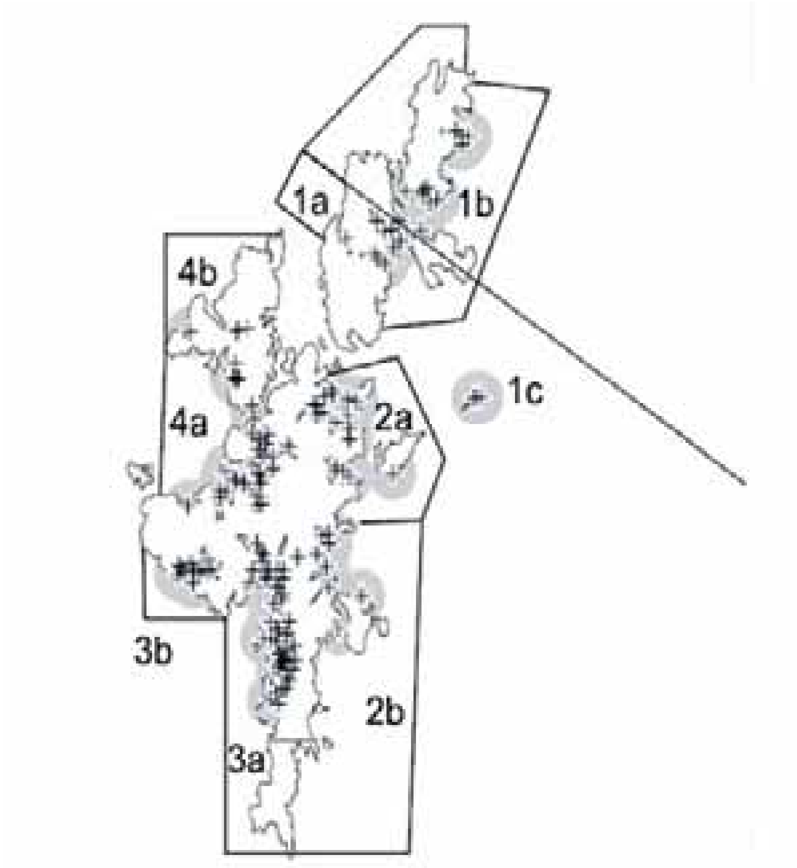
Source: Tiensongrussmee, Pontjoprawiro and Mintarjo (1988)

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.

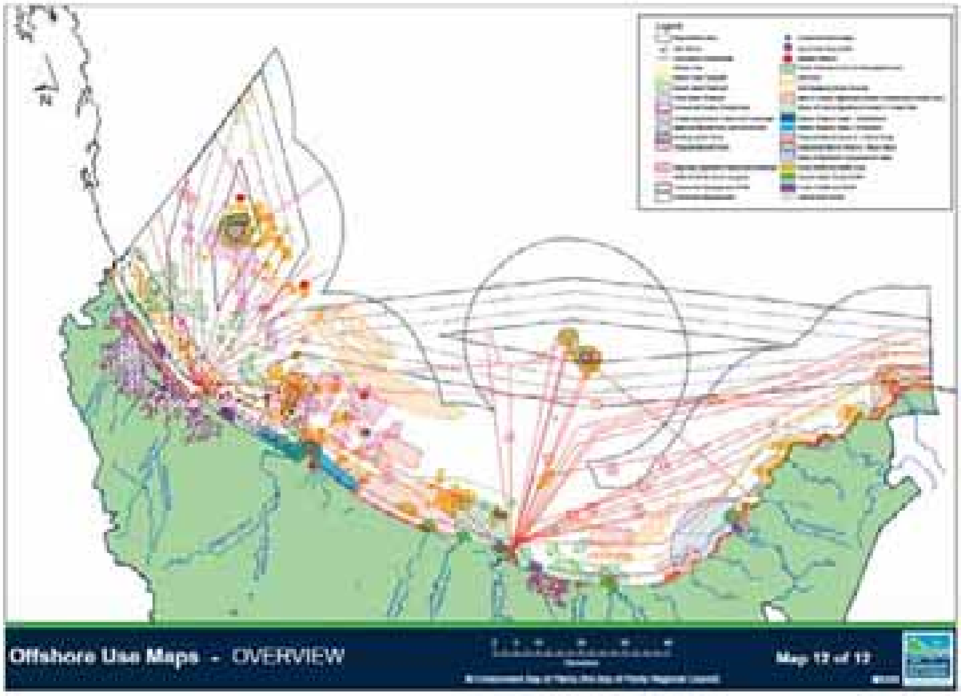
Source: Scottish Executive (2000)

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

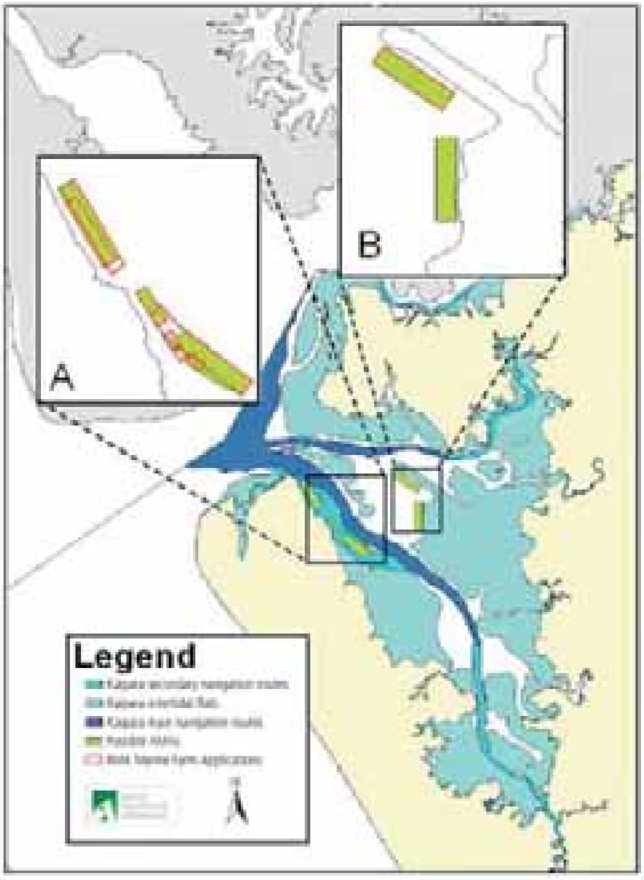
Source: Auckland Regional Council (no year)

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

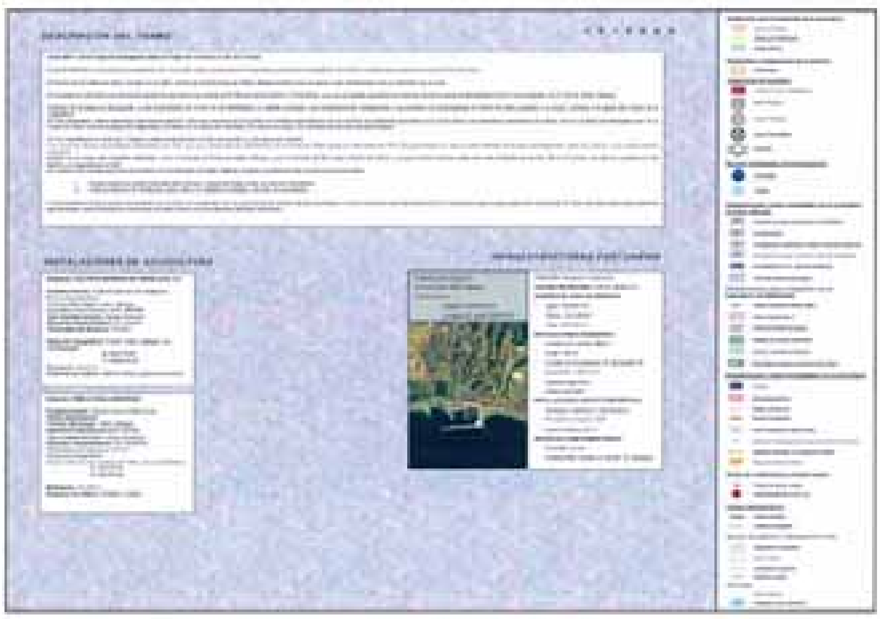
Based on the degree of compatibility among the criteria considered, three kinds of zones were demarcated: (1) suitable zones (no incompatibilities), (2) zones with limitations, and (3) exclusion zones (aquaculture incompatible with already existing uses). The result amounts to a coastal aquaculture use 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).

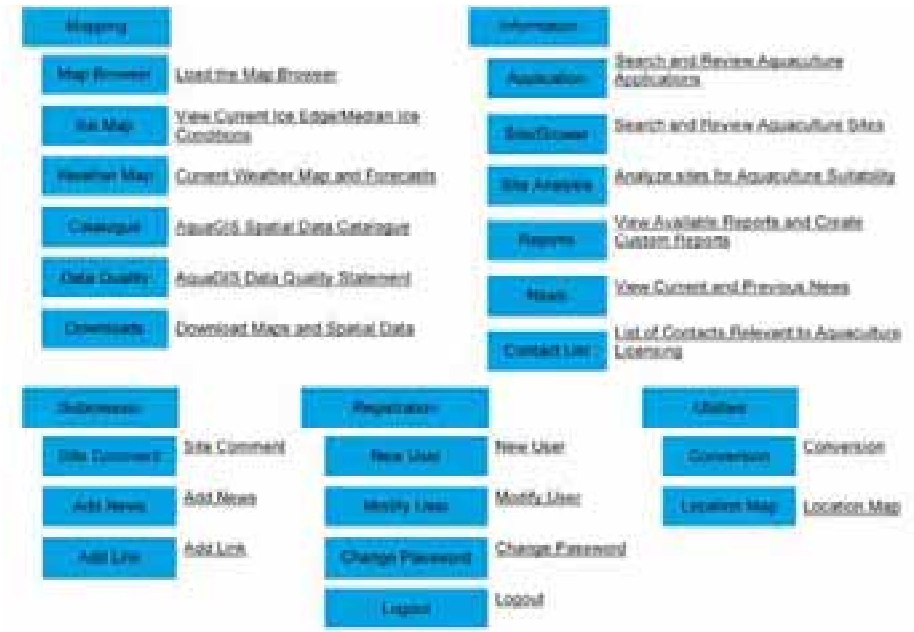
The Mapping Service contains two map browsers, one of which shows aquaculture sites, site boundaries and communities throughout the province. Sites are defined by the kind of product cultured (Figure 3.6b). Another browser is based on the South Coast Regional Aquaculture GIS. Figure 3.6c shows the layers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

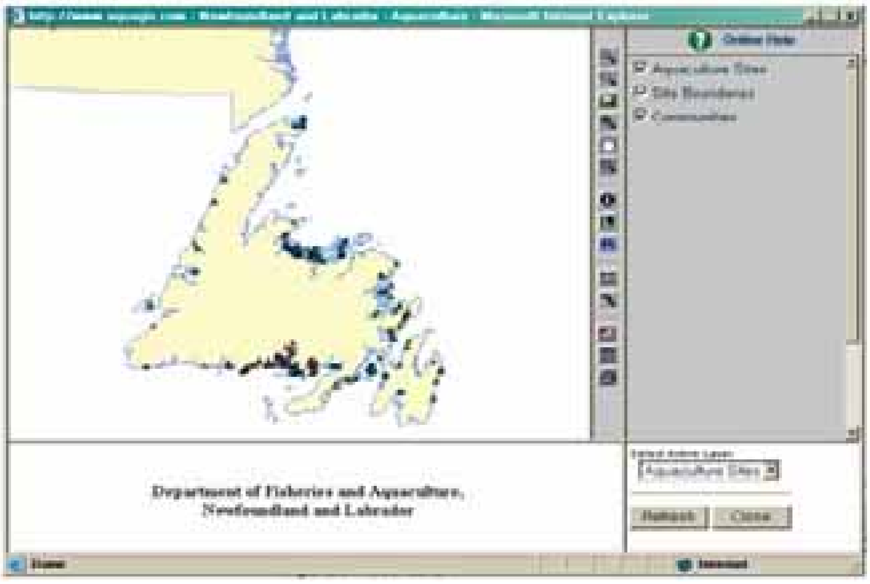
As part of the NOAA National Marine Aquaculture Initiative, the Marine Policy Center of the Woods Hole Oceanographic Institution (2003) has developed several interactive functions on the Internet. One of the interactive functions is the "Site Suitability Modelling Process" (SSMP). The SSMP can be used 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

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).

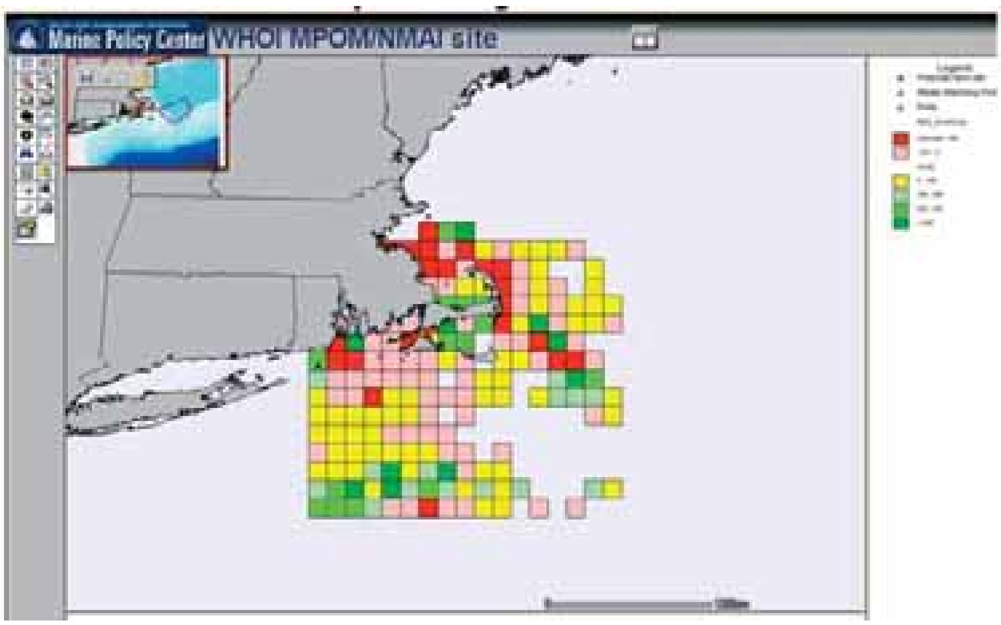
The potential of remote sensing in fisheries and aquaculture was appreciated and promoted early on by Kapetsky and Caddy (1985), Mooneyhan, (1985) and Travaglia and Appelkamp (1985). Since then remotely sensed data have proven to have many uses in marine aquaculture development and management, but the 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)

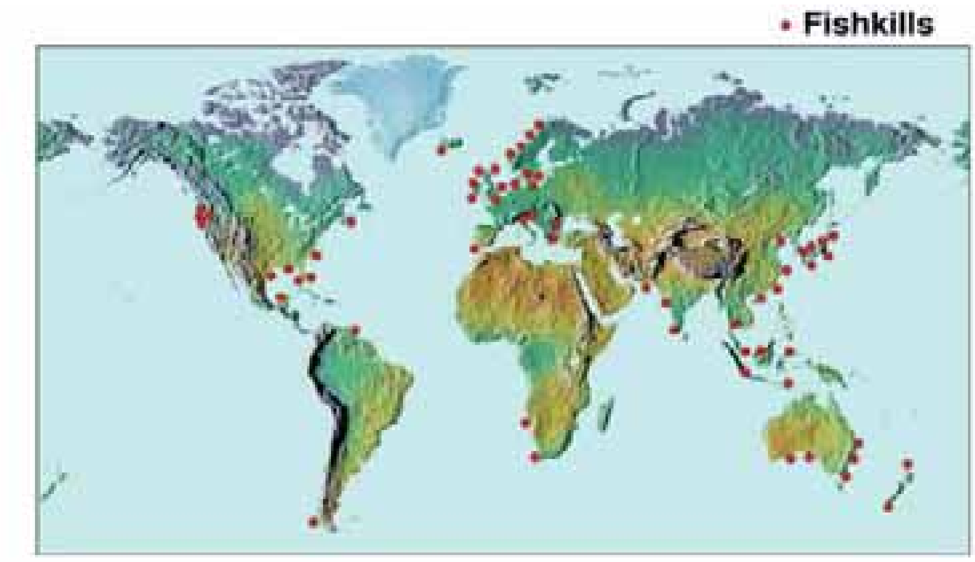
3.2.3 Remote sensing for aquaculture practice and management

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).

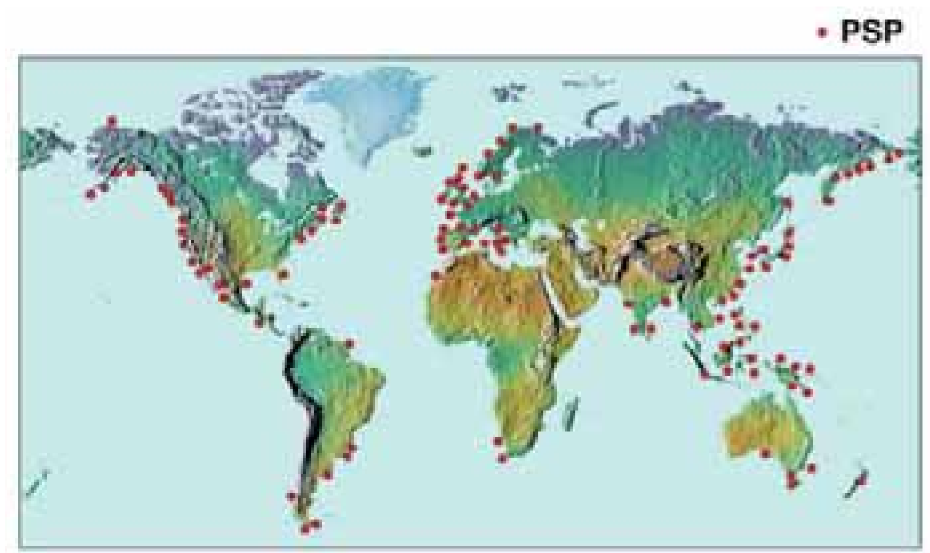
One of the earliest operational applications of airborne satellite remote sensing to marine aquaculture is described by Johannessen, Johannessen, and Haugan (1988) and also summarized as a case study by Meaden and Kapetsky (1991). A HAB was detected and monitored for four weeks as it moved from Sweden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

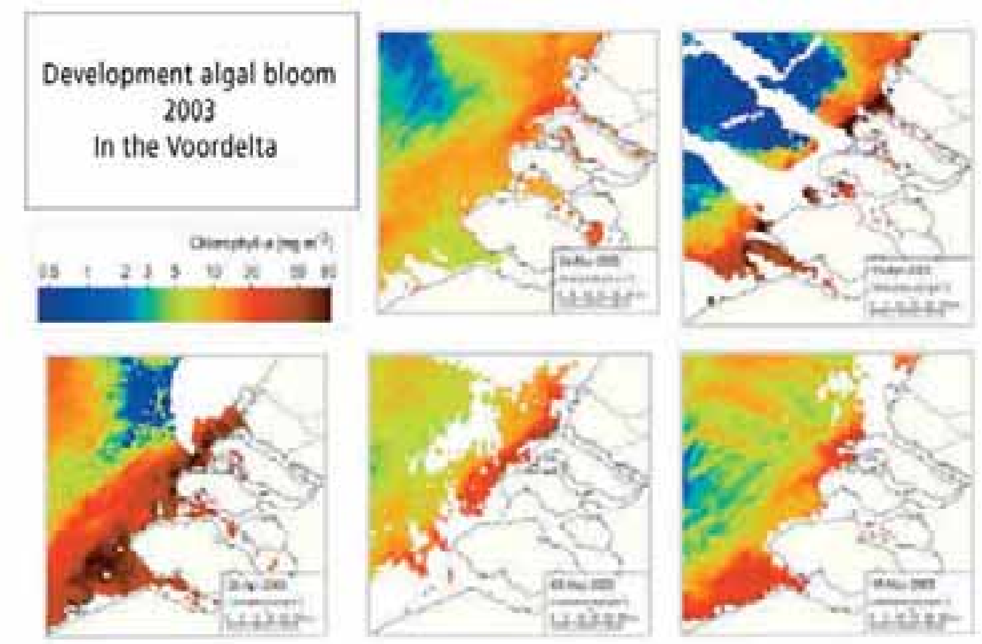


Source: http://www.whoi.edu/redtide/HABdistribution/PSP_worldmap_2005.gif

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).

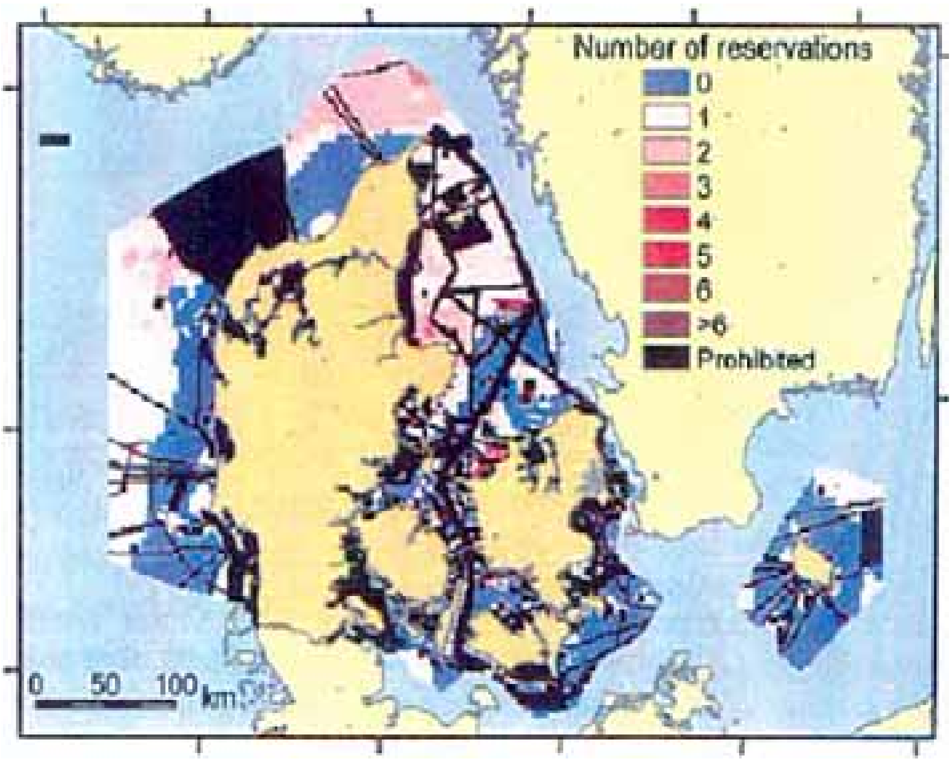
TABLE 3.4
Summary of GIS applications to culture of finfishes in cages organized by main issues

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.

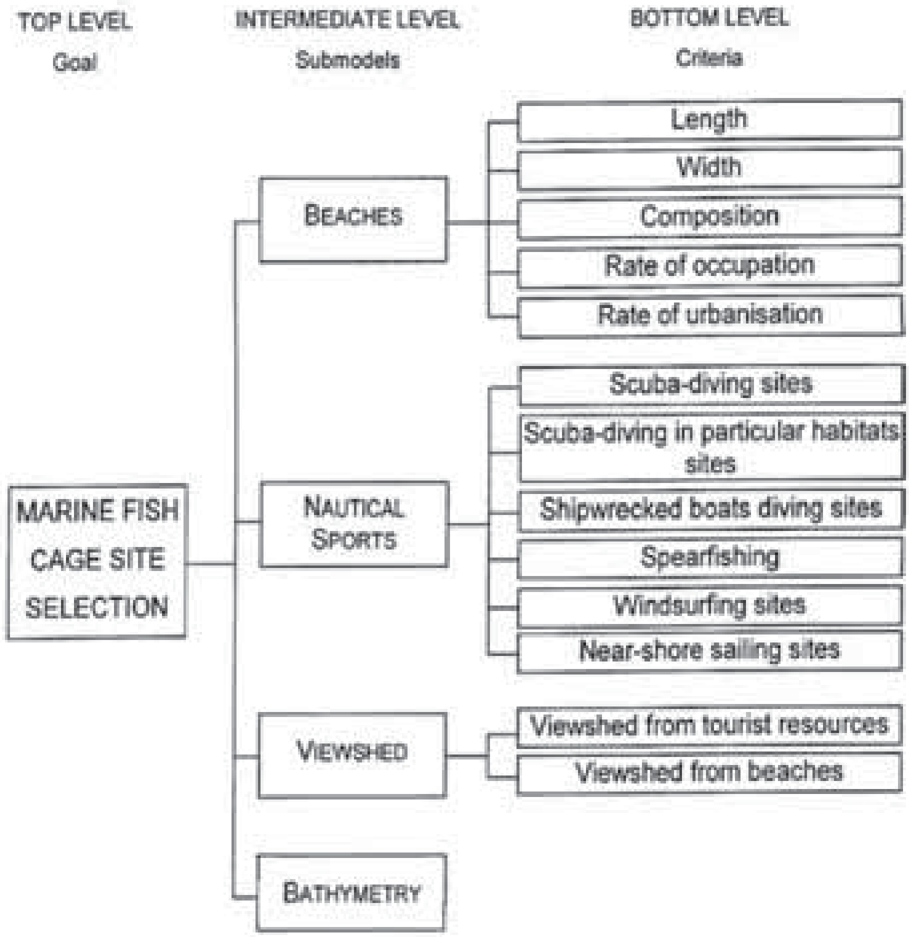
Additional criteria to improve the model included distance from a shore facility to a suitable area, as well as beach recreational areas, holiday houses, fishing areas, areas of archeological importance, and occurrence of macro algae. In order to improve analytical capabilities a more sophisticated weighting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

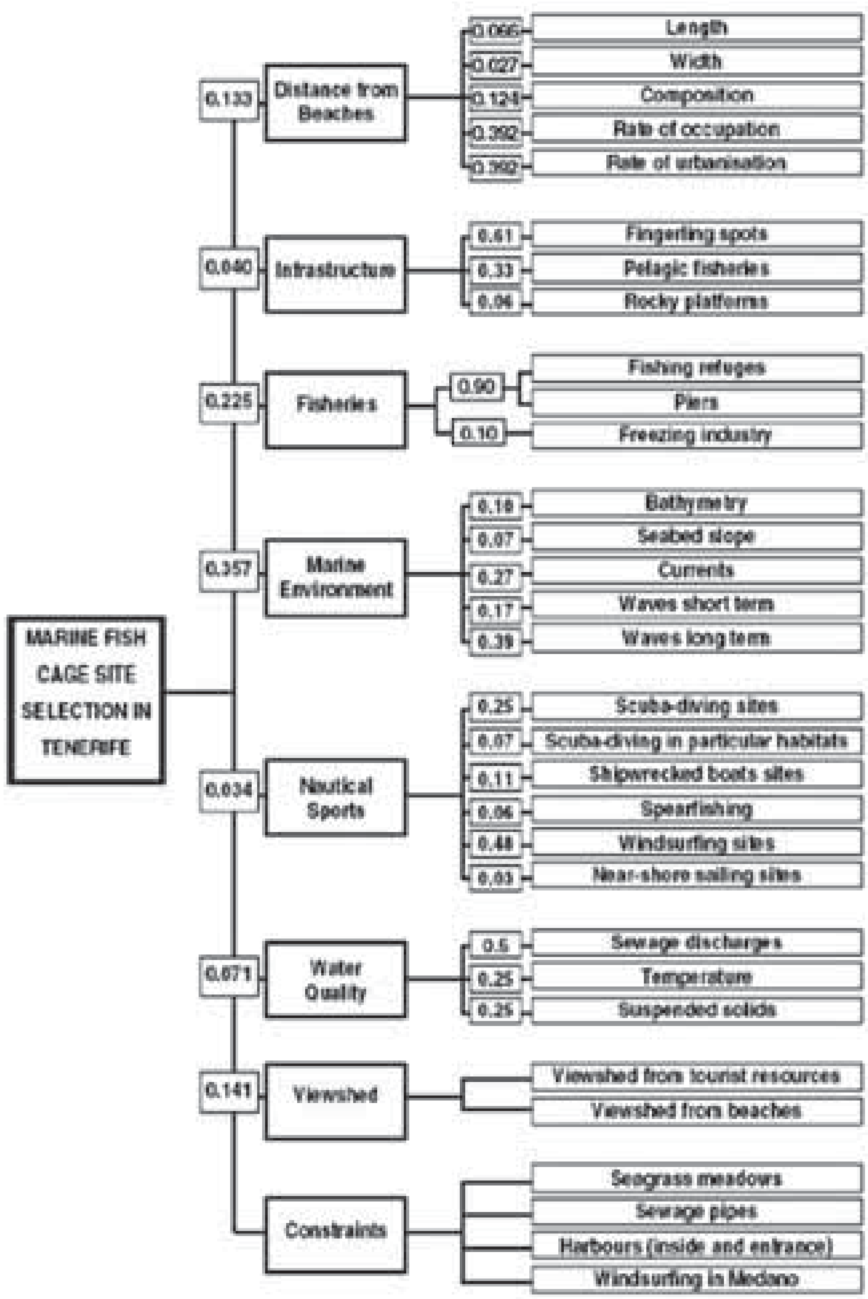
It was concluded that the results were indicative of opportunities for aquaculture development for general planning purposes and that additional verification in the water and on the ground was required. Suggested improvements dealt with updating and adding production factors relating to infrastructure,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

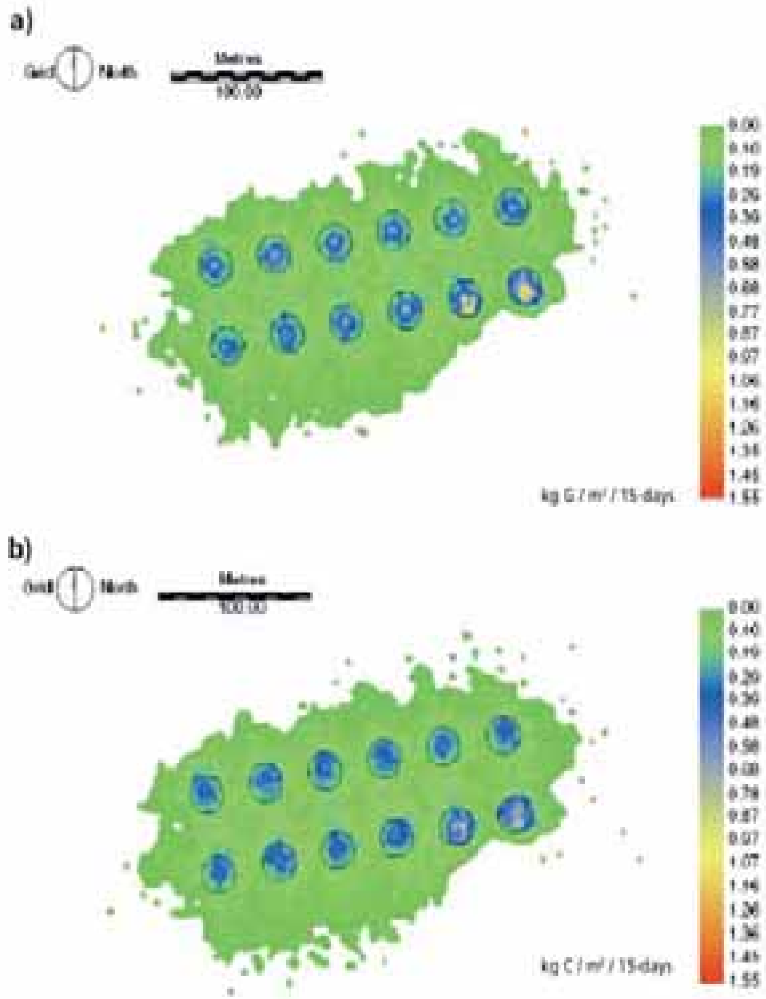
modules as extensions. Also, working within the GIS provides the opportunity to develop new applications.

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



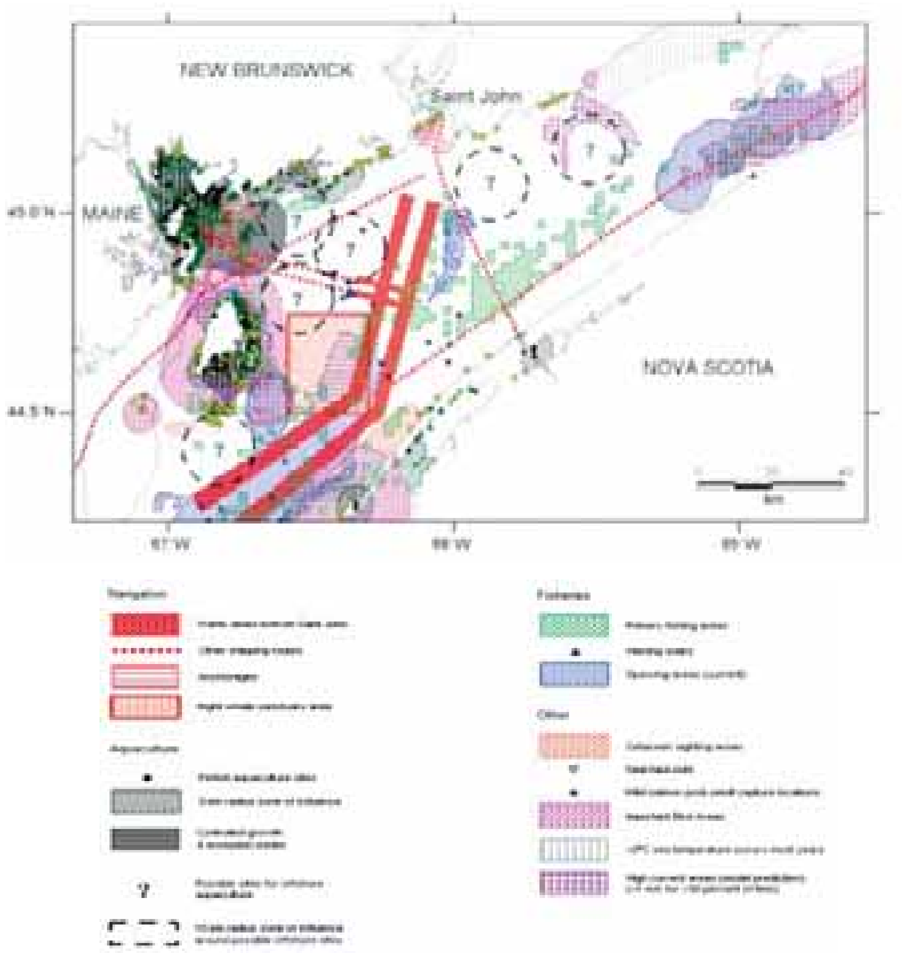
Source: Corner *et al*. (2006)

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).

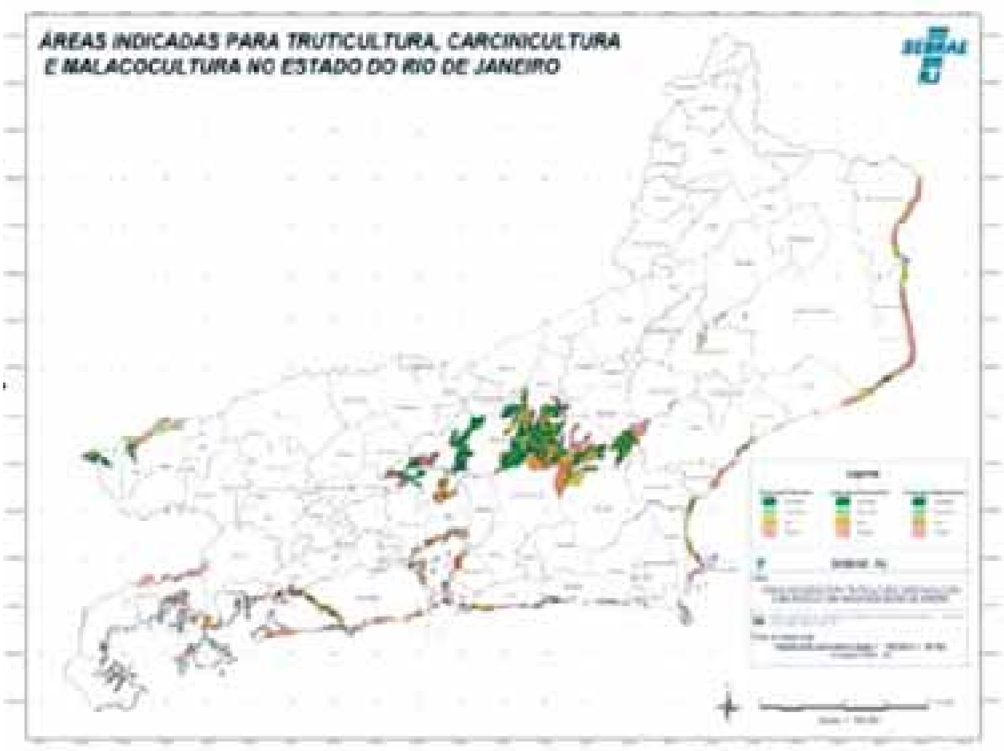
TABLE 3.6
Summary of GIS modelling results for Rio de Janeiro potential and demands

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

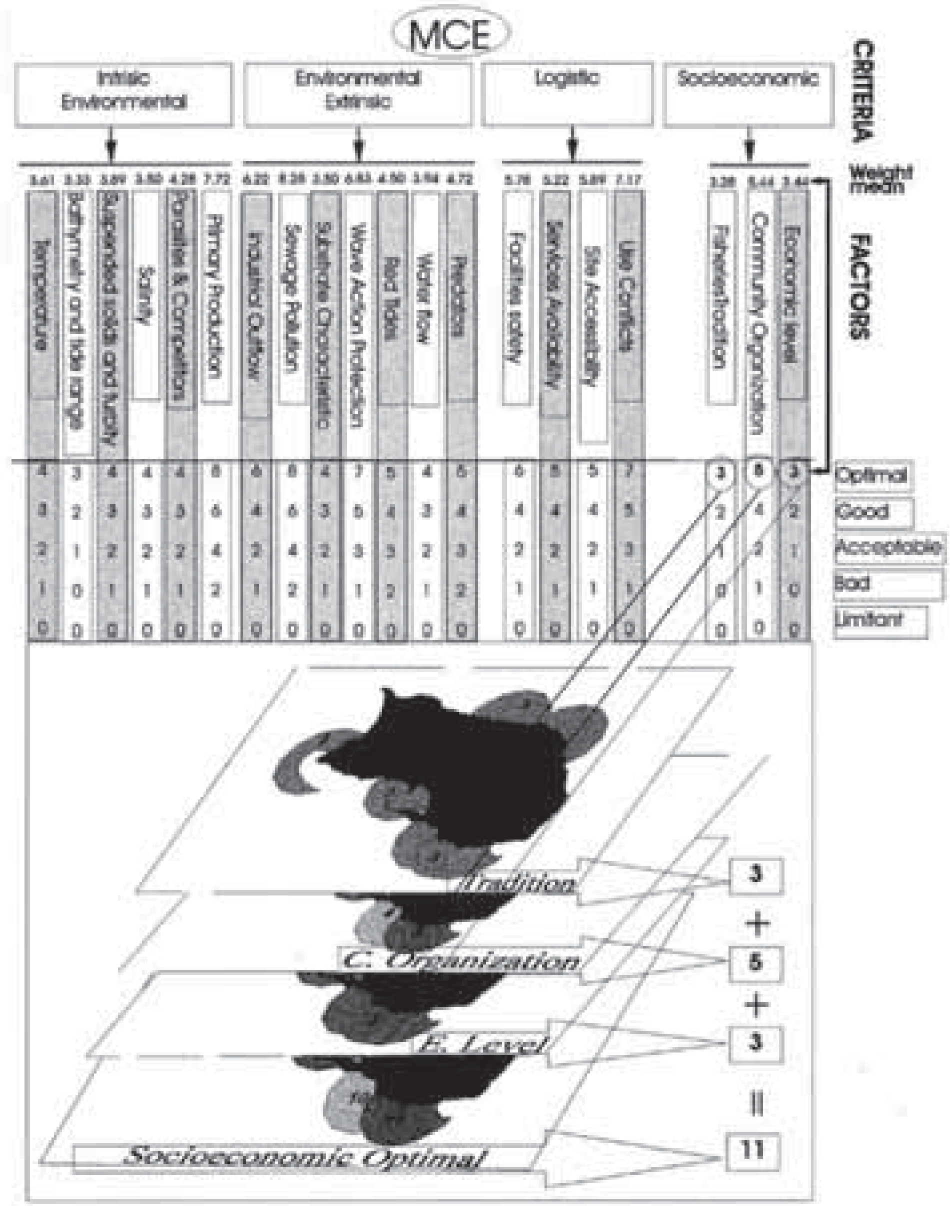
Site suitability			Judgment weights: mean ± SD (range)
Criteria and factors	Optimum	Restrictive	
Intrinsic environmental			
Temperature	22-27°C	N.A	36± 2.7 (0-10)
Bathymetry-tide	> 5 m and small tide	> 5 m or large tide	3.3 ± 3.4 (0-15)
Range	Fluctuation	Fluctuation	
Suspended solids and turbidity	Secchi 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



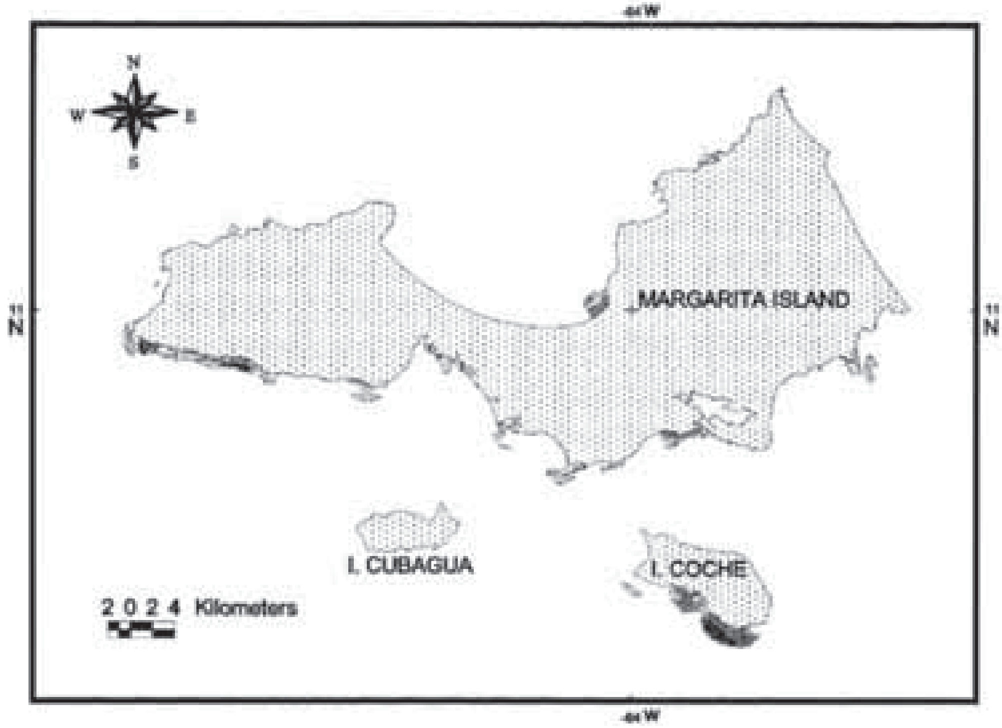
Source: Buitrago *et al*. (2005)

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.

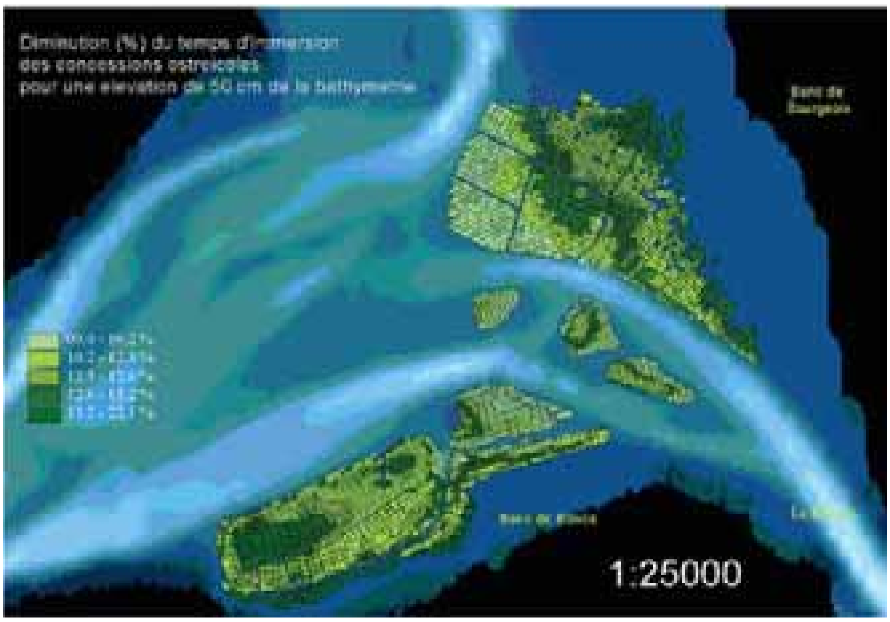


Note: It is considered that those places have the optimum conditions for oyster raft aquaculture in the Margarita Island region. Additional locations meeting 75% (■) or 70% (■) of the demanded criteria for a final suitable selection cover 137 sites encompassing 37.5 km².

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

[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 20^{th}

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.

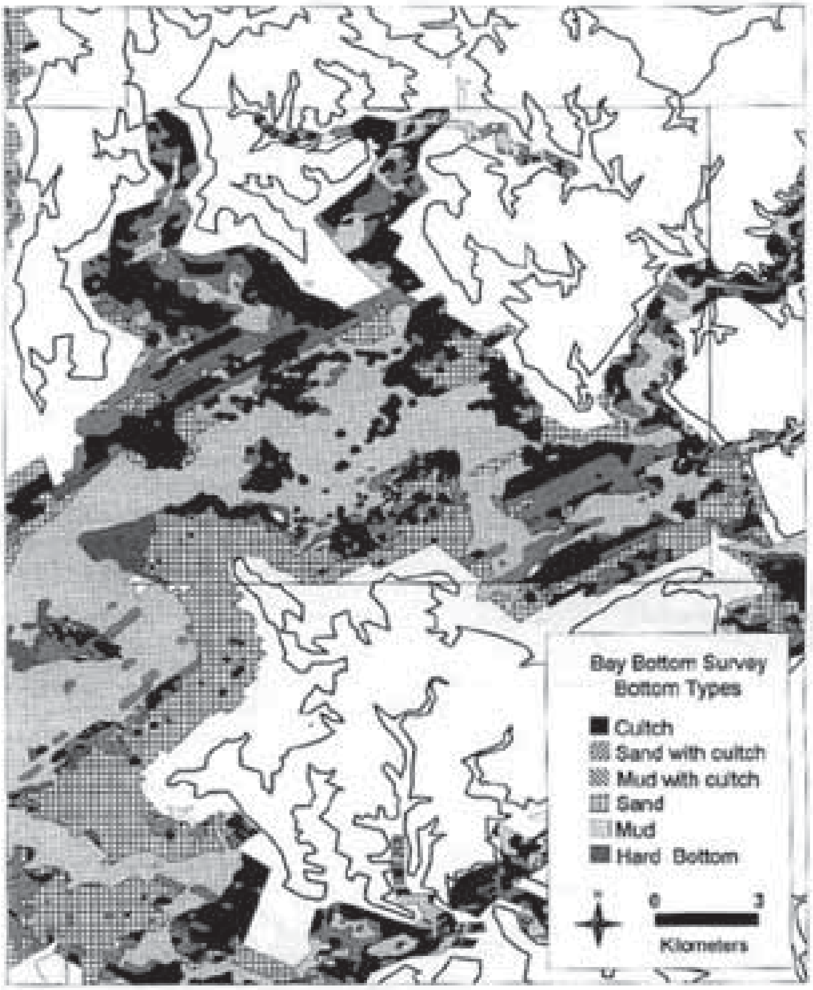
A study of shellfish aquaculture in Baynes Sound, Vancouver Island, BC Canada by Carswell, Cheesman, and Anderson (2006) addresses several issues related to aquaculture development using aerial remote sensing and GIS. The issues include inventory of clam aquaculture and the environment while at the same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

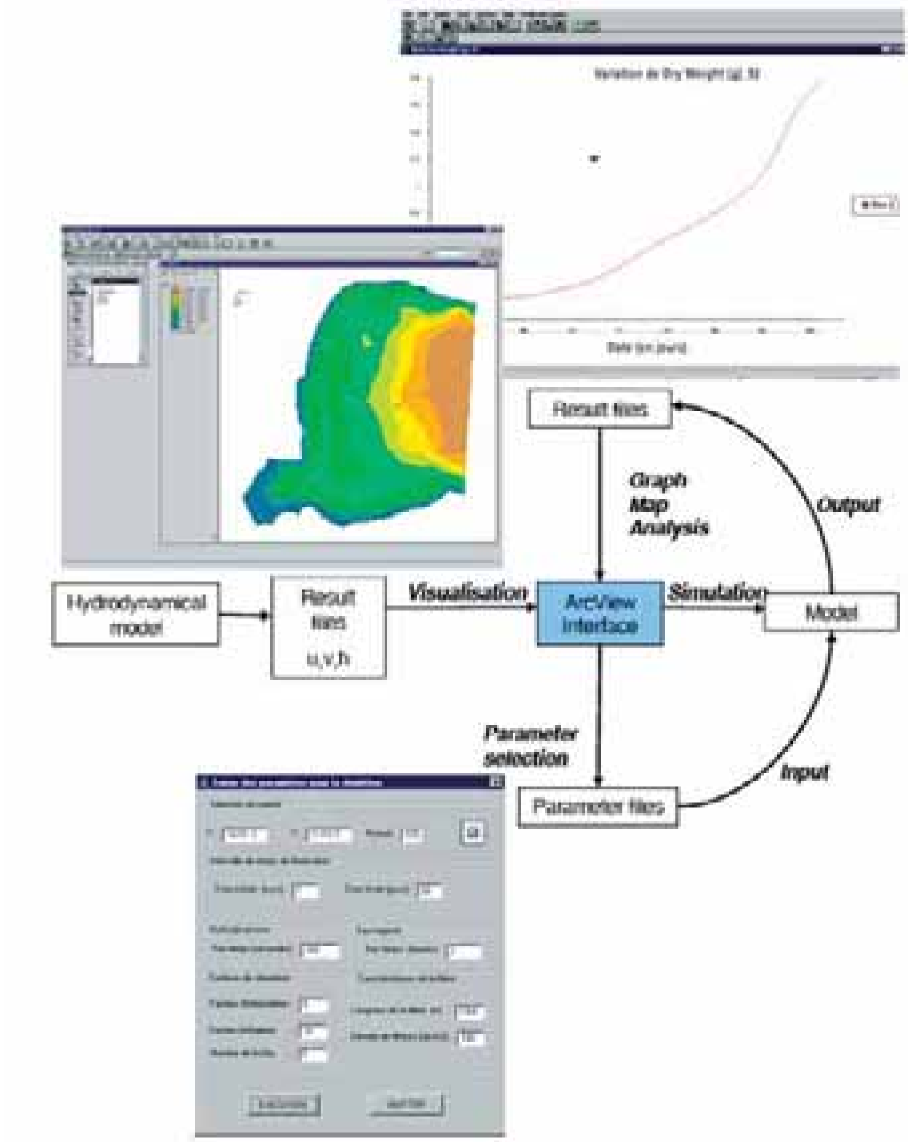
A tool (Figure 3.20) was developed to:

- 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

[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

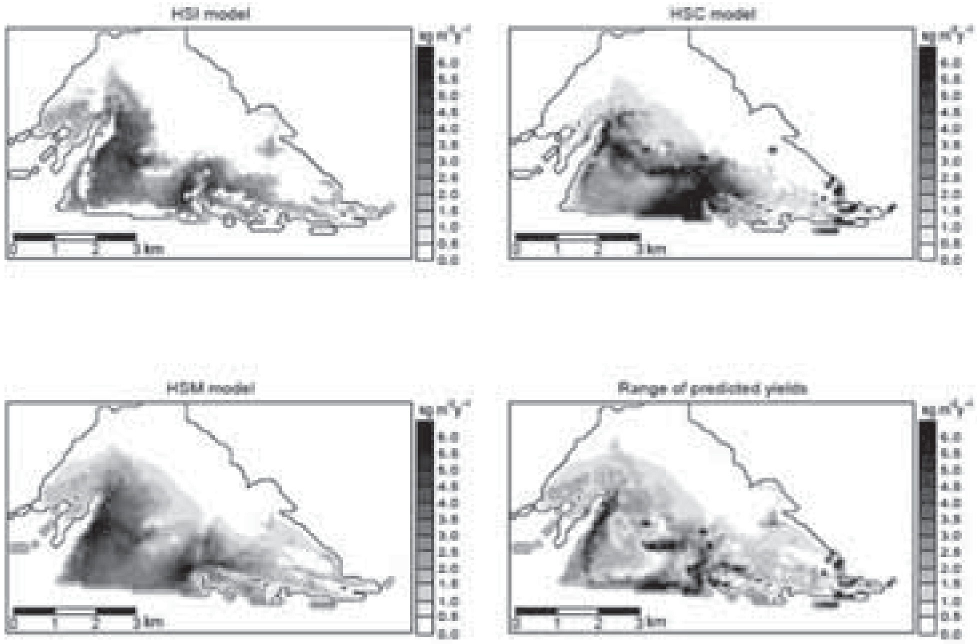
Spatial use conflicts in aquaculture are of many kinds. Two of the most important are reviewed here. They are direct competition for space between aquaculture and fisheries and indirect conflicts for space in which shellfish aquaculture may displace or reduce the biological productive capacity of the 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

[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.

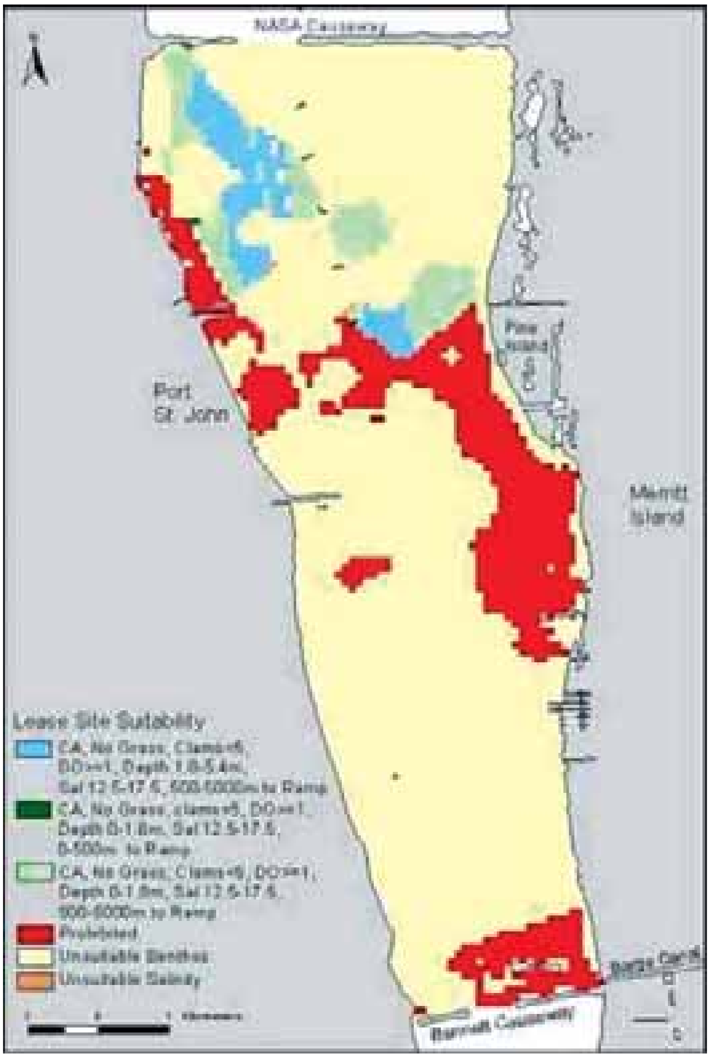
Clam aquaculture in Florida has grown at a rapid pace, but among the issues is that grow-out has to take place on publicly-owned bottom. Going along with this is the need for culture sites to support economically viable growth and survival while not directly or indirectly interfering with other functions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

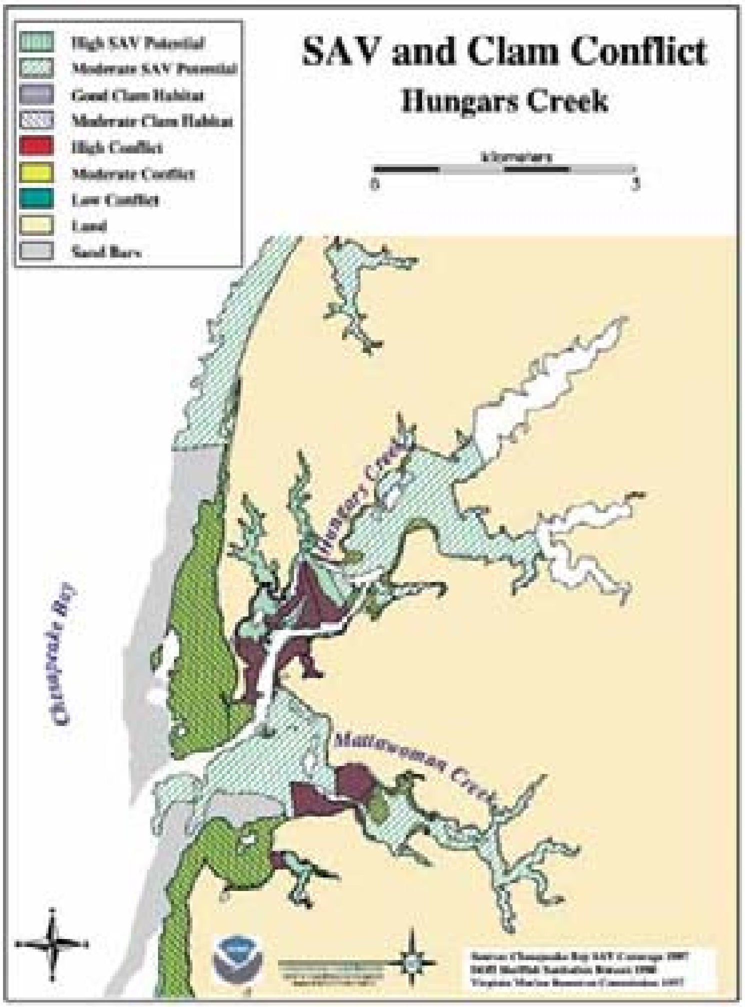
Note: Areas categorized as unsuitable are not appropriate for hard clam aquaculture due to the presence of seagrass, high density clam populations recorded during our 1994 survey, low levels of dissolved oxygen recorded between 1987 and 1998, excessive water depth or the proximity of navigable channels, 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

[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).

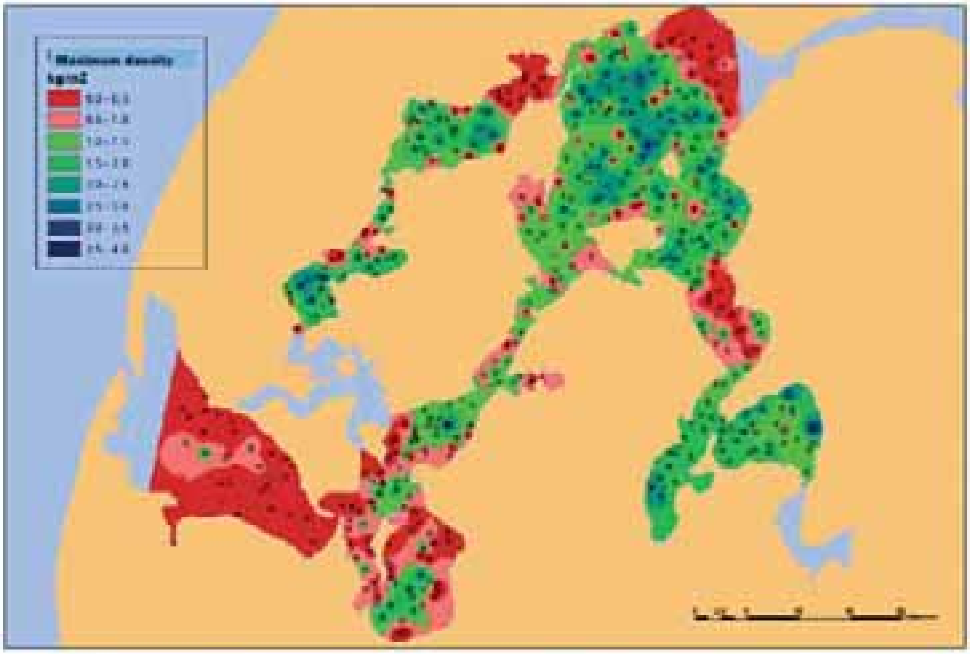
TABLE 3.8
Factors described in a GIS management tool on regulation of bivalve production in Limfjorden

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

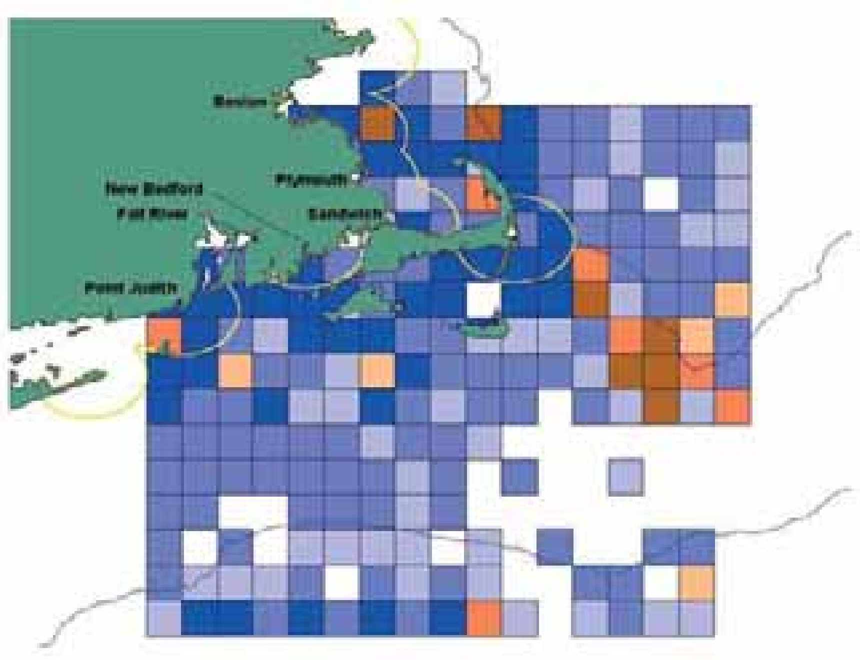
A follow-up to this project is a five-year Unilateral Trust Fund (UTF) project on "Coastal Communities Development" for the period 2006-2010. The UTF will collect and enter the required information in a GIS to pre-select 15 new sites per state for further analysis. The establishment of GIS for integrated 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).

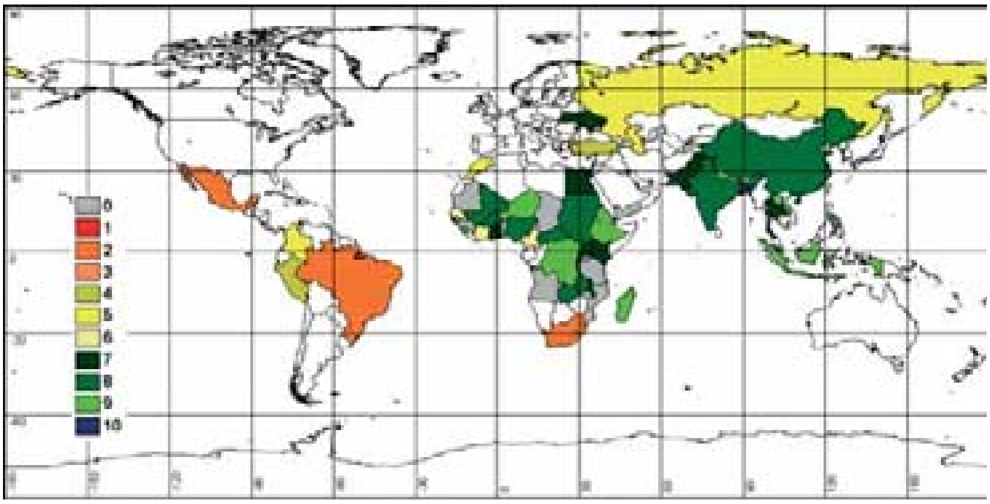
Source: Marine Policy Center, Woods Hole Oceanographic Institute (2003)
http://www.lib.noaa.gov/docaqua/nmaimages2001/finrepwhoi.htm

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

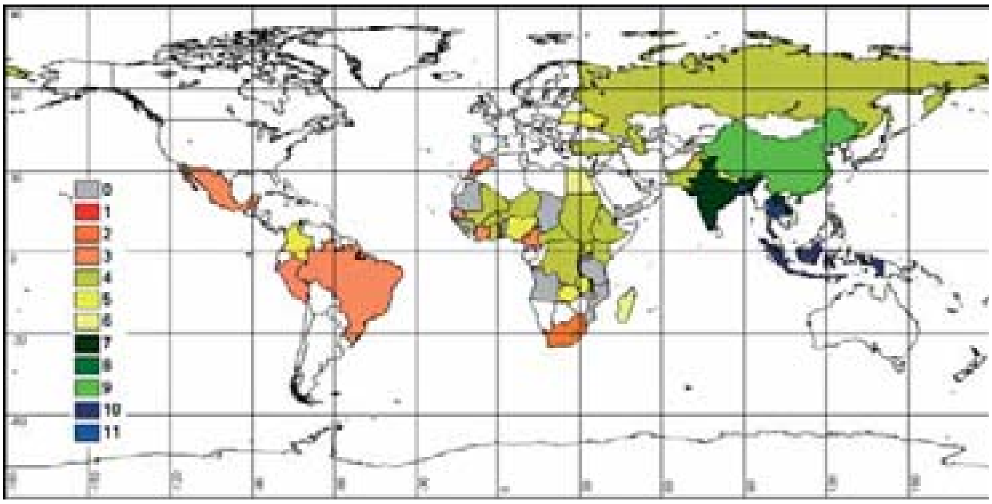
Regarding the economic assessment of competing uses, Hoagland *et al*.,2003 identified and compiled data on the value of commercial fishing in the New England region. Figure 3.26 depicts both the average net value of commercial fish harvests in the coastal ocean off Massachusetts (shaded ten minute squares) 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)



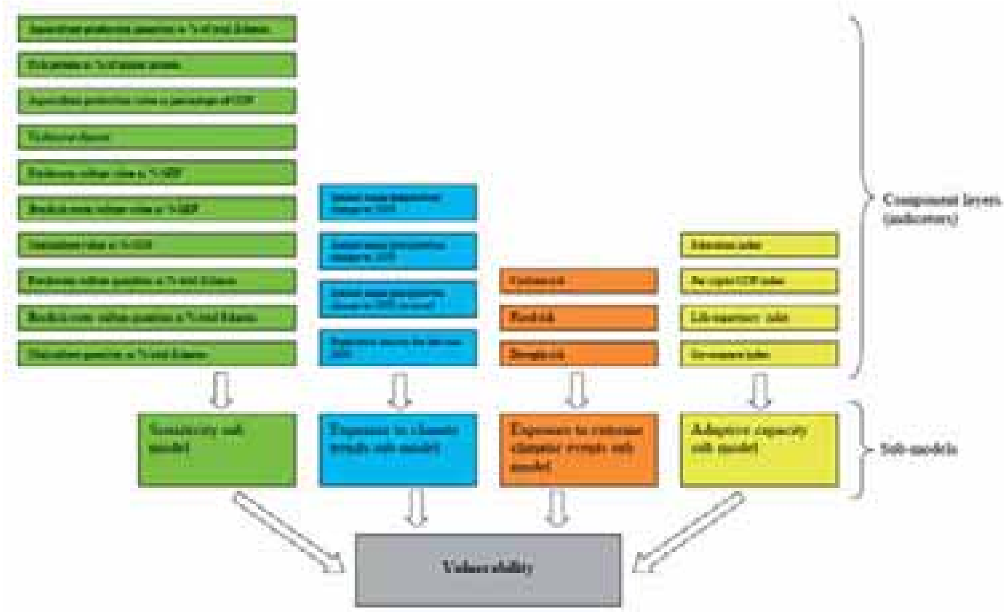
Source: Pérez, Muir and Ross (2000)

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

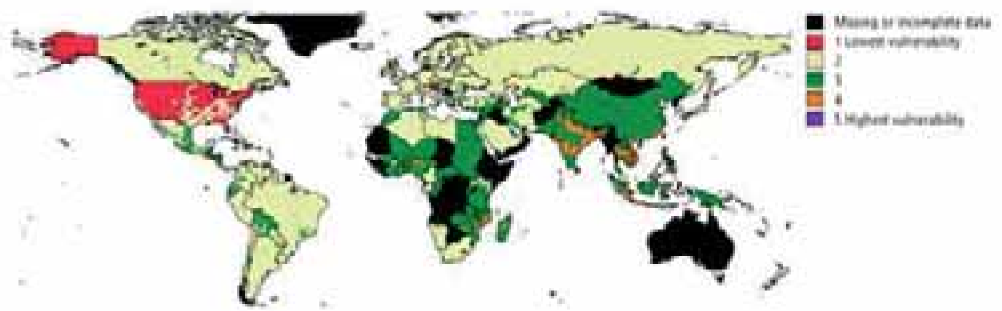
FIGURE 3.29
Schematic representation of the vulnerability assessment model



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.

4. Estimating open ocean aquaculture potential in Exclusive Economic Zones with remote sensing and GIS: a reconnaissance

4.1 INTRODUCTION

In this section we address the question "Are there sufficient freely downloadable basic data available so that any country could assess its Open Ocean Aquaculture (OOA) potential at a reconnaissance level?" Our underlying objective is to encourage developing countries, particularly those presently with modest marine aquaculture production, to explore their own potential for marine aquaculture as part of the strategic planning process for sustainable aquaculture development.

4.2 MATERIALS AND METHODS

The GIS used in this study was Manifold (CDA International Ltd.), versions 6.0 and 6.5. Manifold was used because it is a very affordable (currently about one-fifth of the cost of the most widely used GIS software), but a fully functional GIS.

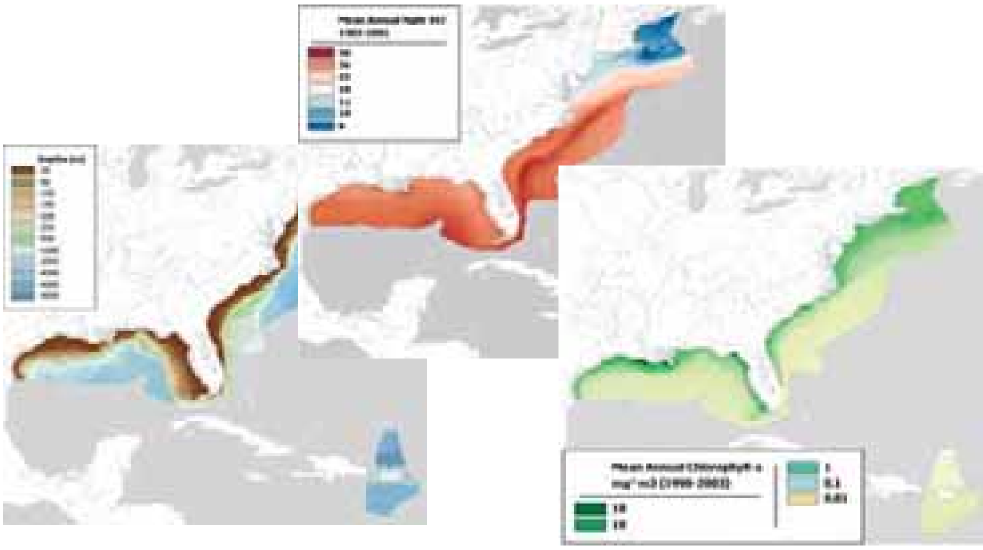
The United States of America was chosen as the target country for the study because the senior author resides there and because he has some familiarity with the offshore aquaculture issues at a national level and a first-hand knowledge of some of the coastal areas included in the study. A reconnaissance level study of open ocean aquaculture potential in the US EEZ is timely because an offshore aquaculture bill has recently been introduced to the US legislative branch.

Study area, indicator species and culture systems. Our objective was to estimate indicative aquaculture potential by selecting diverse environments, species, and culture structures. In this regard, our study area comprises the Atlantic, Gulf of Mexico and Puerto Rico-US Virgin Island (PR-USVI) EEZs. Thus, the study area, about 1.6 million km^2, is comprehensive of US territory on one coast and encompasses a very broad range of climatic and environmental conditions (Figure 4.1).

For realism and wide applicability, we selected species already being cultured in near shore US waters and that are cultured in other countries, as well. The cobia, *Rachycentron canadum*, is cultured in four countries and the total production in 2004 was about 20 000 tonnes. Cobia is a promising candidate for aquaculture because of its rapid growth rate, hardiness, and high quality of flesh. Cobia can grow to 4-6 kg in 1 yr (Arnold, Kaiser and Holt, 2002). The importance of the blue mussel is well established. It was cultured in 16 countries with an output of about 423 000 tonnes in 2004 (FAO 2006a). Additionally, we wanted to draw a contrast between the trophic levels of the organisms cultured, their temperature regimes, and culture systems. To this end, the cobia is a warm water fish and a top predator. It provides an example of "fed aquaculture" in that the cobia requires formulated feeds. In contrast, the blue mussel is a cold water, filter-feeding shellfish and in this latter regard provides an example of "extractive aquaculture". The former is cultured in cages and the latter using several types of suspended devices including longlines.

FIGURE 4.1
Study Area

FIGURE 4.2
Basic data: Bathymetry, SST and chlorophyll-a



GIS data

Spatial data for this study are in three components: (1) boundaries, (2) bathymetry and (3) SST and chlorophyll-a environments. EEZ data were readily available from the Office of Coast Survey (2006) however, data on state seaward boundaries, usually 3 miles (4.8 km), but sometimes 9 miles (14.5 km) had to be digitized for areas where the limits remain unresolved between states and the federal government.

Bathymetry (Figure 4.2) is from, the 2-minute resolution global relief data set, ETOPO2 (2001 version; National Geophysical Data Center, 2006). The data can be interactively downloaded with a choice of file formats for any geographic area desired via the National Geophysical Data Center Grid Translator (GEODAS) (2006).

The environmental data are SST and chlorophyll-a climatologies (Figure 4.2). The SST climatology has a resolution of 4 km and is based on data acquired at night from 1985 to 2001(National Oceanographic Data Center, NOAA (2005). The chlorophyll-a data resolution is approximately 9 km and the data are from 1998 to 2003 (National Oceanographic Data Center, NOAA (2004).

Thresholds

Thresholds relating temperature to growth were established for the cobia based on Ueng *et al*. (2001) and M.J. Osterling (personal communication, 2005). Ueng *et al*. (2001) state that cobia growth rates were highest from 28 to 32 °C and that growth decreased below 20 °C. They concluded that that half of the growth rate variation was from temperature variation. M.J. Osterling (personal communication, 2005) notes that he has raised cobia at temperatures from 21 to 28 °C and that better growth was attained at higher temperatures. He and others have observed that cobia "go off their feed" at temperatures below 20 °C. Accordingly, the thresholds were conservatively set as < 20 °C, no feeding; 20-25 °C, growth; >25 °C better growth. The spatial distribution of these conditions is shown in Figure 4.3.

Regarding, thresholds for the blue mussel relating temperature to growth Langan and Horton (2003) state that within a temperature range of 5-16 °C food quantity and quality are the most important factors affecting growth. Saxby (2002) made a world wide review of conditions at commercial bivalve culture sites among 10 countries. He concluded that temperature and food availability are the major factors affecting growth, and he also concluded that temperatures between 10 and 18 °C promoted good mussel growth. Newell (2001) stated that maximum temperature should be below 20 °C to prevent summer mortalities and he also indicated that blue mussels would survive and grow rapidly in some locations under 21.1 °C maximum summer temperature (Newell, 2003). The Island Institute (1999) produced a guide to blue mussel culture in Maine, the United States of America. It was found that temperatures from 4.4 °C to 21.1 are required for growth, but that at temperatures above 18.3 they begin to suffer mortality and lose byssal strength. Accordingly, the growth thresholds in relation to temperature were conservatively set at <4.4 °C, too cold for growth; 4.4 to 18.3 °C growth; >18.3 °C, too warm for growth and survival. The spatial distribution of these thresholds is shown in Figure 4.4.

Saxby (2002) found that mean chlorophyll-a concentrations of the order of 1-10 mg/m^3 were predominant at sites where bivalve growth did not appear to be greatly limited by lack of nutrients. Inglis (2000) reviewed carrying capacity of embayments in New Zealand for sustainable culture of the greenshell mussel, *Perna canaliculus*, a relative of the blue mussel, and developed "generic" guidelines for chlorophyll concentrations in relation to growth. He found that in concentrations less than 1 mg/m^3 growth was poor, but above that growth increased with increasing chlorophyll concentratioin up to 8 mg/m^3, above which it was uncertain whether growth would

FIGURE 4.3
Cobia growth and water temperature

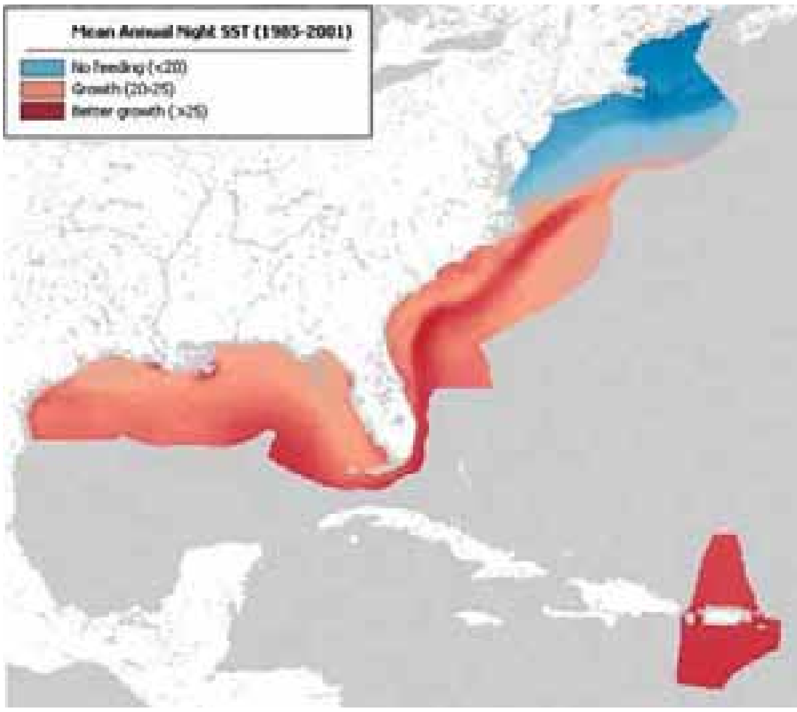


FIGURE 4.4
Blue mussel growth and water temperature

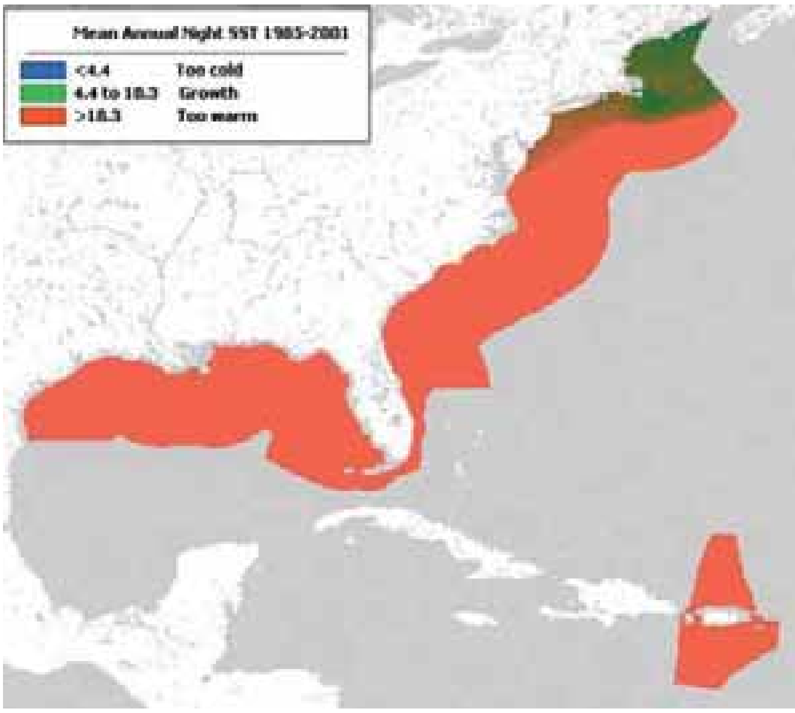


TABLE 4.1
Depth characteristics of experimental and commercial cage installations and specifications from manufacturers

Entity	Location	Cage type	Species	Depth at site (m)	Cage vertical depth (m)	Submersed depth from surface (m)	Apparent depth below cage (m)	Sources
Experimental and commercial installations								
Snapperfarm, Inc.	Puerto Rico, USA	SeaStation™ offshore submersible	Mutton Snapper (*Lutjanus analis*) and Culebran Cobia™ (*Rachycentron canadum*).	30	15	12	3	O'Hanlon *et al*, 2003 p. 263 in OOA ;http://www.snapperfarm.com/2006/aboutsnapperfarm.htm
Cates International	Hawaii, USA	SeaStation™ offshore submersible 3000	Pacific threadfin (*Polydactylus sexfilis*)	31	15	12	4	http://www.oceanicinstitute.org/_oldsite/techtransfer/seacage.html; Bybee and Bailey-Brock, 2003 p. 119 in OOA
Kona Blue Water Farms	Hawaii, USA	SeaStation™ offshore submersible 3000	Hawaian yellowtail (*Seriola rivoliana*)	61-67	20	6-9	32-41	http://seattlepi.nwsource.com/local/260433_kampachi22.html Kona Blue Water Farms (2003)
University of New Hampshire	New Hampshire, USA	Sea Station™ fish cage (SS600)	Atlantic halibut (*Hippoglossus hippoglossus*)	52				http://ooa.unh.edu/
Gulf of Mexico Offshore Aquaculture Constortium	Mississippi, USA	Sea Station™ fish cage 600 m3	Red drum (*Sciaenops ocellatus*)	25				http://www.masgc.org/oac/Phase%201%20RP1.pdf
SUBFlex, Ltd. (manufacturer)	Israel	Open Ocean Subflex submersable	N/A	60				http://www.subflex.org/
Specifications from manufacturers								
Ocean Spar LLC, (manufacturer)	Washington, USA	Sea Station fully submerged or floating	N/A	>25				http://www.oceanspar.com/files/OceanSpar_SeaStation.pdf
Farmocean International (manufacturer)	Sweden	Farmocean 4500	N/A	25		3		http://www.farmocean.se/General.pdf
Helgeland Holdings AS (manufacturer)	Norway	Polarcirkel Submersible	N/A			3-20		http://www.polarcirkel.no/gbframenedsenk1.htm
SUBFlex, Ltd. (manufacturer)	Israel	Open Ocean Subflex submersable	N/A	50-80	12			http://www.subflex.org/

FIGURE 4.5
Blue mussel growth and chlorophyll-a concentration

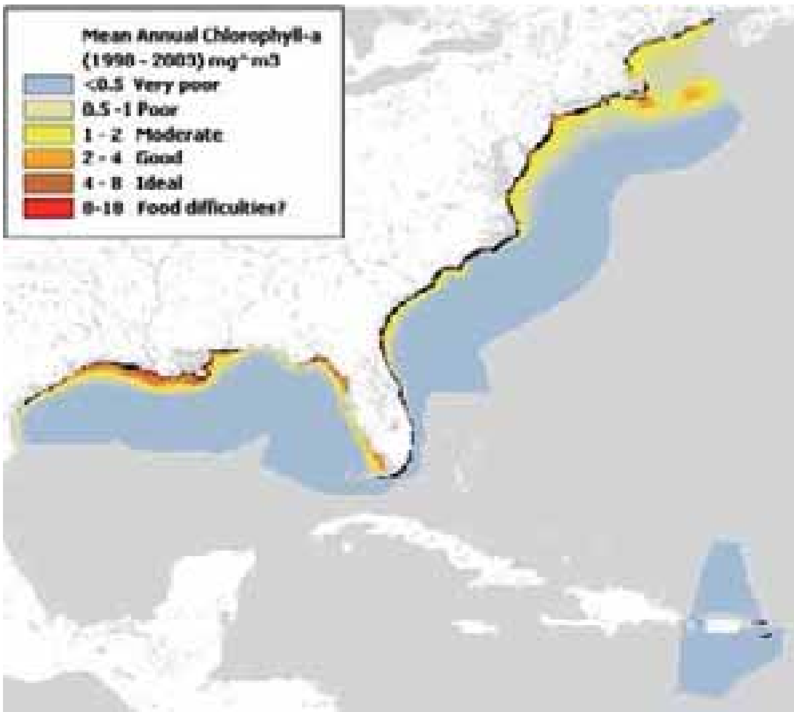
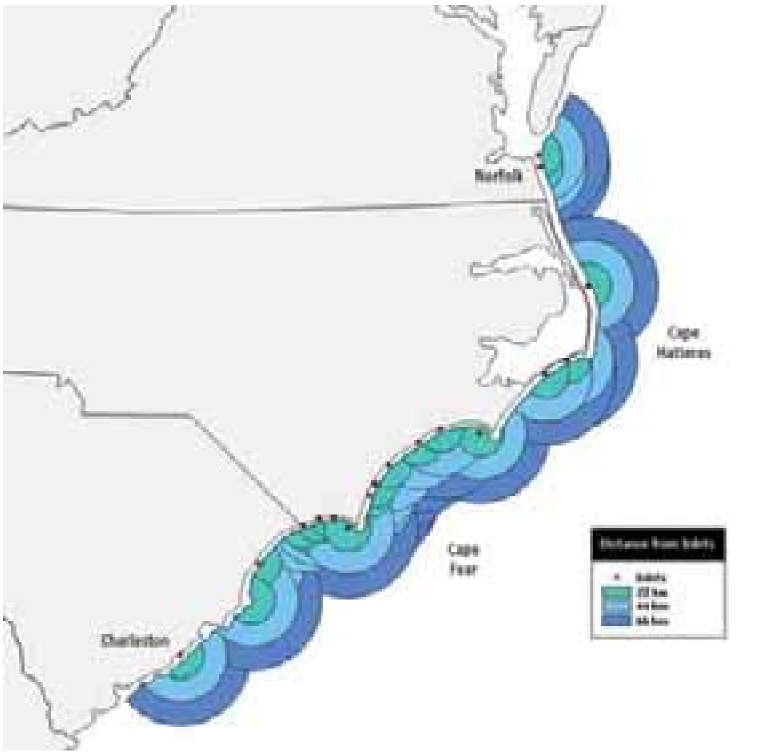


FIGURE 4.6
Access from inlets to the sea in 1, 2, and 3 hour one-way boat trips (22, 44, and 66 km)



continue to improve or would decrease due to food handling difficulties. The spatial distribution of thresholds relating mussel growth to chlorophyll-a concentration are shown in Figure 4.5; however, because of uncertainty of these thresholds for the blue mussel, the thresholds for the analyses were conservatively set at <1 mg/m^3, no growth; 1-8 mg/m^3, growth; >8 mg/m^3 possible difficulties with food handling.

Depth thresholds for cages were based on a review of current practice at experimental and commercial installations, and specifications given by cage manufacturers (Table 4.1). The minimum site depth found was 30 m, but one manufacturer recommends >25 m. Thus, a minimum depth of 25 m was established in order to avoid self-pollution under cages. The maximum depth found was 67 m. Although one manufacturer suggests that depths greater than 100 m would be possible, special moorings and anchoring would be required and these are still on the drawing boards. Additionally, inspection of mooring and anchoring structures in depths greater than 100 m would be tricky (Johan Obling, Farmocean International, personal communication, 2006). Thus, 100 m was set as a practical technological and economic limit of presently available cages. The University of New Hampshire (UNH) offshore mussel installation is at a depth of 40 m and the longlines are submersed to 12 m (CINEMAR, 2005). Thus, the -25 to -100 depth limits set for cages also approximate the depths that are suitable for structures to support mussel culture on submerged longlines.

Unthethered structures (free-floating or propelled cages) could occupy depths as shallow as the minimum cage depth, 25 m, and all deeper areas.

Access data

As pointed out in Section 1.4.1, access from a shore support facility to an offshore culture installation is an indispensable criterion for assessment of potential. A portion of the Atlantic coastline from southern Virginia near Norfolk to southern South Carolina near Charleston, about 700 km, was selected for analysis of time and distance from an inlet to the nearest area suitable for cobia culture. This stretch of the coast was selected because one of the authors lives in the approximate center and has first hand knowledge of some of the inlets. Furthermore, the digital nautical chart data were complete for this section of the coast. The chart data were important because the locations of inlets on nautical charts are signaled by "safe water" buoys that mark the seaward entrances to inlet channels. One-way service boat trips were set at 1, 2, and 3 hour (22, 44, and 66 km) ranges. These thresholds were based on the senior author's observation of the cruising speed of an approximately 11-meter long, fiberglass displacement hull, single screw, diesel-powered fishing boat (Figure 4.6). In contrast, Kite-Powell *et al*. (2003), used a much larger, somewhat slower boat in their bioeconomic model of finfish grow-out. The speed was 15 km/h and the payload capacity was 30 tonnes.

The above categories of data together with their corresponding thresholds are summarized in Table 4.2, and formed the basis of evaluating open ocean aquaculture potential in the United States of America (Atlantic, Gulf of Mexico and Puerto Rico –USVI EEZs).

GIS analyses

The analyses were basic to GIS and included importing, georegistering, cropping, surface contouring, buffering, overlaying and querying.

TABLE 4.2
Summary of thresholds used to evaluate open ocean aquaculture potential in USA (Atlantic, Gulf of Mexico and Puerto Rico –USVI EEZs)

Spatial Data and Source	Date	Resolution / Scale	Attribute data range	Thresholds
Mean Annual SST National Oceanographic Data Center, NOAA (2005) ftp://data.nodc.noaa.gov/pub/data.nodc/pathfinder/Version5.0_Climatologies/	1985-2001	4 km	6 – 30 °C	Cobia growth and water temperature: No feeding (<20) Growth (20-25) Better growth (>25) Blue mussel growth and water temperature: Too cold (< 4.4) Growth (4.4 to 18.3) Too warm (>18.3)
Mean Annual Chlorophyll-a National Oceanographic Data Center, NOAA (2005) ftp://data.nodc.noaa.gov/pub/data.nodc/pathfinder/CoralAtlas/	1998-2003	9 km	0.01 – 18 (mg ^m^3)	Blue mussel growth and Chlorophyll-a concentration: No growth (< 1) Growth (1 - 8) Food handling difficulties possible (> 8)
Bathymetry ETOPO2 (2001 version; National Geophysical Data Center 2006) http://www.ngdc.noaa.gov/mgg/gdas/gd_designagrid.html	2001	2-min	-25 to – 8000 (m)	Cages for cobia and longlines for blue mussels Too shallow (< 25) Tethered and untethered structures (25 -100) Too deep for tethered structures; suitable for untethered structures (>100)
Access (Inlets) MapTech Chart Navigator and NOAA ENC Direct (2006) http://ocs-spatial.ncd.noaa.gov/encdirect/viewer.htm	Various	> 1:50 000	Virginia to South Carolina	Distances from inlets 22 km 1 hour one-way trip 44 km 2 hours one-way trip 66 km 3 hours one-way trip
Boundary Office of Coast Survey (2006) NOAA: http://chartmaker.ncd.noaa.gov/csdl/eez.htm	2006	N/A	US Exclusive Economic Zones for the Gulf of Mexico, Atlantic and Puerto Rico-US Virgin Islands	N/A

4.3 RESULTS

Depth and structures There is a narrow fringe in most places along the Gulf and Atlantic coasts that is too shallow for tethered structures such as cages and longlines (Figure 4.7). These make up 9% of the EEZ area. The adjacent seaward area, 19%, has depths suitable for tethered structures. There is a vast area, 72%, too deep for cages and longlines, where untethered (free or propelled floating farms) structures could be deployed. In contrast to the Gulf and Atlantic coasts, nearly all of the Puerto Rico – USVI area is too deep for tethered structures. Of course, untethered structures could also occupy the areas suitable for tethered structures.

Suitability for cobia Four classes of areas suitable for cobia culture and one unsuitable area have been defined based on growth and depth thresholds (Figure 4.8a and 4.8b). Despite the widespread favorable temperatures for cobia growth shown in Figure 4.3, only about 12% of the EEZ area would be suitable for tethered culture (i.e., anchored cages) when depth also is considered. Tethered cages are presently the only culture mode technologically available in depths less than 100 m. Much of the area that is suitable is not in close proximity to the shore.

FIGURE 4.7
Depth and suitability for culture structures

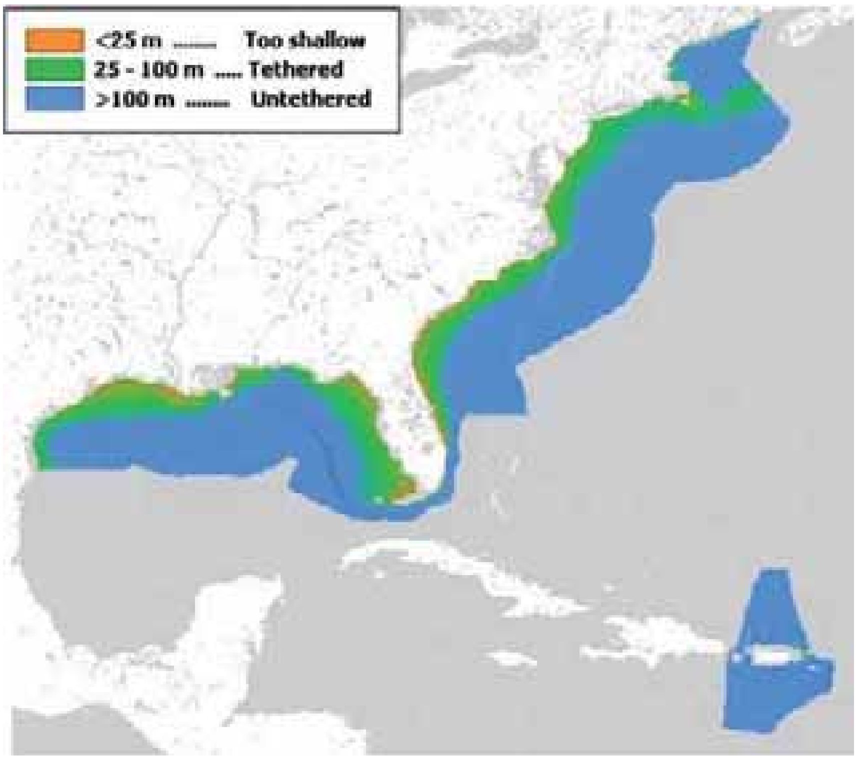


FIGURE 4.8A
Suitability for cobia culture in terms of culture structures and growth

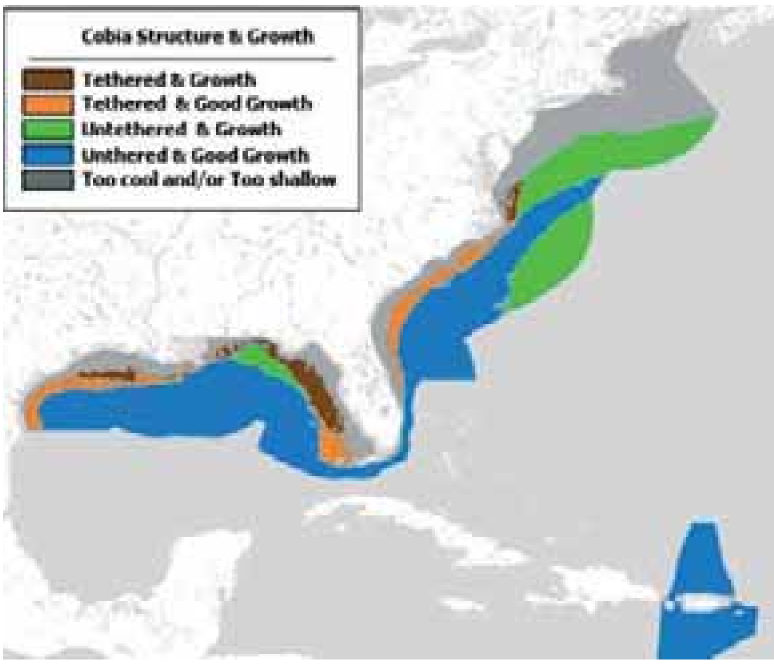


FIGURE 4.8B
Area-wise suitability for cobia culture (km²)

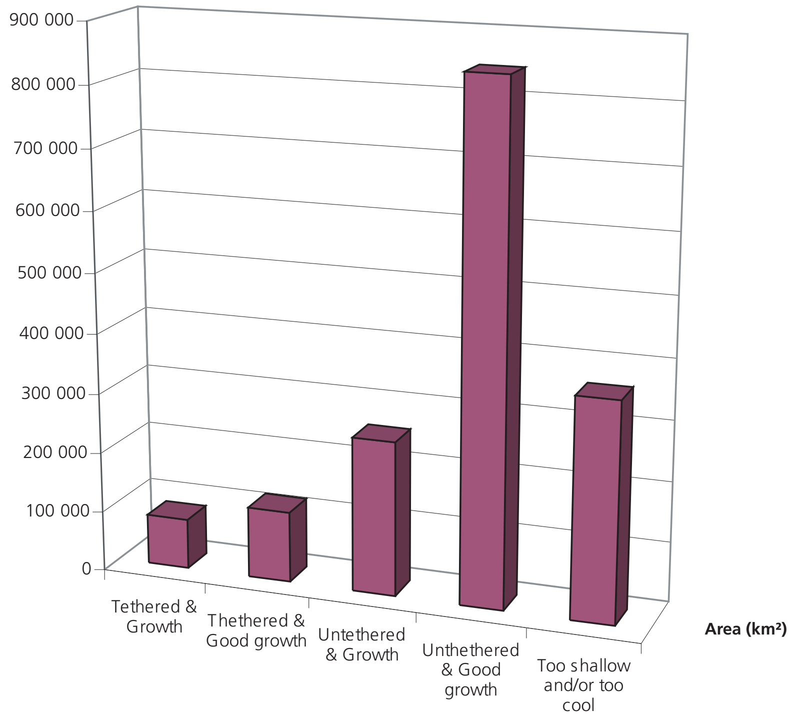
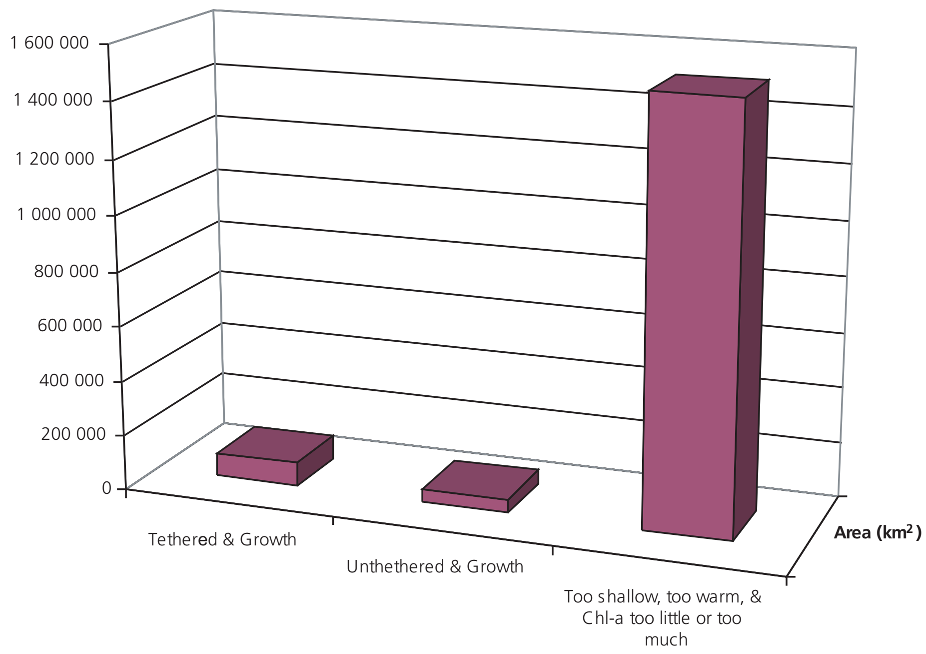


FIGURE 4.9A
Suitability for blue mussel culture in terms of temperature, chlorophyll-a concentration and depths

FIGURE 4.9B
Area-wise suitability for blue mussel culture (km²)



Suitability for blue mussel Taking into account blue mussel temperature-related growth (Figure 4.4), food availability in terms of chlorophyll-a concentration (Figure 4.5), as well as depths, only about 9% of the total EEZ area is suitable for blue mussel aquaculture on longlines, the available technology (Figure 4.9a and 4.9b).

Access Areas with different suitabilities for cobia culture are identified in relation to the three travel time-distance zones (Figure 4.10a and 4.10b). In summary, there are only a few inlets from which areas suitable for cobia culture are within 22 km (one hour) and these make up only 6% of the total area within the 22 km zones. Only 4 of the 17 inlets are within reach of suitable areas. The problem is not temperatures that are too cool. Rather, the depths are too shallow. As the depths increase the situation improves. At from 22 to 44 km from inlets, about 40% of the area is suitable and from 44 to 66 km the suitable area increases to 66% and suitable sites for aquaculture can be found associated with all the inlets. Not taken into account is that many of the inlets are not reliable, or inlets may not be close to the goods and services required of a marine aquaculture shore support facility.

4.4 DISCUSSION

Marine aquaculture potential for two "indicator" species has been shown in terms of surface areas of EEZs in which the species and culture systems could be established with present technologies and with depth-independent future technologies. Our results show, in a very general way, that temperatures in the Atlantic, Gulf of Mexico and PR-USVI EEZs favor the selection of plants and animals for culture that grow well in warm temperate and sub-tropical areas, that the bathymetry favors free-floating structures over anchored structures, and that the chlorophyll-a concentrations favor the culture of filter feeders only relatively close to shore. With particular respect to access, availability of inlets as well as time-distance from inlets to suitable sites could

FIGURE 4.10A
Suitability for cobia culture in terms of time-distance from an inlet

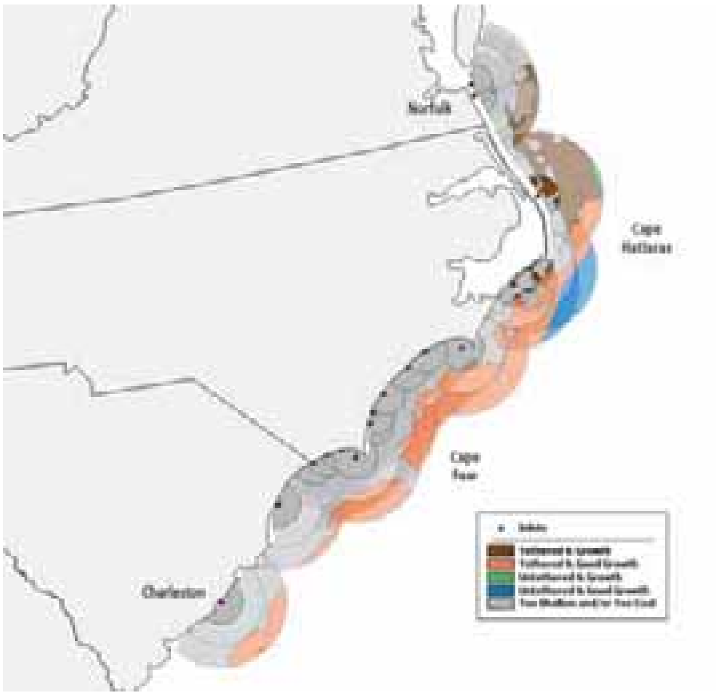
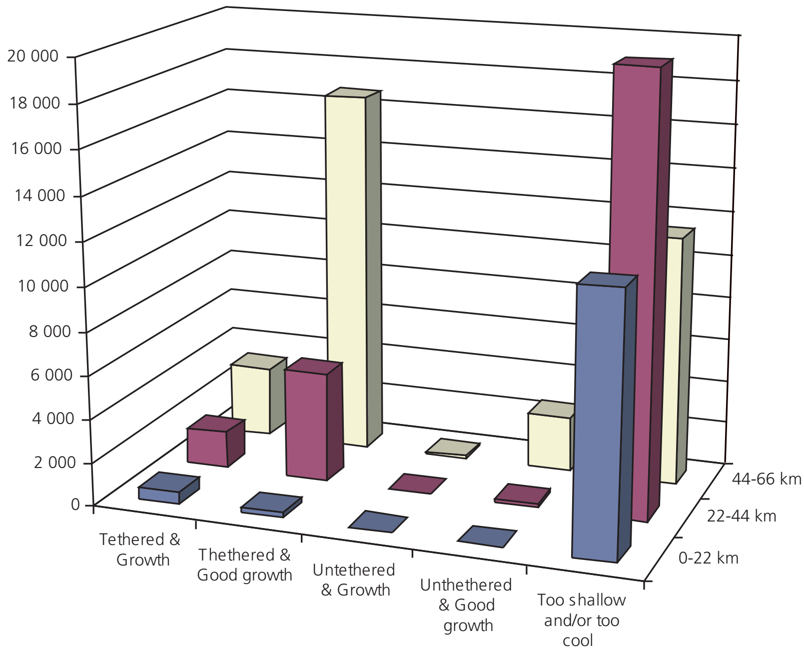


FIGURE 4.10B
Area-wise suitability for cobia culture in time-distance from an inlet



be important limiting factors on the development of OOA in the near future. More autonomous open ocean technologies will have to be devised to take full advantage of the vast EEZ areas available to most countries.

We have shown that it is possible to develop a useful reconnaissance-level GIS aimed at assessing open ocean aquaculture potential in an indicative way that is based on spatial data with a global extent that are readily available for download from the Internet. Because the spatial and attribute data are freely available, it should be possible to replicate our approach in any country by substituting the relevant species and culture systems for those used herein.

As our title indicates, this is a reconnaissance of aquaculture potential, not a definitive study. However, our results do point the way to several kinds of improvements that would result in better estimates of potential. One improvement would be to take into account additional production factors and constraints where the spatial data are available to do so. As an example, freely available GIS data, mainly from US government Internet sites, arranged according to where those data are to be applied – Culture structure; Shore support facility; Transport and maintenance trips - are assembled in Table 4.3. It can be seen that many varied and useful data are available; however, spatial continuity of the data remains a problem. In short, not all of the data are available for the entire coastline nor do they extend seaward to cover the entire EEZs. Nevertheless, it is encouraging that data are becoming more varied, that geographic coverage is growing wider and that the data are free to download.

The SST and chlorophyll-a climatologies that we used are averages over several years of data; however, in assessing potential, analysis of the extremes also is important as are seasonal and inter-annual variations. Thus, an additional improvement would be to analyze these data using shorter time intervals beginning with seasonal and monthly analyses. These results, in turn, could be used to identify areas and time periods where extreme conditions exist.

Implicit in our study is that the production factors –SST, bathymetry and chlorophyll-a – are of equal importance in estimating aquaculture potential. Clearly this is not the case. We have shown that access to the sea and distance from an inlet to an area suitable for culture can vary greatly. Studies carried out to estimate aquaculture potential for smaller areas at higher resolutions and that are more specific about culture systems and the culture environment can include weighting and ranking of production factors that marry GIS analyses with bioeconomic models.

It is noteworthy that two of three data sets, SST and chlorophyll-a, are based on remotely sensed data and the third set, bathymetry, is partly based on satellite altimetry.

The main problem was in finding sufficient reliable data to use to develop temperature and chlorophyll-a thresholds in relation to growth. One aspect is that different races of the same species may react differently to temperature so that results from one location may seem contradictory to those from another place. Another aspect is that temperature alone may not be the only determinant in actual culture operations. For example, cobia grows faster at the higher end of its temperature range, but may be more susceptible to some diseases in that part of the range, so, in practice, they may be raised at a less than optimum temperature for growth (M.J. Osterling, personal communication, 2005). Our thresholds were purposely kept rather broad firstly for simplicity of illustration and secondly because of some uncertainty in their reliability over the broad areas included in this study.

Finally, with only one open ocean location each for cobia and blue mussel culture near to our study area an attempt to verify our indicative estimates of potential would not have had any meaning.

TABLE 4.3
Freely downloadable spatial data and their application to assess marine aquaculture potential: cultured organisms (CO), offshore culture facilities (OF) and transport and maintenance trips from shore facilities to offshore culture facilities (TM)

Production factors	Application	Uniform Resource Locator (URL)
Bathymetry (depth & slope)	CO & OF	http://www.ngdc.noaa.gov/mgg/gdas/gd_designagrid.html
Bottom types	OF	http://www.csc.noaa.gov/opis/html/meta_lite/mseamap.htm
Chlorophyll-a	CO	ftp://data.nodc.noaa.gov/pub/data.nodc/pathfinder/CoralAtlas/
Coastal risk/vulnerability	SF, OF, TM	http://www.ncddc.noaa.gov/cra/gislibrary/
Coastal transport of organic and inorganic material	OF	http://www.nrl.navy.mil/content.php?P=03REVIEW199-2
County business patterns	SF	http://www.census.gov/epcd/cbp/view/cbpview.html
Current speed at 15 m depth	TM, OF & CO	http://oceancurrents.rsmas.miami.edu/atlantic/spaghetti-speed.html
Current speed at surface	OF & CO	http://www.aoml.noaa.gov/phod/dataphod/work/trinanes/INTERFACE/index.html
Dead zones	CO	http://serc.carleton.edu/images/microbelife/topics/map_of_gulf_of_.jpg
Fish spawning locations	OF	http://ocean.floridamarine.org/efh_coral/ims/viewer.htm
Fishing gears	OF & TM	http://ocean.floridamarine.org/efh_coral/ims/viewer.htm
Fish Processing facilities	SF	(should be among census data)
Harmful algal blooms	CO	http://www.ncddc.noaa.gov/habsos/Mapping/
Hurricane hazzard	TM, OF & CO	http://www.usgs.gov/hazards/hurricanes/
Inlet/outlet to sea	SF & TM	http://ocs-spatial.ncd.noaa.gov/encdirect/viewer.htm?
Major ports	SF & TM	http://www.csc.noaa.gov/opis/html/meta_lite/mports.htm
Marine protected areas	OF & TM	http://gis.mpa.gov/website/mma/viewer.htm
Marine offshore fish and shellfish distribution	OF	http://www.ncddc.noaa.gov/ecosystems/GISMapping/document_view
Minerals Management Services (MMS) Active and inactive oil and gas platforms	OF	http://www.gomr.mms.gov/homepg/pubinfo/repcat/arcinfo/index.html
Mixed layer depths	CO	http://www.nodc.noaa.gov/OC5/mixdoc.html
MMS uses outer Continental Shelf	OF & TM	http://www.mms.gov/ld/PDFs/atl-use.pdf
National highway planning network	SF	http://www.bts.gov/publications/north_american_transportation_atlas_data/
Population, business and geography centers	SF	http://quickfacts.census.gov/qfd/
Public use airports	SF	http://www.bts.gov/publications/north_american_transportation_atlas_data/
River plumes	CO	http://www.nrl.navy.mil/content.php?P=03REVIEW199-2
Sea surface temperature	CO	ftp://data.nodc.noaa.gov/pub/data.nodc/pathfinder/Version5.0_Climatologies
Species management zones	OF	http://ocean.floridamarine.org/efh_coral/ims/viewer.htm
Storm tracks	SF, OF ,TM	http://hurricane.csc.noaa.gov/hurricanes/download.html
Subsurface temperature	CO	http://las.pfeg.noaa.gov/las6_5/servlets/metadata?catitem=60
Time-distance to markets	SF	(should be among census data)

Production factors	Application	Uniform Resource Locator (URL)
Water port facilities	SF & TM	http://www.bts.gov/publications/north_american_transportation_atlas_data/
Wave height & Wind speed	SF, OF, TM	http://polar.ncep.noaa.gov/marine.meteorology/marine.winds/
Constraints		
Artificial reefs	OF	http://www.csc.noaa.gov/opis/html/meta_lite/martreef.htm
Coral HAPC	OF	http://www.nmfs.noaa.gov/gis/data/hapc.htm
Dredging disposal sites	OF	http://ocs-spatial.ncd.noaa.gov/encdirect/viewer.htm?
Essential fish habitats	OF	http://ocean.floridamarine.org/efh_coral/ims/viewer.htm
Marine protected areas	OF	http://www3.mpa.gov/exploreinv/explore.aspx
Marine sanctuaries	OF & TM	http://sanctuaries.noaa.gov/library/imast_gis.html
Military zones	OF & TM	http://ocs-spatial.ncd.noaa.gov/encdirect/viewer.htm?
Right whale critical habitat	OF	http://www.nmfs.noaa.gov/pr/pdfs/shipstrike/critical_habitat_traffic.pdf
Shipping lanes	OF	http://ocs-spatial.ncd.noaa.gov/encdirect/viewer.htm?
Wrecks	OF	http://ocs-spatial.ncd.noaa.gov/encdirect/viewer.htm?
Baseline data		
Coastline extractor	OF, SF, & TM	http://rimmer.ngdc.noaa.gov/coast/
Exclusive Economic Zones	OF	http://nauticalcharts.noaa.gov/csdl/EEZ.HTM
Maritime limits	OF	http://chartmaker.ncd.noaa.gov/csdl/mbound.htm
Mean high water shoreline	OF	http://www.nauticalcharts.noaa.gov/csdl/ctp/cm_vs.htm
Minerals management	OF	http://www.mms.gov/ld/atlantic.htm#SOBD
Nautical charts	OF, SF, & TM	http://www.nauticalcharts.noaa.gov/csdl/ctp/cm_vs.htm

5. Data availability

One of the first questions to be addressed when possible GIS and remote sensing marine aquaculture applications come to mind relates to data availability and quality. The kinds of data required necessarily depend on the application. The applications reviewed in Section 3 provide good sources from which lists of the data and data characteristics required for specific activities such as site selection and strategic planning can be assembled. Additionally, the study on aquaculture potential, Section 4, provides a list of data needs and sources for a marine aquaculture GIS data at national and sub-national levels. There are many overlaps in the kinds of data needed, but the differences will be evident in the resolution and the temporal and geographic distribution of the data.

Data availability for GIS can be considered in two realms: spatial data and attribute data. Spatial digital data can be viewed by broad use type. For example, there are shoreline data for base maps, and data layers to add to the base map such as bathymetry, temperature, and mineral claims. Acquiring data of a resolution appropriate for the study is an important consideration and often a challenge. For example, most of the data available for the open ocean are of too coarse resolution to be used for investigations of near shore aquaculture. There usually is a fairly close correlation between data resolution and extent of geographic coverage. Thus, data sets can be conveniently categorized as global, national, sub-national and local. Sub-national data sets usually pertain to first and second level administrative boundaries.

Attribute data are used to set thresholds on production factors. Two examples are (1) temperature thresholds relating to the growth rates of cultured organisms, and (2) thresholds relating to minimum and maximum depths for locating cages. Attribute data may take a long time to identify, compile and synthesize because of the need for extensive searches of the scientific literature and the Internet as well as for correspondence with experts.

Another important distinction is between data available to be freely downloaded from the Internet and commercially prepared data that must be purchased.

5.1 GEOGRAPHIC INFORMATION SYSTEMS DATA WITH A GLOBAL COVERAGE

Our emphasis is on global data, freely available via download from the Internet and that will support a first assessment of marine offshore aquaculture potential for any country as illustrated by the study of aquaculture potential (Section 4). In order to assess near shore aquaculture potential national and sub-national level data will be required. It is beyond the scope of this study to attempt to comprehensively compile national level data sets that could be employed for a marine aquaculture GIS; however, we do provide some examples of national level data that are readily available.

We make a distinction between two kinds of data (1) compilations of "static" data such as shorelines and climatologies, the latter usually based on relatively long streams of data, and (2) real-time, or near real time, data for aquaculture operations and management. It is worth noting that most of the data are based on various kinds of remote sensing.

Data compilations with a global marine reach include shorelines, bathymetry and climatologies of Sea Surface Temperature (SST) and chlorophyll at various resolutions and time intervals. Also included are compilations of remotely sensed data over land that can be useful for siting marine aquaculture shore support installations. The global data are briefly described below and summarized in Table 4.1, including the Uniform Resource Locator's (URLs) for downloads.

5.1.1 Geographic Information Systems data compilations

Shoreline data as a base map are important as a framework for all other layers. The World Vector Shoreline (WVS) is a digital data file containing the shorelines, international boundaries, and country names of the world. The WVS is divided into ten ocean basin area files. Together the ten files form a seamless world, with the exception of Central America, where there is an overlap between the Western North Atlantic file and the Eastern North Pacific file.

Bathymetry and elevation are available together in the 2-Minute Gridded Global Relief Data (ETOPO2). ETOPO2 is a compilation of several data sets and part of the data is based on satellite altimetry.

Useful climatologies, including SST, chlorophyll-a, Photosynthetically Active Radiation (PAR), wind speed, and oxygen concentration at 100 m, are provided for several averaging periods (e.g., monthly seasonal, annual) and at various resolutions. The SST climatologies are noteworthy in being provided for several additional averaging periods, including daily, 5-day (Pentad), 7-day (weekly), and 8-day and also because of the higher resolution, 4 km. In addition, each period is provided as daytime-only, nighttime-only, and day-night combined.

Although currents are among the most important data to assess marine aquaculture potential, current data are among the most difficult to realize at temporal and spatial resolutions that are useful globally, regionally and locally. A drifter-derived climatology of the world's near-surface currents has been assembled. A drifter is composed of a surface float which includes a transmitter to relay data, and a thermometer which reads temperature a few centimeters below the air/sea interface. The surface float is tethered to a subsurface float which minimizes rectification of surface wave motion. This in turn is tethered to a holey sock drogue, centered at 15 m depth. The resolution is only 1 degree x 1 degree. One version contains annual mean values of the near-surface currents and subskin sea surface temperature while another has monthly averages; however, it is available only for the tropical Atlantic.

Exclusive Economic Zone (EEZ) delineations are indispensable for the assessment of offshore aquaculture potential, particularly in areas that are disputed. Until recently the global data were commercial (i.e.Global Maritime Boundaries Database available from General Dynamics Advanced Information Systems at: http://www.gd-ais.com/capabilities/offerings/sr/gmbd.htm); However, the IOC's International Oceanographic Data and Information Exchange (IODE) through Flanders Marine Data and Information Centre has developed an open source version of EEZ GIS layer and is available for download at http://www.vliz.be/vmdcdata/marbound. Already used as part of GoogleEarth. It consists of lines features, with qualifiers describing meaning of these lines and why (i.e. sources) they were generated. The Flanders Institute will ensure maintenance of this EEZ GIS source. EEZ boundaries and accompanying area estimates can be viewed via the Sea Around Us Project (http://www.seaaroundus.org/eez/eez.aspx#).

Data useful for assessing potential for the development of shore facilities to support marine aquaculture include populated places, transportation systems (roads, railroads, airports), and administrative boundaries. Google Earth (http://earth.google.com/) offers the possibility of viewing and easily manipulating a satellite image backdrop at varying resolutions (generally 15 m, usually less than 3 years old) and acquiring such data for many areas of the world. An area of interest can be viewed, features of interest can be added, control points for georeferencing the selected area can be placed as needed, and the image can be exported in jpg format to make a simple map that can be georeferenced in a GIS to data from other sources. You can also use Keyhole Markup Language (KML), to share places and information with other users of Google Earth. Likewise, you can find KML files on the Google Earth Community site that describe interesting features and places.

Also potentially useful for the same purpose is the WMS Global Mosaic, a high resolution global image mosaic of the earth, produced from more than 8200 individual Landsat 7 scenes with a maximum resolution of 15 m.

The Munich Re Group provides NATHAN, a map with global coverage of natural hazards of obvious importance to marine aquaculture. The natural hazards include tsunamis, earthquakes, volcanic eruptions, storms, storm surges, tornados, hail storms, lightening, and sea ice. The hazard maps can be interactively viewed by zooming from global to sub-national levels on the Internet. The GIS data have to be purchased.

Harmful algal bloom maps already have been mentioned in Section 3.2. Some maps are available at regional levels. Global and regional maps could be useful, if the underlying data, including the causative organism, frequency of occurrence and precise locations can be obtained.

FAO and the United Nations World Food Programme (WFP), and more recently the United Nations Environment Programme (UNEP), have combined their research and mapping expertise to develop GeoNetwork opensource (http://www.fao.org/geonetwork/) as a common strategy to easily share geographically referenced thematic information between different FAO Units, other UN Agencies, NGOs and other institutions.

GeoNetwork opensource is a standardized and decentralized spatial information management environment, designed to enable access to geo-referenced databases, cartographic products and related metadata from a variety of sources, enhancing the spatial information exchange and sharing between organizations and their audience, using the capacities of the Internet. This approach of geographic information management aims at facilitating a wide community of spatial information users to have easy and timely access to available spatial data and to existing thematic maps that might support informed decision making.

The main goal of the GeoNetwork opensource software is to improve the accessibility of a wide variety of data, together with the associated information, at different scale and from multidisciplinary sources, organized and documented in a standard and consistent way.

The general kinds of data that can found in GeoNetwork that are relevant to marine aquaculture include: Administrative boundaries, coastlines, fishery resources distribution, fishing area locations, major cities, population density, roads, and watersheds.

The challenge is to enhance the data exchange and sharing between the organizations to avoid duplication, increase the cooperation and coordination of efforts in collecting data and make them available to benefit everybody, saving resources and at the same time preserving data and information ownership.

GeoNetwork opensource has been developed to connect spatial information communities and their data using a modern architecture, which is at the same time powerful and low cost, based on the principles of Free and Open Source Software (FOSS) and International and Open Standards for services and protocols.

An inventory and comparison of globally consistent geospatial databases and libraries has been compiled as an FAO publication by Dooley (2005). This publication presents an inventory of global data sources which can be used to provide consistent geospatial baselines for core framework data layers in the support of generalized base mapping, emergency preparedness, and response, food security and poverty mapping, and also includes data which is of relevance to marine aquaculture for both open ocean and shore support. In the publication, only globally consistent data sources at the scales of 1:5 million or larger for vector data and a nominal pixel size of 5 arc minutes or higher resolution for raster data, were considered. The sources of data presented in the inventory were identified based on a review of on-line Internet resources conducted in the first quarter of 2004 and updated in January 2005.

5.1.2 Real time remotely sensed data for operational management

The kinds of data pertinent to marine aquaculture that are acquired by satellite sensors include sea-surface temperature, oceanic-current patterns, formation of eddies and rings, upwelling, surface-wind action, wave motions, ocean color (in part indicative of phytoplankton concentrations), and sea ice status in the high latitudes (important for organisms, operations and structures).

Real time data, and more importantly predictions that can be made based on them, can be vital for the operational management of marine aquaculture installations. Real time remote sensing applications satisfy basic needs for management information. They are applications for the management of: (1) the cultured organisms, (2) the culture structures, and (3) access (sea and air communications) and shore support facilities. Data relating to the cultured organisms are temperature, chlorophyll-a, surface winds (wavelength, period, and height) and current speed. Data relating to the culture structures and access to it are current speed, wave height and wind velocity. These latter needs are largely satisfied by marine weather forecasts that are based on a combination of satellite remote sensing and data from fixed and free-floating sensors in the sea. Therefore, they are not dealt with in detail here and the focus is on data pertinent to the cultured organisms.

Looking to the future use of untethered (free floating) aquaculture installations on the open ocean, as described by Goudey (1998), current velocity is an important management variable in order to maintain the installation in locations that are the most favorable for the well-being of the organisms and for the safety of the installation itself with the least use of the supplemental propulsion system. On a longer time scale, knowledge of current patterns also is essential in order to predict optimum launching sites and to plan routes to achieve optimum environmental conditions. It is interesting to observe that the data required for these purposes are not raw, but already compiled or processed in some way through modelling or the combination of data from multiple sensors.

Chlorophyll-a

There are many opportunities to acquire chlorophyll-a data that have a global reach. An overview of the sources, characteristics, institutions involved is provided by the International Ocean Color Coordinating Group (http://www.ioccg.org/). As an example, the variety of products in terms of spatial and temporal resolution for only the MODIS Aqua sensor is shown by the NASA (USA) at http://oceancolor.gsfc.nasa.gov/PRODUCTS/L3_sst.html

Other real-time marine data

The Physical Oceanography Distributed Active Archive Center (NASA, USA) provides a single location from which data catalogs and downloads for a variety of global SST, current and waves data can be obtained (http://podaac.jpl.nasa.gov/catalog/). It is possible to subset, plot and view many of the data sets before downloading (http://poet.jpl.nasa.gov/).

5.2 NATIONAL DATA

A GIS aimed at near shore aquaculture potential will require data of higher resolution than those provided by the data sets with global coverage. Regional, national and local data sets will be of use. The reconnaissance study (Section 4) was created to illustrate a GIS to estimate marine aquaculture potential using a combination of global and nationally-available data sets.

In order to locate ocean-related data for other countries, the Global Change Master Directory (http://gcmd.nasa.gov/index.html), a directory to Earth science data and services, offers one opportunity. For example, this site can be used to identify national spatial data portals such as for India. Another approach is through Internet searches for national marine and oceanography center compilations (e.g., via the Open Directory Project http://dmoz.org/Science/Earth_Sciences/Oceanography/Data_and_Information_Resources/) or for specific countries.

The United States of America and Canada are world leaders in providing spatial data useful for the development and management of marine aquaculture although these data have not been made available specifically for this purpose. Some of the US data can be tailored as to geographic extent using Internet Map Server (IMS) technology and then downloaded with some choices of file format. An example of useful IMS data is the South Atlantic Habitat and Ecosystem IMS (http://ocean.floridamarine.org/efh_coral/ims/viewer.htm). GISFish includes links to sources of downloadable spatial data useful for aquaculture and fisheries.

6. Decision-making and modelling tools in GIS

6.1 INTRODUCTION

Fisher (in press) has looked at the evolution of GIS in fisheries applications apart from aquaculture. Although there is increasing sophistication in the use of GIS in fisheries, and as shown here, in marine aquaculture, too, there is an impression that the available modelling and decision-making tools are not being taken advantage of. Each of the commercial GIS packages has modelling and decision-making "built-in" to some extent.

For the purpose of this report, the terms "decision support tool" (DST) and "model" are defined as follows: A "DST" refers to an interactive, computer-based system that manipulates and presents spatial data to support informed, objective, and, in some cases, participatory decision making. A "model" is a simplified representation of reality used to simulate a process, understand a situation, predict an outcome, or analyse a problem. A model can be viewed as a selective approximation, which, by elimination of incidental detail, allows some fundamental aspects of the real world to appear or be tested (FAO 2006b).

The objective of this section is to provide an overview of the decision-making approaches and modelling tools used in selected applications of GIS to marine aquaculture. First, the basics of data classification and multi-criteria evaluation are presented. Following this, a description of the GIS-based models used for decision-making is provided; then an overview of GIS-Based decision support tools used for Marine Protected Areas is given together with a tabulated summary listing aquaculture issues that could be addressed using these tools. To sum-up this section an overview of DST used in selected applications of GIS to marine aquaculture is given.

6.2 CLASSIFICATION

Classification is an essential part of any data reduction process, whereby complex sets of observations are made understandable. It is almost always the case that the source data, whether in real or integer format, will need to be further classified before further use. Although any classification process involves some loss of information, a good scheme not only aims to minimize this loss, but by identifying natural groups that have common properties, provides a convenient means of information handling and transfer (Burrough, 1986). Furthermore, in any classification process, care must be taken to preserve the appropriate level of detail needed for sensible decision making at a later stage (Burrough, 1986; Aguilar-Manjarrez, 1996; Ross, 1998).

Aguilar-Manjarrez (1996) provides an exhaustive review of five methods that have been explored to classify data on land types for various uses that are equally relevant for classifying marine aquaculture data:

1. The FAO land evaluation methodology which assesses land suitability in terms of an attribute set corresponding to different activities.
2. The limitation method in which each land characteristic is evaluated on a relative scale of limitations.
3. The parametric method in which limitation levels for each characteristic are rated

on a scale of 0 to 1, from which a land index (%) is calculated as the product of the individual rating values of all characteristics.

4. The Boolean method which assumes that all questions related to land use suitability can be answered in a binary fashion, and that all important changes occur at a defined class boundary.

5. The fuzzy set method in which an explicit weight is used to assess the impact of each land characteristic. Fuzzy techniques are then used to combine the evaluation of each land characteristic into a final suitability index. Apart from a dominant suitability class, the fuzzy set method equally provides information on the extent to which a certain land unit belongs to each of the suitability classes discerned.

For GIS applications, any of the above methods can be used to classify source data into a four- or five-point scale of suitability (with one being the least suitable). However, the choice among classification methods is dependent on the type of data and intended uses of the output information. Classification allows normalization of all data layers, an essential pre-requisite for further modelling.

Fuzzy logic was applied to an inventory of aquaculture suitability in the Tiwi Islands, Australia (Field, 2001). Circumstances were that a substantial part of the coastline is Aboriginal land and the communities demand involvement in decisions for development. However, it was necessary for them to work in linguistic rather than mathematic terms. Also, it was recognized that conventional GIS based on sharply defined boundaries does not adequately reflect the actual situation of gradual transitions between areas of different suitabilities. A Team Approach Geographic Information System was created with four features (1) the use of linguistic terms in criteria evaluation rather than mathematical terms to define suitability, (2) semi-automatic pair-wise comparisons to estimate weights on criteria in Microsoft Excel, (3) application of a visual modelling environment in ModelBuilder (extension of ESRI Spatial Analyst 2.0), and (4) the final GIS running on Arc/View software.

The general approach was to define thresholds for criteria, to rate the thresholds in numerical and linguistic terms (e.g., a range in slope of 4-5 degrees is assigned a rating of one with an equivalent linguistic description of "very low" for suitability. The corresponding fuzzy number series in four sets is 0.0, 0.0, 0.1, 0.2. The two 0.0 values in different categories demonstrate that there are no sharp boundaries between slopes of different suitabilities. This approach, when all of the criteria are considered in the four fuzzy number sets, results in four maps ranging from the most stringent to the least stringent. Stated differently, four different interpretations of the same criteria statements result in four maps of suitability.

6.3 MULTI-CRITERIA EVALUATION

Complexities in development planning and management for marine aquaculture can be difficult without the aid of decision making-aids such as multi-criteria decision making. However, their use in marine aquaculture is limited. Many of the development and managerial issues of marine aquaculture have underlying geographic or spatial contexts, so there is considerable potential for using GIS.

GIS has considerable potential for both policy decisions and resource allocation decisions. Policy decisions are intended to influence the decision behaviour of decision makers whilst resource allocation decisions involve decisions that directly affect the utilization of resources.

GIS for policy decisions also has potential (almost unrealized at this time) as a process modelling tool, in which the spatial effects of predicted decision behaviour might be simulated. Simulation modelling, particularly those that incorporate socio-economic issues are still in their infancy. However, it is to be expected that GIS will play an increasingly important role in this area in the future.

Resource allocation decisions are also prime candidates for analysis with a GIS. Land evaluation and allocation is one of the most fundamental activities of resource development. However, without procedures and tools for the development of decision rules and the predictive modelling of expected outcomes, this opportunity will largely go unrealized.

GIS-based Multi-Criteria Evaluation (MCE) involves the utilization of geographical data, the decision maker's preferences and the combination of the data and preferences according to specified decision rules. Over the last decade, a number of multi-criteria methods have been implemented in the GIS environment including: weighted linear combination (WLC), ideal point methods, concordance analysis, Analytical Hierarchy Process (AHP), Analytical Network Process (ANP), and the Order Weighted Average (OWA). Among these procedures, the WLC and Boolean overlay operation are considered the most straightforward and have traditionally dominated the use of GIS as decision support tools (Malczewski, 1999; Malczewski; 2006).

In the WLC criteria are standardized to a common numeric range, and then combined by means of a weighted average. The result of a WLC is a map of suitability that may then be masked by one or more constraints and finally thresholded to yield a final decision. In the Boolean procedure all criteria are reduced to logical statements of suitability and then combined by means of one or more logical operators such as intersection (AND) and union (OR).

The Order Weighted Averaging (OWA) module provides an interesting alternative to the commonly-used linear weighted combination approach to aggregation of multiple criteria. By varying the importance of the factors in particular order positions, one can adjust the levels of tradeoff between factors and risk aversion in the solution incorporated into the final model. Malczewski (2006) presents an interesting implementation of the OWA approach as a platform for integrating multi-criteria decision analysis and GIS to a real-world environmental management problem that involved developing management strategies in the Cedar Creek watersheds in Ontario, Canada.

6.4 MODELLING

Multi-criteria evaluation decision-making models

A comprehensive review on "GIS and Multi-criteria Decision Analysis' is provided by Malczewski (1999). The emphasis of Malczewski's review is on GIS-based modelling of spatial multi-criteria problems, with a primary goal being to "introduce the readers to the principles of spatial multi-criteria decision analysis and the use of multi-criteria decision techniques in GIS environments". The text of this review is organized as follows: Chapter 1: Geographical data, information, and decision-making; Chapter 2: Introduction to GIS; Chapter 3: Introduction to multi-criteria decision analysis; Chapter 4: Evaluation criteria; Chapter 5: Decision alternatives and constraints; Chapter 6: Criterion weighting; Chapter 7: Decision rules; Chapter 8: Sensitivity analysis; Chapter 9: Spatial decision support systems; and Chapter 10: Multi-criteria-Spatial decision support systems case studies. The structure of the text and ordering is logical. The intended audience is GIS and decision analysts and both undergraduate and graduate students in applied GIS, quantitative analysis, and spatial decision support systems courses. Malczewski notes that the text assumes that the reader has limited mathematical background. Rather than derive formulations and formalize solution techniques, the text identifies associated software packages that may be utilized.

Nath *et al*. (2000), in the context of applications of GIS for spatial decision support 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. Nath's review remains relevant as a background document on multiple criteria evaluation (MCE) basics for aquaculture.

A number of publications that have been produced at the Institute of Aquaculture (http://www.aquaculture.stir.ac.uk/GISAP/gis-group/) have focused on the construction of "Hierarchical models" (Aguilar-Manjarrez, 1992; Aguilar-Manjarrez 1996; Salam, 2000; Pérez, 2003; and Scott, 2004) for strategic planning of aquaculture development using MCE. In this approach, naturally grouped variables are first considered together to produce 'sub-model' outcomes such as water needs, soil suitability, input availability, farm gate sales, and markets. It is often the case that a source variable or processed layer will be used in more than one sub-model and that the layer may need to be transformed depending on the intended purpose. Each of these sub-models may, in turn, be derived from lower-level models which pre-process variable data into useful factors. Once the variables (i.e. production functions and constraints) are organized into sub-models weights are derived for each sub-model and then combined in rank order using the MCE technique.

Multi-criteria decision making models (MCDM) can be very useful to support decision making, however, there is not much done in aquaculture. While MCDM have been widely used for agricultural operational as well as strategic planning purposes, only a handful of applications to aquaculture were found in the literature: Sylvia and Anderson (1993) describe an economic policy model for net-pen salmon farming; Martinez-Cordero and Leung (2004) present a MCDM developed for the purpose of evaluating the sustainable development of shrimp farming in northwest Mexico, and El-Gayar and Leung (2006) developed a MCDM framework for the planning of regional aquaculture development.

Marine data model

The ArcGIS Marine Data Model represents a new approach to spatial modelling via improved integration of many important features of the ocean realm, both natural and manmade. The goal is to provide more accurate representations of location and spatial extent, along with a means for conducting more complex spatial analyses of marine and coastal data by capturing the behaviour of real-world objects in a geodatabase. The model also considers how marine and coastal data might be more effectively integrated in 3-D space and time. Although currently limited to 2-D, the model includes "placeholders" meant to represent the fluidity of ocean data and processes (http://dusk2.geo.orst.edu/djl/arcgis/about.html)

Commercial models for aquaculture

AquaModel is an information system to assess the operations and impacts of fish farms in both water column and benthic environments, the first of its kind. AquaModel is a "plug-in" model that resides within the EASy Marine Geographic Information System which has been used on numerous studies and investigations involving fisheries and oceanographic topics. All environmental information from field measurements to satellite imagery is readily available for model development and use. AquaModel can be used to examine near and far field effects of individual or clusters of farms in the coastal shelf where nearshore or open-ocean aquaculture may develop. It is being adapted to deal with multiple, separate cages and multiple farm sites to meet this challenge. AquaModel is designed for: Administrators, who establish and enforce rules and extent of impact; Fish farmers, who wish to plan farms and obtain permits and; Investors, who wish to assess risks and opportunities (http://netviewer.usc.edu/aquamodel/Overview.html).

6.5 DECISION SUPPORT TOOLS

Software for decision-making

Belton and Stewart (2002) state that software is essential for effective multi-criteria analysis. In this way the facilitator, analyst and decision-maker are free from the technical implementation details and are able to focus on the fundamental value judgment and choices. They conclude that although it is possible to set-up macros in a spreadsheet to achieve this, it is more convenient to use specially designed software.

Table 6.1 shows a list of software tools compiled by Janssen and van Herwijnen (2006) to support multi-criteria analysis that may aid marine aquaculture activities (siting, zoning, monitoring, etc). The list becomes rapidly outdated. Therefore, other listings of MCE software can be found in Belton and Stewart (2002) and at http://www.lionhrtpub.com/orms/surveys/das/das-html.

TABLE 6.1
Software to support multi-criteria analysis (updated from Janssen and van Herwijnen, 2006)

Package	Short description
Problem structuring for discrete choice problems	
Decision Explorer 3.2	Qualitative data analysis, linking concepts through cognitive or cause maps(http://www.banxia.com)
Mind Manager 4.0	Structures complex situations through organizing ideas and concepts, graphical visualization with icons, graphics, colors and multimedia (http://ww.mind-map.com)
Discrete choice problems	
Criterium Decision Plus 3.0	Value function model based on trade-off analysis (http://www.infoharvest.com)
DEFINITE 3.1	Multiattribute value functions including option for imprecise preference information, cost-benefit analysis, outranking. (http://www.definite-bosda.nl)
HIPRE	Multiattribute value functions with imprecise preference information (http://www.hipre.hut.fi)
Hiview	Multiattribute value functions (www.enterprise-lse.co.uk)
Logical Decisions 5.1	Multiattribute value functions and the analytical hierarchy process (AHP) (http://www.logicaldecisions.com)
VISA	Multiattribute value functions graphical interaction and presentation (http://www.simu18.com/visa.htm)
Discrete group choice problems	
Team Expert Choice	AHP, pairwise comparisons (http://www.expertchoice.com)
Super Decisions Software	ANP, analytical network process (http://www.superdecisions.com/index_tables.php3)
VISA Groupware	Multiattribute value functions (http://www.simu18.com/visa.htm)
Web-HIPRE	Multiattribute value functions and AHP (http://www.hipre.hut.fi)
Discrete spatial choice problems	
Idrisi 32	A GIS that includes the following decision support procedures: WEIGHT (AHP), MCE (Boolean combination, weighted linear combination or ordered weighted average), RANK (rank order the cells), MOLA (allocate pixels to multiple objectives), and OWA (provides ordered weighted average of factors to adjust the level of tradeoff between factors and risk adversion) (http://www.clarklabs.org/).
EMDS	Ecosystem management decision support; combines ArcGISTM, NetWeaver and Criterium DecisionPlus (http://www.fsl.orst.edu/emds)

Based within the Graduate School of Geography at Clark University, Clark Labs is known for pioneering advancements in decision support. Clark Labs is best known for its flagship product, the IDRISI GIS and Image Processing software. Over the past several years, the research staff at the Clark Labs have been specifically concerned with the use of GIS as a direct extension of the human decision making process—most particularly in the context of resource allocation decisions. In 1993, IDRISI introduced the first instance of Multi-Criteria and Multi-Objective decision making tools in GIS. To date, IDRISI is still the industry leader for the development of decision support software.

Another noteworthy software is DEFINITE. The software is novel for two main reasons; first because it is not designed around one multi-criteria technique like most software packages, on the contrary, it is toolbox, and second because it is visual and interactive and facilitates communication about the problem and the evaluation of results. Janssen and van Herwijnen (2006) describe the characteristics of this tool.

The Super Decisions software is used for decision-making, and it implements the Analytic Network Process (ANP) developed by Saaty (2006). The program was written by the ANP Team, working for the Creative Decisions Foundation. The ANP is an essential tool for articulating our understanding of a decision problem. It is a process that allows one to include all the factors and criteria, tangible and intangible that have a bearing on making a best decision.

The ANP, provides a way to input judgments and measurements to derive ratio scale priorities for the distribution of influence among the factors and groups of factors in the decision. Because the process is based on deriving ratio scale measurements, it can be used to allocate resources according to their ratio-scale priorities. The well-known decision theory, the Analytic Hierarchy Process (AHP) (Saaty, 1980) is a special case of the ANP. Both the AHP and the ANP derive ratio scale priorities for elements and clusters of elements by making paired comparisons of elements on a common property or criterion. Although many decision problems are best studied through the ANP, one may wish to compare the results obtained with it to those obtained using the AHP or any other decision approach with respect to the time it took to obtain the results, the effort involved in making the judgments, and the relevance and accuracy of the results.

The ANP has been applied to a large variety of decisions: marketing, medical, political, social, forecasting and prediction and many others. Its accuracy of prediction is impressive in applications that have been made to economic trends, sports and other events for which the outcome later became known. Detailed case studies of applications are included in the ANP software manual and in the book; "The Analytic Network Process: Decision Making with Dependence and Feedback" by Saaty (2006).

Decision-support Tools for Marine Protected Areas (MPAs)

To manage the complex issues affecting MPAs, managers often turn to technology for help in understanding and analyzing the resources and environments of their MPAs. MPA managers and scientists are increasingly using GIS and remote sensing to map and analyze the resources under their jurisdiction.

In an effort to document existing GIS decision-support tools to aid MPA managers, the MPA Center and the NOAA Coastal Services Center compiled an "Inventory of GIS-Based Decision-Support Tools for MPAs (Pattison, dos Reis and Hamilton, 2004) . The aim of this inventory is to make the MPA community aware of existing GIS-based decision-support tools that may aid them in a variety of MPA-related activities (siting, zoning, monitoring, etc). The tools highlighted in this inventory provide functionality ranging from visualizing and integrating oceanographic data to site suitability modelling and incorporating stakeholder input. Custom made GIS-based tools mainly include ArcView 3x extensions, and other tools/software are CI-SSAT, EwE, GiDSS, HSM, OCEAN, MARXAN, e-Site, Sites v1.0, and CARIS GIS and CARIS LOTS (Table 6.2). Some of these tools were designed with customized algorithms to produce habitat suitability maps, select planning unit's reserve siting, or to establish marine reserve networks. Many tools are adaptable to any location provided the appropriate site-specific data layers are available and most tools are freely available for download. Of interest is the incorporation of socio-economic data in many of the tools and that two of these tools (i.e. Great Barrier Reef Marine Park's Representative Areas Program (RAP) and EcoTrust's Use of OceanMap) have been used in actual zoning and monitoring activities.

Some tools demonstrate a process for incorporating local knowledge into decision-making, which adds an important participatory component for stakeholders and yields significant information. Interactive mapping sites include "GiDSS" where users will be able to specify their particular problem or issue, and the tool, using a herring-bone decision tree, will return suggested data layers related to the issue, and "e-Site' an on-line geographic information system that enhances the involvement of stakeholders in the public participation processes of site selection issues in the marine environment.

Notably the only decision support tool that included aquaculture was the study by O'Donnell, Cronin, and Cummins on "Sustainable coastal habitats: GIS tools for effective decision support". Despite this, our impression is that these tools for MPAs could also be used in marine aquaculture to address aquaculture issues as illustrated in Table 6.2.

Each tool summary includes a description of what the tool does, the data and software needed to run it, and contact information. The references and specific project descriptions in this inventory give additional technical background and illustrate how these spatial tools can be used in conjunction with other mechanisms to facilitate MPA related management decisions.

Because new tools and techniques will invariably be developed and improved upon, it is the intent of MPA staff to maintain this inventory as a living document. As such, the inventory will be updated on a regular basis to reflect these changes and will be available in hard copy or online at http://www.mpa.gov. The MPA community are encouraged to alert MPA staff to any tools, projects, or papers that would be appropriate for future inclusion.

Selected applications of GIS to marine aquaculture

The general approach used in the GIS application reviews presented in Section 3, included a classification phase to define thresholds for each factor to cast them into suitability classes for further modelling.

Decision support amongst reviews of marine cage aquaculture applications mainly included the integration of expert opinion using MCE techniques, which occasionally included field verification and/or estimates of carrying capacity or productivity. Only two custom-made tools were created amongst the selected cage applications; (a) the paper on particulate waste distribution for Atlantic salmon and (b) the design of a GIS based tool for coastal zone management personnel with only basic knowledge of GIS.

Shellfish reviews included MCE, productions models, Acoustic Classification Systems (ACS) to classify habitat types; sub-bottom and side-scan sonar; and estimates of carrying capacity for mussel and scallop culture. One review dealt with the development of a GIS based oyster management information system.

It is worth noting that very few reviews on marine cage aquaculture or shellfish included socio-economic data or field verification in their analysis. There was only one paper found in the literature on seaweeds, however, it is a good example as it illustrates how simple models can be constructed to integrate environmental and social data for decision-making.

In terms of software, most GIS applications in the present document relied on: ArcView, Idrisi and MapInfo and on the decision support tools that these three software provide.

In the context of MCE, applications show that some advances have been made on the assignments of weights and how these are combined in MCE via ranking techniques. However, since weight assignment and combination are the core of the decision making process, we believe that there is a need to further develop these weighting techniques.

TABLE 6.2
GIS-based decision-support tools for MPAs

Author	Title	Software	Aquaculture issues that could be addressed
NOAA Coastal Services Center. http://www.csc.noaa.gov/communities/agreement.html	Channel Islands - Spatial Support and Analysis Tool	CI-SSAT	Suitability of the site and zoning
University of British Columbia's Fishery Centre http://www.ecopath.org	Ecopath with Ecosim, Ecopath.	EwE	Anticipating the consequences of aquaculture
NOAA Coastal Services Center. http://www.csc.noaa.gov/mpa/stellwagen.pdf	Evaluating Vessel Speed Restrictions to Mitigate Impacts to Marine Mammals in the Stellwagen Bank National Marine Sanctuary.	ArcGIS8x tool	Anticipating the consequences of aquaculture
National Center for Caribbean Coral Reef Research.	Geographic Information and Decision Support Tool	GiDSS	Web-Based Aquaculture Information System
NOAA's Biogeography Program, National Centers for Coastal Ocean Science. http://biogeo.nos.noaa.gov/products/apps/hsm/	Habitat Suitability Modelling	HSM (HSM was designed to be used on a Windows NT computer with ArcView3.2 and requires the Spatial Analyst extension).	Anticipating the consequences of aquaculture
Rikk Kvitek, Pat Iampietro, and Erica Summers-Morris. http://seafloor.csumb.edu/publications/Kvitek_NA17OC2586_Rpt.pdf	NOAA Technical Report: Integrated Spatial Data Model Tools for Auto-Classification and Delineation of Species-Specific Habitat Maps from High-Resolution, Digital Hydrographic Data.	Methods can be performed with any GIS software that has vector and GRID/raster analysis tools.	Restoration of Aquaculture Habitats
EcoTrust http://www.ecotrust.org/gis/ocean.html	Ocean Communities 3E Analysis Network, EcoTrust.	OCEAN	Planning for aquaculture among other uses of land and water
USGS, Alaska Biological Science Center http://www.absc.usgs.gov/glba/gistools/index.htm#OCEANOGRAPHIC	The Oceanographic Analyst Extension	ArcView 3x extension and Spatial Analyst.	Suitability of the site and zoning
The Nature Conservancy. http://www.biogeog.ucsb.edu/projects/tnc/overview.html	Sites	Sites (ArcView 3x extension).	Suitability of the site and zoning
Two processes using decision support tools			
Great Barrier Reef Marine Park Authority	Great Barrier Reef Marine Park's Representative Areas Program (RAP)	MARXAN (Basic extensions of a FORTRAN 77 program SIMAN)	Suitability of the site and zoning
California Department of Fish and Game (CDFG)	EcoTrust's Use of OceanMap	Collection of scripts within an ArcView project file.	Strategic planning for development

Author	Title	Software	Aquaculture issues that could be addressed
Annotated bibliography			
Adams, Christiaan Scott. MIT, Department of Civil and Environmental Engineering. http://dogfish.mit.edu/eSite/thesis/AdamsCS_Text.pdf	An interactive, online geographic information system (GIS) for stakeholder participation in environmental site selection.	e-Site	Web-Based Aquaculture Information System
Ardron, Jeff. http://www.livingoceans.org/files/complexity_draft8.pdf	A GIS recipe for determining benthic complexity: An indicator of species richness.	A methodology is proposed.	Restoration of Aquaculture Habitats
Ardron, J., J. Lash, and D. Haggarty. Living Oceans Society. British Columbia, Canada. http://www.livingoceans.org/documents/LOS_MPA_model_v31_web.pdf	Modelling a network of marine protected areas for the central coast of British Columbia.	MARXAN (v.1.2)	Suitability of the site and zoning
Beck, M.W., M.Odaya, J.J. Bachant, J. Bergan, B. Keller, R. Martin, R. Matthews, C. Porter, and G. Ramseur. http://www.epa.gov/gmpo/habitat/NGoM_Final_allfigs.PDF	Identification of priority sites for conservation in the northern Gulf of Mexico: An ecoregional plan. The Nature Conservancy, Arlington, VA.	Sites v1.0	Suitability of the site and zoning
Grober-Dunsmor, Rikki, Jason Hale, Jim Beets, Tom Frazer, Nick Funicelli, and Paul Zwick. http://cars.er.usgs.gov/posters/Coral_and_Marine/Mngmt_of_Marine_Reserves/mngmt_of_marine_reserves.html	Applying landscape ecology principles to the design and management of marine reserves.	Not specified	Restoration of Aquaculture Habitats
Leslie, H., M. Ruckelshaus, I.R. Ball, S. Andelman,and H.P. Possingham. http://www.sam.sdu.dk/fame/menu/pdfnov/leslie.pdf	Using siting algorithms in the design of marine reserve networks. Ecological Applications.	Simulated annealing	Suitability of the site and zoning
O'Donnell, V., Cronin, M. & Cummins, V.Coastal & Marine Resources Centre, Environmental Research Institute, University College Cork, Ireland. http://www.gisig.it/coastgis/papers/o%27donnell.pdf	Sustainable coastal habitats: GIS tools for effective decision support.	Evetully a GIS, via the Internet or an ArcView extension	Environmental impacts of aquaculture
Sala, E., O. Aburto-Oropeza, G. Paredes, I. Parra, J. C.Barrera, and P. K. Dayton. http://www.cciforum.org/pdfs/Sala_Marine_Reserves.pdf	A general model for designing networks of marine reserves.	Not specified	Strategic planning for development
Sutherland, Michael, Sam Machari Ng'ang'a, and Sue Nichols. http://www.isprs.org/commission4/proceedings/pdfpapers/272.pdf	In search of New Brunswick's marine administrative boundaries.	CARIS GIS and CARIS LOTS	Suitability of the site and zoning

7. Summary, discussion and conclusions

7.1 SUMMARY

The purpose of this review is to bring to light applications of GIS, remote sensing and mapping for the development and management of marine aquaculture as a means to improve sustainability with the focus on developing countries.

Marine aquaculture

Marine aquaculture is becoming increasingly important in the fisheries sector both in production and value. Mariculture is the second most important source of production in the fisheries sector and accounted for nearly 20% of total production in the sector in 2004.

Considered by production weight in broad groups in 2004, mariculture production was dominated by aquatic plants (46%) and mollusks (43%) while diadromous fishes (salmonids) accounted for 5% and marine fishes for 4%, respectively. Crustaceans made up the remaining 2%.

Of 186 coastal countries, only 86 had a mariculture output in 2004. Of those, 15 countries accounted for 97% of the world output. Thus, there appear to be ample opportunities for the expansion of marine aquaculture among those countries not yet producing, or producing relatively little at present.

Countries have jurisdiction over development and management of all kinds within their Exclusive Economic Zones and most countries possess vast EEZ areas associated with their homelands or territories. Thus, the lack of space does not appear to be an impediment to the expansion of marine aquaculture at present.

Marine aquaculture can be viewed as occupying two environments, near shore and offshore or, the open ocean. The development of near shore aquaculture appears to be impeded by a number of issues relating to competing uses and the environment. Offshore aquaculture shares the same issues in kind, but to a lesser degree and is presently impeded by lack of open ocean technologies and an enabling framework for development.

Geographic Information Systems, remote sensing and mapping in the marine environment and fisheries sector

GIS, remote sensing and mapping aimed at aquaculture use the data and techniques applied for other purposes such as for coastal area management and fisheries, thereby making technical innovations and applications in these fields of fundamental interest. The literature on the use of these tools in the marine environment is basically promotional in nature and covers the conceptual, technical and institutional issues as well as a variety of applications. Useful stepping stones are syntheses of experience in the form of reviews and manuals. The breadth of experience is most handily available in the form of proceedings of symposia, workshops and at Internet sites.

Nevertheless, in quantitative terms GIS, remote sensing and mapping applications in aquaculture have been found to be skewed in terms of environments, species cultured, issues addressed, and countries represented. Thus, a key need was for comprehensive information on GIS, remote sensing and mapping tools as applied to aquaculture that could be widely and cheaply disseminated. GISFish, an FAO Internet portal of GIS, remote sensing and mapping experience, was created to address this problem.

Using selected examples from the literature we have shown that GIS, remote sensing and mapping have important roles to play in many geographic and spatial aspects of the development and management of marine aquaculture.

Mapping applications in marine aquaculture

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.

Mapping applications are shown relating to aquaculture siting and zoning, as key components of an Internet-based aquaculture information system aimed at a broad audience of government, commercial and private users, and in the form of interactive and downloadable GIS map data useful for aquaculture that are available from Internet Map Servers (IMS).

Remote sensing applications in marine aquaculture

Remote sensing, using satellite, airborne, ground and undersea sensors, is viewed mainly as a frequently and widely used tool for the capture of data subsequently to be incorporated into a marine aquaculture GIS. In this regard, hydroacoustical remote sensing is presented in the section on GIS applications to shellfish aquaculture rather than as a stand alone application. Similarly, satellite remote sensing as a source of physical data on the ocean is handled under the chapter on data. This view is not intended to diminish the importance of remote sensing relative to the other tools. On the contrary, "dynamic" remote sensing for real time, or near real time, monitoring of environmental conditions for operational management of aquaculture facilities will become increasingly important. Early warning of harmful algal blooms is one important application of this type that is covered in several examples. Dynamic remote sensing also is useful for routine monitoring of sea state, temperature, and current velocity for open ocean aquaculture.

From the early days of development to the present, digital data from satellite sensors have been useful as base maps for near shore aquaculture as well as for providing essential information on land use, land cover and some water features. Likewise, monitoring and mapping aquaculture development is another use of satellite data in areas where aquaculture is regulated.

Geographic Information Systems applications in marine aquaculture

GIS applications to near shore and offshore marine aquaculture naturally fall into two main categories: culture of finfishes in cages and near shore culture of shellfishes.

Geographic Information Systems and cage culture of finfish

Regarding cage culture, site selection and "pre-zoning" are the most numerous and most highly developed of the applications. Most of the examples pertain to pre-siting studies that cover relatively large areas, the results of which are indicative of locations with potential for further detailed field investigations among the specific areas or sites identified in the GIS. The more detailed or finer resolution data can then be incorporated in the existing GIS so that it can be used for the selection of individual sites.

There is a clear evolution from site selection in which only the suitability for the culture system and cultured organisms are taken into account to broader-based studies in which the objective is to accommodate marine aquaculture amongst competing uses. Going along with this is increasing sophistication in decision-making that includes the use of experts and formalized procedures to identify and quantify production functions in models. The result is more complete and reliable information on which to base decisions.

More specialized investigations of cage culture use GIS to address wave climate and cage effluents.

Geographic Information Systems and shellfish culture

GIS applications to shellfish culture are much more numerous than for cage culture of fish for a number of reasons relating to the much greater production of the former. On issues related to development, the reviews cover applications on siting, estimating potential, anticipating competing uses and avoiding conflicts. Regarding issues relating to aquaculture practice and management, the reviews address, pollution, diseases in aquaculture operations, habitat evaluation using hydroacoustical remote sensing, resources, carrying capacity, and seasonal mortality.

Most of the applications are aimed at oysters, but hard clams, mussels and scallops are included. Most of the culture takes place on the bottom although raft and longlines are represented.

Among the problems that continue to impede these applications is a lack of data of sufficient scope or resolution. This may be related to a paucity of studies in which decision-making is formalized in an objective way.

Among the gaps are applications that identify shore support facilities along with sites or zones for culture. Surrogates for such applications are site selection studies for shrimp farming in ponds that have many data layers in common.

Economics and Geographic Information Systems

Given that all spatial aspects of marine aquaculture have an economic underpinning, it is noteworthy that there is a dearth of GIS applications to the economic aspects of marine aquaculture development and management. This is despite the fact that some existing economic studies and models clearly lay out geographically related cost variables. It has been suggested that GIS could be applied to several elements of these economic studies to improve choices of tradeoffs mainly by spatially hindcasting environmental variables.

The few applications of GIS in socio-economics are mainly global studies that encompass all of aquaculture. The potential of GIS to contribute to the improvement of human welfare in the development of marine aquaculture at sub-national levels is beginning to be realized.

Data availability

Data of the appropriate temporal and spatial resolution as well as geographic coverage for the intended use is one of the most important considerations for GIS implementation. Early investigators were well aware of the spatial factors and constraints associated with marine aquaculture. Their main difficulty was in finding or generating data appropriate to the task. To some extent this problem continues today and is manifest in the lack of some kinds of compiled data, among which currents stand out. Spatial gaps in data, and data of too low resolution continue to be issues.

There usually is a fairly close correlation between data resolution and geographic coverage. Thus, for marine aquaculture spatial investigations, data sets can be conveniently categorized as global, national, sub-national and local in consideration of the spatial area of interest. Temporal characteristics of the data sets also are important. For “static” data such as shorelines access to the most recent updates is necessary. For dynamic data such as SST, temporal needs may range from climatologies based on years of observations to real time data, the latter for operational management of aquaculture installations and the former for commercial or governmental development planning.

Attribute data are used to set thresholds on production factors. Attribute data may take a long time to identify, compile and synthesize because of the need for extensive literature and Internet searches as well as for correspondence with experts.

With the objective of pointing the way to data that could be used for a first approximation of offshore aquaculture potential, we have placed our emphasis on describing data that have a global coverage and that are mainly freely downloadable from the Internet. The most basic of these data sets include shorelines, EEZ boundaries, bathymetry, SST, and chlorophyll-a.

Real time data, and more importantly predictions that can be made based on them, can be vital for the operational management of marine aquaculture installations. We point the way to sources of real time data that include SST, chlorophyll, wave heights and current velocity.

Data sets at national and sub-national resolutions appear to vary greatly in availability among countries. Obviously, there is a correlation between the availability of data and the numbers of applications in marine aquaculture. The current count on applications by country at GISFish casts light on this problem.

Models and decision-making in marine aquaculture

Our impression is that there is a need to go further beyond the fisheries sector in order to pick up the latest methods and applications for GIS-based decision support. It is our belief that many lessons can be learnt from MCE used in other sectors such as MPAs analysis (Pattison, dos Reis and Hamilton, 2004), integrated coastal management decision support frameworks (e.g. Fabbri, 2006) and location-based methodologies applied by the business community. It was not possible to conduct a detailed review of MCE for marine aquaculture, but we may conclude that a separate paper on the state of Decision Support Tools (DST) in the aquaculture sector would be a much needed contribution and it could be used as a guideline for future work on MCE for the development and management of marine aquaculture. To this end, Leung (2006) provides an up-to-date review of MCE applications in fishery management. Therefore, a review on MCE for aquaculture is considered complementary and very timely.

7.2 DISCUSSION AND CONCLUSIONS

Marine aquaculture

- Marine aquaculture overall is growing rapidly and offshore aquaculture is becoming more important as more experience is gained. From a spatial point of view there appear to be ample opportunities for the expansion of offshore marine aquaculture in countries presently producing little or not producing at all in this sector.
- Sustainable growth of marine aquaculture will require an enabling environment that includes sound plans for continued development and management. Such plans can come only by addressing and successfully resolving the main issues concerned. According to Muir (2004), the main questions in open ocean aquaculture are:
    - Can complete offshore systems be defined and developed?
    - Can these be developed and operated in a cost-effective manner?
    - What are the economic implications?

  - Will they be suitable for regional conditions?
  - Will there be an appropriate policy environment?
  - Will there be the appropriate market and investment conditions to stimulate their use?
- Along these lines, it has been emphasized by Cicin-Sain *et al*. (2005) 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, conflicts with other users, reduced production, leasing issues, licensing and other regulatory requirements, or ultimately, project failure.

GIS, remote sensing and mapping applications

- GIS, remote sensing and mapping applications have been assembled to illustrate the capabilities of these tools to address many issues facing the development and management of marine aquaculture. We have framed the applications in a broad set of fundamental aquaculture issues. Obviously, the emphasis on some issues may vary from situation to situation, and new issues may arise. In any case, we deem it essential that the deployment of spatial tools is based on a careful prior assessment of issues. Although there is much room for refinement as well as for the expansion of applications to more fully and broadly address issues, it is safe to say that these tools can be advantageously deployed to improve the sustainability of marine aquaculture, particularly for pre-siting and identifying and quantifying competing and conflicting uses. Said differently, the use of GIS, remote sensing and mapping has reached the point of becoming an essential part of providing the enabling environment for the development of marine aquaculture.
- A noteworthy gap is that the culture of marine plants, by weight the most important output of marine aquaculture, has not been fully covered by GIS, only one application was found in the literature.
- A legitimate question is that, despite the many varieties of applications presented herein, why is the use of GIS, remote sensing and mapping in aquaculture not more common and widespread as in other disciplines such as water resources? We believe that part of the answer is a lack of information about the capabilities of these tools among administrators and managers and a lack of access to experience among practitioners, especially in developing countries. This technical paper represents one solution and GISFish is another. However, other possible constraints need to be considered. One is that there is too little opportunity for formal education in GIS that should accompany undergraduate and graduate studies in all fields of natural resource research and management. Another is lack of access to computer equipment, software and the bandwidth in order to operate on the Internet effectively, especially with regard to communicating and acquiring data and especially in developing countries. Clearly, the impediments to more effective and widespread use of spatial tools in aquaculture need to be examined. Possibilities for next steps in this direction include the formation of a FAO-sponsored working group to address specific items that could include (1) a review of the aquaculture sector's present and future needs for spatial analyses, (2) a critical analysis of why GIS has not taken off, and (3) the role GIS, remote sensing and mapping for the management and development of aquaculture and in strategic and operational decision-making. The discussion forum offered by GISFish could be the initial meeting place for the working group. As a means of broadening the input to the working group, it could meet in conjunction with an international meeting such as the International Symposium on GIS and Spatial Analysis in Fishery

and Aquatic Sciences. Another way to broaden the perspective of the working group would be to empanel members from disciplines other than fisheries and aquaculture in which the use of GIS has become widespread and effective (e.g., coastal area management). A report as the final output of the working group would not be sufficient. Rather, the working group should be convened not just with the idea of identifying problems, but also with the mandate to design practical solutions, and to identify organizations with the capabilities to finance and implement the solutions.

Economics, socio-economics and GIS

- There is a dearth of applications of GIS to the economic issues of aquaculture. It is ironic that, in contrast to many other kinds of applications, the economic data appear to be readily available for GIS analysis from economic studies in which spatial analysis has not been employed. Some examples are highlighted below.
- Spatial bioeconomic modelling requires estimating spatial differences in culture production. A step in coupling GIS with bioeconomic modelling was taken by Kapetsky and Nath (1997) who integrated a GIS with a bio-energetics model to assess inland aquaculture potential in Latin America, and Aguilar-Manjarrez and Nath (1998) followed a similar procedure for Africa.
- It appears that there are many other opportunities for integrating GIS with already-developed marine aquaculture bioeconomic models. For example, Kite-Powell *et al*. (2003) have developed a bioeconomic model for open-ocean finfish culture in the Atlantic off of the New England region of the United States of America that they have applied to salmon, cod and flounder. The model optimizes stocking and harvesting schedules, projects financial flows and allows for alternative grow-out sites. Among the spatial (locational) parameters that figure in their model is water temperature related to growth, depth related to mooring and installation costs of cages, wave profile, and distance from shore. Because their model calculates the financial performance of the operation month by month over a 15-year period, there is an unrealized opportunity to make the model more dynamic temporally and spatially by hind casting performance in a GIS by employing monthly historical SST and/or Drifter data. The authors deemed distance traveled and vessel operating and crew expenses as substantial costs to the overall operation. In this regard they conclude that it makes good economic sense to locate grow-out sites as close to shore as possible, given other constraints. GIS could be applied to this problem as well, not only in locating the sites that would be most suitable distance-wise, but also by estimating the risk in terms of variability by hind casting sea and weather conditions affecting boat operating and performance in a way similar to spatial variability in growth performance as outlined above.
- GIS could be applied in similar ways to the economics of shellfish culture, but there are differing needs for analyses. Langan and Forbes (2003), describe the design, operation and economics of submerged longline mussel culture in the open ocean. They indicate that food quality and quantity are the most important factors affecting grow-out time. Thus, identifying areas with consistently high chlorophyll-a, low turbidity and relatively high dissolved oxygen would be important considerations in consideration of limiting boat travel time. Kite-Powell, Hoagland and Jin (2003) studied the economics of open ocean grow-out of sea scallops (*Plagopecten magellanicus*) and blue mussels. Grow-out of the former species would depend on reliable capture fisheries for juveniles, thus adding a criterion for site selection that would be

areas with suitable sea scallop juvenile stocks and with available fishing craft and personnel to supply the culture operation. Hoagland, Kite-Powell and Lin (2003) developed a business plan for open ocean culture of mussels in the New England, the United States of America area. They estimate vessel operation costs, including crew, at $1,000/d for 90 days/y at sea. Once the operation is well established, these costs account for from 21% to 23% of the total cost of the operation. Therefore, site selection that minimizes vessel "commuting" time, along with the other needs outlined above, is quite important for the business plan and the sustainability of the operation.

Estimating open ocean aquaculture potential

- The study of open ocean aquaculture potential in the US EEZ (Section 4) clearly illustrates that it is possible to create a simple GIS to make a first approximation of offshore aquaculture potential for any country wishing to do so. The basis for such studies is sufficient spatial data with global coverage that are freely available for download from the Internet. Attribute data have to be identified, compiled and synthesized according to the culture systems and species appropriate to the country's marine waters.

Data availability

- There are two data problems that impede the use of GIS in marine aquaculture, one of which is access to spatial data and the other of which is the availability of attribute data. Regarding spatial data, there are still many data gaps that fall into three categories: (1) gaps in geographic coverage and time, (2) resolution, and (3) gaps in kinds of data. Most of the time spent in a GIS study of marine aquaculture can go to identifying, collecting, organizing and compiling the attribute data that define the environmental requirements for the culture of organisms and for the optimum and working limits for culture structures.

Data models and decision-making in marine aquaculture

- Key improvements on decision support tools (DST) for marine aquaculture include: an increased use of socio-economic data, and the development of custom made tools and/or the use of DST used/created in other sectors to better address specific decision problems for marine aquaculture. Given the contrasts between the DST tools used in the GIS applications described in the present document and those used in MPA analysis it is believed that better communication amongst experts from different sectors would enhance DST for marine aquaculture. Also, the impression is that more marine aquaculture experts with more experience on MCE are required to fully benefit from existing tools and/or to create new tools.

Final consideration and recommendations

- The potential of spatial tools can be realized through cooperative, cross-disciplinary approaches that emphasize addressing common issues and by constituting teams with expertise on each of the ramifications of the issues.
- From the viewpoint of organization and implementation of GIS, it is clear that marine fisheries and marine aquaculture share common needs for environmental and economic data, and many of the species are both cultured and captured. Furthermore, spatial analytical procedures are the same or similar in marine aquaculture and fisheries. Therefore, it would seem that there is much to be gained by cooperation between, or integration, of GIS activities in aquaculture and fisheries at national government levels and among academic institutions.

- From the viewpoint of attribute data for thresholding, there is a need for (1) syntheses of information on the biophysical requirements of species presently being cultured, or with potential for marine aquaculture, (2) physical environmental requirements of culture structures, and (3) bioeconomic models.

8. Glossary

Geographic Information Systems A computer system for capturing, storing, checking, integrating, manipulating, analysing and displaying data related to positions on the Earth's surface. Typically, a Geographical Information System (or Spatial Information System) is used for handling maps of one kind or another. These might be represented as several different layers where each layer holds data about a particular kind of feature. Each feature is linked to a position on the graphical image of a map. In aquaculture, it has been used to assess the suitability of geographical sectors, and also to investigate the suitability of a species to an area.

ENVISAT (Environment Satellite). ENVISAT satellite is an Earth-observing satellite built by the European Space Agency. It was launched on March 1, 2002 aboard an Ariane 5 into a Sun synchronous polar orbit at a height of 790 km (+/– 10 km). It orbits the Earth in about 101 minutes with a repeat cycle of 35 days

Fuzzy classification Any method for classifying data that allows attributes to apply to objects by membership values, so that an object may be considered a partial member of a class. Class membership is usually defined on a continuous scale from zero to one, where zero is nonmembership and one is full membership. Fuzzy classification may also be applied to geographic objects themselves, so that an object's boundary is treated as a gradated area rather than an exact line. In GIS, fuzzy classification has been used in the analysis of soil, vegetation, and other phenomena that tend to change gradually in their physical composition and for which attributes are often partly qualitative in nature.

Geodatabase A collection of geographic datasets for use by ArcGIS. There are various types of geographic datasets, including feature classes, attribute tables, raster datasets, network datasets, topologies, and many others.

Keyhole Markup Language XML grammar and file format for modelling and storing geographic features such as points, lines, images, polygons, and models for display in Google Earth. A KML file is processed by Google Earth in a similar way that HTML and XML files are processed by web browsers. Like HTML, KML has a tag-based structure with names and attributes used for specific display purposes. Thus, Google Earth acts as a browser of KML files.

Landsat The U.S. Landsat satellites are the first series of Earth Observation satellites providing global, repeated coverage of the Earth surface. The sensors onboard these satellites operate in the visible up to middle infrared wavelengths, and in the thermal infrared. The first satellite of the mission, ERTS-1 (later renamed Landsat-1) was launched in 1972. The current Landsat-7 mission hosts the Enhanced Thematic Mapper sensor; of its nine channels, seven acquire data in the visible up to middle infrared, at 30 m resolution. More information on the Landsat-7 mission can be found in the USGS Web pages (http://landsat7.usgs.gov/index.php) and in the NASA Web pages (http://landsat.gsfc.nasa.gov/).

Maps 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.

Marine aquaculture Cultivation, management and harvesting of marine organisms in their natural habitat or in specially constructed rearing units, e.g. ponds, cages, pens, enclosures or tanks. For the purpose of FAO statistics, mariculture refers to cultivation of the end product in seawater even though earlier stages in the life cycle of the concerned aquatic organisms may be cultured in brackish water or freshwater.

MCE is a decision support tool for Multi-Criteria Evaluation. A decision is a choice between alternatives (such as alternative actions, land allocations, etc.). The basis for a decision is known as a criterion. In a Multi-Criteria Evaluation, an attempt is made to combine a set of criteria to achieve a single composite basis for a decision according to a specific objective. For example, a decision may need to be made about what areas are the most suitable for industrial development. Criteria might include proximity to roads, slope gradient, exclusion of reserved lands, and so on. Through a Multi-Criteria Evaluation, these criteria images representing suitability may be combined to form a single suitability map from which the final choice will be made.

MERIS (Medium Resolution Imaging Spectrometer). MERIS is a programmable, medium-spectral resolution, imaging spectrometer operating in the solar reflective spectral range. Fifteen spectral bands can be selected by ground command, each of which has a programmable width and a programmable location in the 390 nm to 1 040 nm spectral range. The instrument scans the Earth's surface by the so called "push-broom" method. Linear CCD arrays provide spatial sampling in the across-track direction, while the satellite's motion provides scanning in the along-track direction. MERIS is designed so that it can acquire data over the Earth whenever illumination conditions are suitable. The instrument's 68.5° field of view around nadir covers a swath width of 1150 km. This wide field of view is shared between five identical optical modules arranged in a fan shape configuration.

Metadata Information that describes the content, quality, condition, origin, and other characteristics of data or other pieces of information. Metadata for spatial data may describe and document its subject matter; how, when, where, and by whom the data was collected; availability and distribution information; its projection, scale, resolution, and accuracy; and its reliability with regard to some standard. Metadata consists of properties and documentation. Properties are derived from the data source (for example, the coordinate system and projection of the data), while documentation is entered by a person (for example, keywords used to describe the data).

Pixels (Picture elements) Cells of an image matrix. The ground surface corresponding to the pixel is determined by the instantaneous field of view (IFOV) of the sensor system, e.g. the solid angle extending from a detector to the area on the ground it measures at any instant. The digital values of the pixels are the measures of the radiant flux of electromagnetic energy emitted or reflected by the imaged Earth surface in each sensor channel.

Projection A method by which the curved surface of the earth is portrayed on a flat surface. This generally requires a systematic mathematical transformation of the earth's graticule of lines of longitude and latitude onto a plane. Some projections can be visualized as a transparent globe with a light bulb at its center (though not all projections emanate from the globe's center) casting lines of latitude and longitude onto a sheet of paper. Generally, the paper is either flat and placed tangent to the globe (a planar or azimuthal projection) or formed into a cone or cylinder and placed over the globe (cylindrical and conical projections). Every map projection distorts distance, area, shape, direction, or some combination thereof.

Remote Sensing 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.

SAR (Synthetic Aperture Radar) An imaging radar is an active instrument that transmits microwave pulses toward the Earth surface and measures the magnitude of the signal scattered back towards it. The return signals from different portions of the ground surface are combined to form an image. A Synthetic Aperture Radar (SAR) is a special type of imaging radar. It is a complex system that measures both the amplitude and phase of the return signals; their analysis exploits the Doppler effect created by the motion of the spacecraft with respect to the imaged surface to achieve high ground resolution. As the source of the electromagnetic radiation used to sense the Earth surface is the system itself, it can be operated during day and night. The atmospheric transmittance in the microwave interval used by remote sensing SAR systems (2 to 30 GHz) is higher than 90%, also in presence of ice and rain droplets (except under heavy tropical thunderstorms); thus, SAR can acquire data in all weather conditions.

Scale The ratio between a distance or area on a map and the corresponding distance or area on the ground.

Resolution The area of the ground surface corresponding to a pixel in a satellite image.

Glossary compiled from the following sources:

Anonymous. 1998. AQUALEX. Multilingual glossary of aquaculture terms/ Glossaire multilingue relatif aux termes utilisés en aquaculture. CD ROM, John Wiley & Sons Ltd. & Praxis Publ., UK.

Association for Geographic Information (AGI) GIS Dictionary (http://www.geo.ed.ac.uk/agidict/welcome.html)

Barnabé, G. (ed..) 1990 Aquaculture. Chichester, UK, Ellis Horwood. Vol.1, 528p. Vol.2, 584p. Transl. by L.M. Laird.

Center for Spatially Integrated Social Science (CSISS): http://www.csiss.org/cookbook/glossary.php

Choudury, K. and Jansen, L.J.M. (UNESCO/WMO) 1999. Terminology for integrated resources planning and management. Rome, FAO. 69p.

Chrisman, N. Glossary for Exploring GIS, by: http://www.wiley.com/college/chrisman/glossary.html

Earth Sciences Sector of Natural Resources Canada. Canada Center for Remote Sensing (CCRS). Glossary of remote sensing terms (http://ccrs.nrcan.gc.ca/glossary/index_e.php).

ESRI. 2001. *The ESRI Press dictionary of GIS terminology*. Environmental Systems Research Institute, Inc. Redlands, California, USA (available at: http://www.esri.com/library/glossary/a_d.html).

FAO 2006.Glossary of Aquaculture. http://www.fao.org/fi/glossary/aquaculture/

FAO Fisheries Department 2003 World Fisheries and Aquaculture Atlas. CD-ROM. Rome, FAO. 2nd ed.

Hoehn, P., and Lynette, M. Dictionary of abbreviations and acronyms in geographic information systems, cartography and remote sensing. (available at http://www.lib.berkeley.edu/EART/abbrev.html).

Perry-Castañeda Library Map Collection. Glossary of Cartographic Terms online at http://www.lib.utexas.edu/maps/glossary.html. The University of Texas.

Voser, S.A. Glossary of glossaries (available at http://www.geocities.com/CapeCanaveral/1224/terms/terms_txt.html)

References

Aguilar-Manjarrez, J. 1992. Construction of a GIS for Tabasco State Mexico. Establishment of technical and social decision models for aquaculture development. Institute of Aquaculture.University of Stirling, UK. 125 pp. (M.Sc.Thesis).

Aguilar-Manjarrez, J. 1996. Development and evaluation of GIS-based models for planning and management of coastal aquaculture: a case study in Sinaloa, México. Institute of Aquaculture, University of Stirling, Scotland, UK. 373 pp. (Ph.D. Thesis).

Aguilar-Manjarrez, J. & Nath, S.S. 1998. *A strategic reassessment of fish farming potential in Africa.* CIFA Technical Paper. No. 32. FAO, Rome. 170 pp. (also available at http://www.fao.org/docrep/W8522e/W8522E00.htm).

AquaGIS. 2006. Newfoundland and Labrador Aquaculture Geographic Information System. Department of Fisheries and Aquaculture, Newfoundland and Labrador. (available at www.aquagis.com).

Arnold, W.S., Norris, H.A. & Berrigan, M.E. 1996. Lease site considerations for hard clam aquaculture in Florida. *Journal of Shellfish Research* 15:478-479.

Arnold, W.S. & Norris, H.A. 1998. Integrated resource management using GIS: Shellfish aquaculture in Florida. *Journal of Shellfish Research* 17: 318.

Arnold, W.S., Kaiser, J.B. & Holt, G.J. 2002. Spawning of Cobia (*Rachycentron canadum*) in captivity. *Journal of the World Aquaculture Society*, 33(2): 205-208.

Arnold, W.S., White, M.W., Norris, H.A. & Berrigan, M.E. 2000. Hard clam (*Mercenaria spp.*) aquaculture in Florida, USA: geographic information system applications to lease site selection. *Aquacultural Engineering*. 23(1-3):203-231.

Auckland Regional Council. 2002. Mapping constraints to future marine farming in the Auckland and Waikato Regions-Stage One. 96 pp.

Auckland Regional Council (no year). Mapping Potential Aquaculture Management Areas in the Auckland Region – Stage 2. (available at http://www.arc.govt.nz/arc/library/b86166_2.pdf).

Bacher, C., Grant, J., Hawkins, A.S.J., Fang, J., Zhu, M. & Besnard, M. 2003. Modelling the effect of food depletion on scallop growth in Sungo Bay (China). *Aquatic Living Resources*, 16(1): 10-24.

Basurco, B. & Sarologia, M. 2002. Seafarming today and tomorrow. European Aquaculture Society. Special Publication No. 32. 562 pp.

Belton, V. & Stewart, T.J. 2002. Multi Criteria Decision Analysis and Integrative Approaches, Kluwer Academic Publishers, New York.

Beveridge, M. 2004. *Cage Aquaculture*. Third Edition. Blackwell Publishing. London. 376 pp.

Booth, A.J. 2004. Spatial statistics and aquatic Geographic Information Systems. In Nishida, T., Kailola, P. and Holliingworth, C. eds. GIS/Spatial analyses in fishery and aquatic sciences (Vol 2.) Proceedings of the Second International Symposium on GIS/Spatial analyses in fishery and aquatic sciences. pp. 3-44. Fishery-Aquatic GIS Research Group. Kawagoe, Saitama, Japan. 733 pp.

Booth, A.J. & Wood, B. 2004. Geographic Information Systems application in offshore marine fisheries. *In* Fisher, W. L. and Rahel, F.J. eds. Geographic information systems in fisheries. pp. 209-236. American Fisheries Society, Bethesda, Maryland, USA. 275 pp.

Breman, J. ed. 2002. Marine geography. GIS for the oceans and seas. ESRI Press. Redlands, California, USA. 204 pp.

Bremen, J., Wright, D. & Halpin, P.N. 2002. The inception of the ArcGIS marine data model. In Breman, J. ed. Marine geography. GIS for the oceans and seas. Pp 3-10. ESRI Press. Redlands, California, USA. 204 pp.

Bridger, C.J. & Costa-Pierce, B.A. eds. 2003. Open Ocean Aquaculture: From Research to Commercial Reality. The World Aquaculture Society, Baton Rouge, Louisiana, USA. 351 pp.

Bridger, C.J., Costa-Pierce, B.A., Goudey, C.A., Stickney, R.R. & Allen, J.D. 2003. Offshore aquaculture development in the Gulf of Mexico: Site selection, candidate species, and logistic alleviation. In Pages 273–283 C.J. Bridger and Costa-Pierce, B.A., eds. Open Ocean Aquaculture: From Research to Commercial Reality. The World Aquaculture Society, Baton Rouge, LA.

Buitrago, J., Rada, M., Hernández, H. & Buitrago, E. 2005. A Single-Use Site Selection Technique, Using GIS, for Aquaculture Planning: Choosing Locations for Mangrove Oyster Raft Culture in Margarita Island, Venezuela. Environmental Management 35(5): 544-556.

Burrough, P.A. 1986. Principles of Geographic Information Systems, 1st ed. Oxford University Press, New York 336 pp.

Butler, M.J.A, LeBlanc, C., Belbin, J.A. & MacNeill, J.L. 1987. *Marine resource mapping : an introductory manual.* FAO Fisheries Technical Paper No. 274. Rome, FAO. 256 pp.

Butler, M.J.A., Mouchot, M.-C., Barale, V. & LeBlanc, C. 1988. *The application of remote sensing technology to marine fisheries : an introductory manual.* FAO Fisheries Technical Paper No. 295. Rome, FAO.

Carswell, B., Cheesman, S. & Anderson, J. 2006. The use of spatial analysis for environmental assessment of shellfish aquaculture in Baynes Sound, Vancouver Island, British Columbia, Canada. Aquaculture, 253(1-4): 408-414.

Center for Coastal Resources Management. 1999. Shallow water resource use conflicts: Clam aquaculture and submerged aquatic vegetation. Virginia Institute of Marine Science, Gloucester Point, Virginia. 30 pp.

Chang, B., Page, F.H. & Hill, W.H. 2005. Preliminary analysis of coastal marine resources use and the development of open ocean aquaculture in the Bay of Fundy. Canadian Technical Report of Fisheries and Aquatic Sciences 2585. 36 pp.

Cicin-Sain, B Knecht, R. W., Rheault, R., Bunsick, S.M., DeVoe, R., Eichenberg, T., Ewart, J. & Halvorson, H. 2001. Development of a Policy Framework for Offshore Marine Aquaculture in the 3-200 Mile U.S. Ocean Zone. Center for Marine Policy, University of Delaware. 167 pp.

Cicin-Sain, B., Bunsick, S.M., Corbin, J., DeVoe, R. M., Eichenberg, T., Ewart, J., Firestone, J., Fletcher, K., Halvorson, H., MacDonald, T., Rayburn, R., Rheault, R. & Thorne-Miller, B. 2005. Recommendations for an operational framework for offshore aquaculture in U.S. Federal waters. Center for Marine Policy, University of Delaware. 118 pp.

CINEMAR. 2005. News Release. New Hampshire Fishermen Are Mussel Bound. (available at http://ooa.unh.edu/news/1_2005/newsMussels.htm).

Cordell, E.V. & Nolte, D.A. 1998. Feasibility of using remote sensing to identify the aquaculture potential of coastal waters. Recon Technologies, Inc. Bend, Oregon, USA.

Corner, R.A., Brooker, A.J., Telfer, T.C. & Ross, L.G. 2006. A fully integrated GIS-based model of particulate waste distribution from marine fish-cage sites. Aquaculture 258: 299–311. (also available at http://www.aqua.stir.ac.uk/GISAP/pdfs/Corner_waste.pdf).

De Graaf, G., Marttin, F., Aguilar-Manjarrez, J. & Jenness, J. 2003. *Geographic information systems in fisheries management and planning. Technical manual.* FAO Fisheries Technical Paper No. 449. FAO, Rome. 162pp. (also available at http://www.fao.org/docrep/006/y4816e/y4816e00.htm#Contents).

DeMers, M.N. 2003. Fundamentals of Geographic Information Systems. Second Edition. John Wiley and Sons, Inc. New York, NY, USA. 636 pp.

Dolmer, P. & Geitner, K. 2004. Integrated Coastal Zone Management of cultures and fishery of mussels in Limfjorden, Denmark. ICES C.M. 2004/V:07. 9 pp.

Dooley J.F. 2005. An Inventory and Comparison of Globally Consistent Geospatial Databases and Libraries. *Environment and Natural Resources Series* No.19 - FAO, Rome. 200 pp. (also available at http://www.fao.org/docrep/008/a0118e/a0118e00.htm#Contents).

Durand, H., Guillaumont, B., Loarer, R., Loubersac, L., Prou, J. & Heral, M. 1994a. An example of GIS potentiality for coastal zone management: pre-selection of submerged oyster culture areas near Marennes Oléron (France). EARSEL Workshop on Remote Sensing and GIS for Coastal Zone Management. Delft, The Netherlands.

Durand, H., Guillaumont, B. & Labbe, S. 1994b. Maquette d'un SIG littoral en vue de la recherche de sites ostreicoles en eau profonde. Gutlar/IFREMER Groupe Sillage. Brest, France. (pages not numbered).

El Gayar, O.F. & Leung, P.S. 2006. A multiple-criteria decision making framework for regional aquaculture development. *European Journal of Operational Research* Vol. 133, pp 462-482.

Environment Bay of Plenty. 2006. Aquaculture Managament Area Project. (available at http://www.ebop.govt.nz/Coast/AMA-project.asp).

Fabbri, K.P. 2006. A strategic decision support framework for integrated coastal zone management. *Int. J. Environmental Technology and Management*, Vol. 6, Nos. 1/2, pp 206-217.

FAO. 1995. Code of conduct of responsible fisheries. FAO, Rome. (available at http://www.fao.org/DOCREP/005/v9878e/v9878e00.htm#PRE).

FAO. 1997. FAO Technical Guidelines for Responsible Fisheries. Aquaculture Development No. 5. Rome, FAO. 40 pp.

FAO. 2006a. FISHSTAT PLUS [online]. Universal software for fishery statistical time series [Version 2.3]. Release date: March 2006. (available at http://www.fao.org/fi/statist/FISOFT/FISHPLUS.asp).

FAO.2006b. Glossary of Aquaculture. Rome, FAO. (available at http://www.fao.org/fi/glossary/aquaculture/).

Field, D. 2001. Practical aquaculture GIS. INFOFISH International 5: 27-30.

Fisher, W.L. (in press). Recent trends in fisheries geographic information systems. In Nishida, T., Kailola, P. and Holliingworth, C. eds. Proceedings of the Third International Symposium on GIS/Spatial analyses in fishery and aquatic sciences. Fishery-Aquatic GIS Research Group. Kawagoe, Saitama, Japan.

Fisher, W.L. & Rahel, F.J. eds. (2004). Geographic information systems in fisheries. American Fisheries Society, Bethesda, Maryland, USA. 275 pp.

Freddi, A. & Aguilar-Manjarrez, J. 2005. TCP/BRA/0065. Small-scale seaweed farming in North East Brazil. FAO Aquaculture Newsletter December 2005 - No. 34. FAO, Rome, pp 34-35 (also available at http://www.fao.org/docrep/009/a0435e/a0435e00.htm).

Geitner, K. 2004. Use of GIS for placement of rainbow trout culture in Denmark. In Nishida, T., Kailola, P. and Holliingworth, C. eds. GIS/Sparial analyses in fishery and aquatic sciences (Vol 2.) Proceedings of the Second International Symposium on GIS/Spatial analyses in fishery and aquatic sciences. pp. 543-558. Fishery-Aquatic GIS Research Group. Kawagoe, Saitama, Japan. 733 pp.

GEODAS. 2006. Grid Translator. National Geophysical Data Center. NOAA Satellite and Information Service. (available at http://www.ngdc.noaa.gov/mgg/gdas/gd_designagrid.html).

GESAMP (IMO/FAO/UNESCO-IOC/WMO/WHO/IAEA/UN/UNEP Joint Group of Experts on the Scientific Aspects of Marine Environment Protection (GESAMP). 2001. Planning and management for sustainable coastal aquaculture development. GESAMP Reports and Studies. 68. 45 pp. (also available at ftp://ftp.fao.org/docrep/fao/007/y1818e/y1818e00.pdf).

Goudey, C. 1998. Model Tests and Operational Optimization of a Self-propelled Open-ocean Fish Farm. In Biran, A. Ed. Proceedings Offshore Technologies for Aquaculture. Haifa, Israel, 13-16 Oct. 1998.

Goulletquer, P., Soletchnik, P., Le Moine, O., Razet, D., Geairon, P., Faury, N. & Taillade, S. 1998. Summer mortality of the Pacific cupped oyster *Crassostrea gigas* in the Bay of Marennes-Oleron (France). International Council for the Exploration of the Sea Copenhagen (Denmark) Theme Session on Population Biology. ICES, Copenhagen, Denmark. 20 pp.

Goulletquer, P. & Le Moine, O. 2002. Shellfish farming and Coastal Zone Management (CZM) development in the Marennes-Oléron Bay and Charentais Sounds (Charente Maritime, France): A review of recent developments. Aquaculture International, 10(6): 507-525.

Guneroglu, A., Kose ,E., Eruz, C., Basar, E., Erkebay, S. & Karsli, F. 2005. Use Of Geographic Information System (GIS) To Select Fish Cage Farming Sites In Surmene Bay, Black Sea. *The Israeli Journal of Aquaculture* – Bamidgeh 57(2), 2005, 81-89.

Handisyde, N.L., Ross, L.G, Badjeck, M.-C. & Allison, E.H. 2006. The effects of climate change on world aquaculture. A global perspective. DFID, UK. (available at http://www.aquaculture.stir.ac.uk/GISAP/pdfs/Climate_full.pdf).

Hoagland, P., Kite-Powell, H. L. & Lin, D. 2003. Business Planning Handbook For The Ocean Aquaculture Of Blue Mussels. Marine Policy Center Woods Hole Oceanographic Institution, Woods Hole, Massachusetts, USA. 31 pp.

Hughes Clark, J.E., Wildish, D. & Duxfield, A. 2002. Acoustic imaging of salmonid mariculture sites. CHC 2002 Proceedings. 17 pp.

Inglis, G.J., Hayden, B.J. & Ross, A.H. 2000. An overview of factors affecting the carrying capacity of coastal embayments for mussel culture. NIWA Client Report: CHC00/69 Project No. MFE00505. National Institute of Water and Atmospheric Research Ltd Christchurch New Zealand. 31 pp.

Island Institute. 1999. The Maine Guide to Mussel Raft Culture. Island Institute, Rockland, Maine, USA. 32 pp.

Jacquet, J.-M. 1987. Remote sensing evaluation of water quality in the Gulf of Nicoya (Costa Rica). Annex 1. in Kapetsky, J.M. McGregor, L. and Nanne E., H. (1987). *A geographical information system and satellite remote sensing to plan for aquaculture development: a FAO-UNDP/GRID cooperative study in Costa Rica.* FAO Fisheries Technical Paper No. 287. Rome, FAO.

Janssen, R. & van Herwijnen, M. 2006. A toolbox for multiple criteria decision-making. *Int. J. Environmental Technology and Management*, 6 (1/2): 20-39.

Jefferson, W.H., Michener, W.K., Karinshak, D.A., Anderson, W., & Porter, D.E.1991. Developing data layers for estuarine resource management. Proceedings of GIS/LIS '91. Inforum, Atlanta, Georgia. 1: 331-342.

Johannessen, J.A., Johannessen, O.M. & Haugan, P.M. 1988. Remote sensing and model simulation studies of the Norwegian coastal current during the algal bloom in May 1988. The Nansen Remote Sensing Center. Technical Bulletin No. 16.

Jordan, S.J., Greenhawk, K.N. & Smith, G. F. 1995. Maryland oyster geographical information system: Management and scientific applications. *Journal of Shellfish Research* 14: 269.

Jordana, R. 2004. SIG–Pesca. Sistema deInformación Geográficade la Direcció General de Pesca i Afers Marítims. Lecture delivered at the CIHEAM Advanced Course on Offshore Mariculture, Zaragoza (Spain), 17-22 May 2004 (available at http://www.easonline.org/agenda/en/description.asp?id=264).

Kapetsky,J.M. 1989. A geographical information system for aquaculture development in Johor State. FAO Technical Cooperation Programme Project. Land and Water Use Planning for Aquaculture Development.TCP/MAL/6754. Field Document. FAO, Rome.

Kapetsky, J.M. 2004. Geographic information systems applications in aquaculture. In Fisher, W. L. and Rahel, F.J. eds. Geographic Information Systems in fisheries. pp. 13-48. American Fisheries Society, Bethesda, Maryland, USA. 275 pp.

Kapetsky, J.M. & Aguilar-Manjarrez, J. 2004. Geographical Information Systems in aquaculture development and management from 1985 to 2002: an assessment. *In* Nishida, T., Kailola, P. and Hollingworth, C. eds. GIS/Spatial analyses in fishery and aquatic sciences (Vol 2.) Proceedings of the Second International Symposium on GIS/Spatial analyses in fishery and aquatic sciences. pp. 393-404. Fishery-Aquatic GIS Research Group. Kawagoe, Saitama, Japan. 733 pp.

Kapetsky, J.M. & Caddy, J.F. 1985. Applications of remote sensing to fisheries and aquaculture. FAO Report of the 11th Session of the Advisory Committee on Marine Resources Research, Supplement. FAO, Rome. FAO Fisheries Report, (338) Suppl.:37-48.

Kapetsky, J.M. McGregor, L. & Nanne E, H. 1987. *A geographical information system and satellite remote sensing to plan for aquaculture development: a FAO-UNDP/GRID cooperative study in Costa Rica.* FAO Fisheries Technical Paper No. 287. Rome, FAO. 51 pp.

Kapetsky, J.M. & Nath, S.S. 1997. A strategic assessment of the potential for freshwater fish farming in Latin America. *COPESCAL Technical Paper*. No. 10. Rome, FAO. 128 pp. (also available at http://www.fao.org/DOCREP/005/W5268E/W5268E00.HTM).

Kite-Powell, H., Hoagland, P., Jin, D. & Murray. K. 2003. Open ocean grow-out of finfish in New England: A bioeconmic model. In Pages 319-324. C.J. Bridger and Costa-Pierce B.A, (eds.). Open Ocean Aquaculture: From Research to Commercial Reality. The World Aquaculture Society. Baton Rouge, Louisiana, USA.

Kona Blue Water Farms 2003. Final Environmental Assessment For An Offshore Open Ocean Fish Farm Project Off Unualoha Point, Kona, Hawaii. Prepared for Land Division, Land and Natural Resources, Hawaii. 110 pp.

Langan, R. & Horton, F. 2003. Design, operation and economics of submerged longline mussel culture in the open ocean. Bulletin of the Aquaculture Association of Canada. 103-3: 11-20.

Legault, J.A. 1992. Using a geographic information system to evaluate the effects of shellfish closures on shellfish leases, aquaculture and habitat availability. Canadian Technical Report of Fisheries and Aquatic Sciences 1882E:1-10.

Leung, P.S. 2006. Multiple-criteria decision-making (MCDM) applications in fishery management. *Int. J. Environmental Technology and Management*, 6 (1/2): 96-110.

Loubersac, L., Prou, J. , Kerdreux, M. & Le Moine, O. 1997. Geomatics for the management of oyster culture leases and production. CoastGIS'97. In: D. Green, and G.Massie editors. Proceedings of the Second International Symposium on GIS and Computer Mapping for Coastal Zone Management. University of Aberdeen, Scotland. Aug. 29-31, 1997.

Macias-Rivero, J.C., Castillo y Rey, F. & Zurita, C.A. 2003. Zonas idóneas para el desarrollo de la acuicultura en el litoral andaluz. Dirección General de Pesca y Acuicultura, Consejería de Agricultura y Pesca, Junta de Andalucía. 43 p. y mapas.

Malczewski, J. 1999. GIS and Multicriteria Decision Analysis, Wiley, New York.

Malczewski,J.2006. Integrating multiple-criteria analysis and geographic information systems: the ordered weighted averaging (OWA) approach. *Int. J. Environmental Technology and Management*, 6 (1/2): 7-19.

Marine Aquaculture Task Force. 2007. Sustainable marine aquaculture: Fulfilling the promise; managing the risk. Marine Aquaculture Task Force, Takoma Park, MD, USA. 128 pp. (available at http://www.pewtrusts.com/pdf/Sustainable_Marine_Aquaculture_final_1_07.pdf)

Marine Policy Center, Woods Hole Oceanographic Institute. 2003. Improving the Regulatory Framework for Marine Aquaculture Regional Planning and Economic Decision-making. NOAA National Marine Aquaculture Initiative Final Report (available at http://www.lib.noaa.gov/docaqua/nmaimages2001/finrepwhoi.htm).

Martinez-Cordero, F. & Leung, P.S. 2004. Multicriteria decision making (MCDM) model for regional sustainable shrimp farming development in northwest Mexico. *Aquaculture Economics and Management.* 8 (3/4): 179-192.

National Office for Harmful Algal Blooms, Woods Hole Oceanographic Institution,Woods Hole, Massachusetts, USA. 2006. (available at http://www.whoi.edu/redtide/index.html).

Meaden, G. J. 2004. Challenges of using geographic information systems in aquatic environments. *In* Fisher, W. L. and Rahel, F.J. eds. Geographic information systems in fisheries. pp. 13-48. American Fisheries Society, Bethesda, Maryland, USA. 275 pp.

Meaden, G.J. & Do Chi, T. 1996. *Geographical information systems: applications to marine fisheries*, FAO Fisheries Technical Paper No. 356. Rome, FAO. 335 pp. (also available at http://www.fao.org/docrep/003/W0615E/W0615E00.HTM).

Meaden, G.J. & Kapetsky, J.M. 1991. *Geographical information systems and remote sensing in inland fisheries and aquaculture.* FAO Fisheries Technical Paper *No.* 318. Rome, FAO. 262 pp. (also available at http://www.fao.org/DOCREP/003/T0446E/T0446E00.HTM).

Mooneyhan, W. 1985. Determining aquaculture development potential via remote sensing and spatial modelling. Applications of remote sensing to aquaculture and inland fisheries. Report of the ninth UN/FAO international training course in co-operation with the Government of Italy. FAO Rome RSC Series 27:217-247.

Muir, J., 2004, Offshore Mariculture System Options. Lecture delivered at the CIHEAM Advanced Course on Offshore Mariculture, Zaragoza (Spain), 17-22 May 2004 (available at http://www.easonline.org/agenda/en/description.asp?id=264).

National Geophysical Data Center. 2006. NOAA Satellite and Information Service (available at http://www.ngdc.noaa.gov/mgg/fliers/01mgg04.html).

National Oceanographic Data Center, NOAA. 2005. Pathfinder Version 5.0. Sea Surface Temperature Climatologies (available at ftp://data.nodc.noaa.gov/pub/data.nodc/pathfinder/Version5.0_Climatologies/README.txt).

National Oceanographic Data Center, NOAA. 2004. Climatologies for the Coral Atlas Project (available at ftp://data.nodc.noaa.gov/pub/data.nodc/pathfinder/CoralAtlas/Information_on_Climatologies.txt).

Nath,S. S., Bolte, J. P., Ross, L. G. & Aguilar-Manjarrez, J. 2000. Applications of Geographical Information Systems (GIS) for spatial decision support in aquaculture. *Aquaculture Engineering* 23:233–278.

Newell, C.R. 2001. Sustainable mussel culture: A millennial perspective. Bulletin of the Aquaculture Association of Canada. 101-2:15-21.

Newell, C.R. 2003. Shellfish aquaculture and carrying capacity. Report of a Task Force Meeting. Maine Department of Marine Resources. 5pp. (available at http://www.maine.gov/dmr/aquaculture/aqtaskforce/aqtfwalpole.htm).

Nishida, T., Kailola, P. & Holliingworth, C. eds. 2001. Proceedings of the First International Symposium on GIS in Fishery Science. Fishery-Aquatic GIS Research Group. Kawagoe, Saitama, Japan. 486 pp.

Nishida, T., Kailola, P. & Holliingworth, C. eds. 2004. GIS/Spatial analyses in fishery and aquatic sciences (Vol 2.) Proceedings of the Second International Symposium on GIS/Spatial Analyses in Fishery and Aquatic Sciences. Fishery-Aquatic GIS Research Group. Kawagoe, Saitama, Japan. 733 pp.

Nishida, T., Kailola, P. & Holliingworth, C. eds. (in press). Proceedings of the Third International Symposium on GIS in Fishery Science. Fishery-Aquatic GIS Research Group. Kawagoe, Saitama, Japan.

Office of Coast Survey. 2006. Exclusive Economic Zone. NOAA (available at http://nauticalcharts.noaa.gov/csdl/EEZ.HTM).

Pattison, D., dos Reis, D. & Hamilton, S. 2004. An inventory of GIS-Based Decision Support Tools for MPAs. Prepared by the National Marine Protected Areas Center in cooperation with the National Oceanic and Atmospheric Administration Coastal Services Center. 14 pp (available at http://www.mpa.gov).

Pavasovic, S. 2004. GIS-tool for site suitability analysis: Example of marine aquaculture. ECO-IMAGINE Virtual Permanent Conference (European Conferences and forum for Integrated Coastal Management and Geo-Information Research) / GI and GIS for ICM, Seville (Spain). (available at http://www.gisig.it/eco-imagine/VirtualPConference/siviglia-proceedings/pres entations.htm).

Pérez, O.M. 2003. GIS-based models for optimisation of marine cage aquaculture in Tenerife, Canary Islands. Institute of Aquaculture, University of Stirling, Scotland, UK. (Ph.D. Thesis).

Pérez, O.M., Muir, J.M. & Ross, L.G. 2000. Spatial modelling of aquaculture related development, poverty and needs issues (preliminary study). University Of Stirling. 42 pp. (available at http://www.aquaculture.stir.ac.uk/GISAP/gis-group/dfid.php).

Pérez, O.M., Ross, L.G., Telfer, T.C. & Beveridge, M.C. 2002. Geographical information systems (GIS) as a simple tool for modelling waste distribution under marine fish cages. Estuarine Coastal and Shelf Science 54:761-768.

Pérez, O.M., Telfer, T.C. & Ross, L.G. 2003a. On the calculation of wave climate for offshore cage culture site selection: a case study in Tenerife (Canary Islands). Aquacultural Engineering, 29: 1-21.

Pérez, O.M., Telfer, T.C. & Ross, L.G. 2003b. Use of GIS-Based Models for Integrating and Developing Marine Fish Cages within the Tourism Industry in Tenerife (Canary Islands). Coastal Management, 31:355–366.

Pérez, O.M., Telfer, T.C. & Ross, L.G. 2005. Geographical information systems-based models for offshore floating marine fish cage aquaculture site selection in Tenerife, Canary Islands. Aquaculture Research 36(10), 946-961.

Populus, J., Loubersac, L., Prou, J, Kerdreux, M. & Le Moine, O. 1997. Geomatics for the management of oyster culture leases and production. CoastGIS'97. In: D. Green, and Massie, G. eds. Proceedings of the Second International Symposium on GIS and Computer Mapping for Coastal Zone Management. University of Aberdeen, Scotland. Aug. 29-31, 1997.

Rodriguez-Benito, C., Haag, C. & Alvial, A. 2004. Implementation of new technologies to monitor phytoplankton blooms in the south of Chile. Proceedings of the MERIS User Workshop, Frascati, Italy, 10 – 13 November 2003 (ESA SP-549, May 2004).

Ross, L.G., 1998. The use of Geographical Information Systems in Aquaculture: A Review. Paper presented at I Congreso Nacional de Limnología, Michoacán, México. November 1998.

Ross, L.G., Mendoza, E.A.Q. & Beveridge, M.C. 1993. The application of geographical information systems to site selection for coastal aquaculture: an example based on salmonid cage culture. Aquaculture 112:165-178.

Ryan, J. 2004. Farming the deep blue. Bord Iasscaigh Mhara and Irish Marine Institute. Ireland. 67 pp.

Saaty, T.L. 1980. The Analytic Hierarchy Process. McGraw-Hill, New York.

Saaty, T.L. 2006. Fundamentals of the analytic network process — Dependence and feedback in decision-making with a single network. *Journal of Systems Science and Systems Engineering.* Publisher Systems Engineering Society of China, co-published with Springer-Verlag GmbH. 13 (2): 129-157.

Salam, A. Md. 2000. GIS modelling of coastal aquaculture development in Khulna district, Sunderbans, Bangladesh. Institute of Aquaculture, University of Stirling, Scotland, UK. p400. (Ph.D. Thesis).

Saxby, S.A. 2002. A review of food availability, sea water characteristics and bivalve growth performance at coastal culture sites in temperate and warm temperate regions of the world. Department of Fisheries, Government of Western Australia. Fisheries Research Report 132. 43 pp.

Scott, P.C. 2004. Aquaculture development interactions in Sepetiba Bay, Rio de Janeiro, Brazil. A GIS study.Institute of Aquaculture, University of Stirling, Scotland, UK. (Ph.D. Thesis).

Scott, P.C. & Ross, L.G. 1998. O potencial da mitilicultura na Baía de Sepetiba. Panorama da Aquicultura 8(49):13-19.

Scott, P.C., Vianna, L.F. & de C. Mathias, M.A., 2002. Diagnostico da cadeia aquicola para o desenvolvimento da atividade no Estado do Rio de Janeiro. Panorama da Aquicultura 12(71):15-25.

Scottish Executive 2000. Final Report of the Joint Government/Industry Working Group on Infectious Salmon Anaemia (ISA) in Scotland. Scottish Executive, Aberdeen, Scotland. 142 pp.

Scottish Salmon Producers' Organization. 2005. Code of Good Practice for Scottish Finfish Aquaculture (available at http://www.scottishsalmon.co.uk/aboutus/codes.asp).

Servicio de Pesca y Acuicultura. 2000. Acuicultura marina en la región de Murcia: Identificación de zonas aptas para el cultivo. Dirección General de Ganadería y Pesca, Consejería de Agricultura, Acuicultura y Medio Ambiente, Región de Murcia. Cartagena, España. 35p. + mapas.

Sylvia, G. & Anderson, J.L. 1993. An economic policy model for net-pen salmon farming. In: Hatch, U., Kinnnucn, H. (Eds.) Aquaculture: Models and Economics, Westview Press, Boulder, pp. 17-38.

Simpson, J.J. 1994. Remote sensing in fisheries: A tool for better management in the utilization of a renewable resource. *Canadian Journal of Fisheries and Aquatic Sciences* 51: 743-771.

Smith, G.F., Bruce, E.B. & Roach, D.G. 2001. Remote acoustic habitat assessment techniques used to characterize the quality and extent of oyster bottom in the Chesapeake Bay. Marine Geodesy, 24(3): 171-189.

Smith. G.F. & Greenhawk, K.N. 1996. Morphological differentiation of the fringing and patch oyster reef types in Chesapeake Bay: A comparative evaluation. *Journal of Shellfish Research* 15: 522.

Smith, G.F., Greenhawk, K.N. & Homer, M.L. 1997. Chesapeake Bay oyster reef - An examination of resource loss due to sedimentation. *Journal of Shellfish Research* 16:275.

Smith, G.F., Greenhawk, K.N., Bruce, E.B., Roach, D.G. & Jordan, S.J. 2001. A digital presentation of the Maryland oyster habitat and associated bottom types in the Chesapeake Bay (1974-1983). *Journal of Shellfish Research*, 20(1): 197-206.

Smith, G.F. & Jordan, S.J. 1993. Utilization of a geographical information system (GIS) for the timely monitoring of oyster population and disease parameters in Maryland's Chesapeake Bay. *Journal of Shellfish Research* 12: 130.

Smith, G.F., Jordan, S.J. & Greenhawk, K.N. 1994. An oyster management information system: Integrating biological, physical, and geographical dimensions. *Journal of Shellfish Research* 13:284.

Smith, G.F., Roach, D.G. & Bruce, E.B. 2002. The location, composition, and origin of oyster bars in mesohaline Chesapeake Bay. Estuarine, Coastal and Shelf Science 56: 391-409.

Soletchnik, P., Le Moine, O., Faury, N., Razet, D., Geairon, P., & Goulletquer, P. 1999. Summer mortality of the oyster in the Bay Marennes-Oleron: Spatial variability of environment and biology using a geographical information system (GIS). *Aquatic Living Resources Ressources Vivantes Aquatique* 12:131-143.

Soares de Souza, E.F. 2003. FAO Technical Cooperation Programme Project. Small-scale seaweed farming in Northeast Brazil. TCP/BRA/0065. Field Document. FAO, Rome.

Stickney, R.R., Costa-Pierce, B., Baltz, D.M., Drawbridge, M., Grimes, C., Phillips, S. & Swann, D.L. 2006. Toward sustainable open ocean aquaculture in the United States of America. *Fisheries* 31(12): 607-610.

Subasinghe, R.P., Bueno, P., Phillips, M.J., Hough, C., McGladdery, S.E. & Arthur, J.E. (eds.) 2000. Aquaculture in the Third Millennium - Technical Proceedings of the Conference on Aquaculture in the Third Millennium, Bangkok, Thailand. 20-25 February 2000. NACA, Bangkok and FAO, Rome. 471pp. (also available at http://www.fao.org/fi/meetings/aq2000/tech_proc/third_mill.asp).

Taconet, M. & Bensch, A. 2000. Towards the use of Geographic Information Systems as a decision support tool for the management of Mediterranean fisheries. COPEMED. GCP/REM/057/SPA. Informes y Estudios No. 4. (pages not numbered).

Tiensongrussmee, B. Pontjoprawiro, S. & Mintarjo, K. 1988. Seafarming resources map. Seafarming Development Project, INS/81/008/Manual/7. FAO, Jarkata, Indonesia. 109 pp.

Travaglia, C. & Appelkamp, C. 1985. Applications of Remote Sensing to Aquaculture and Inland Fisheries. Ninth UN/FAO International Training Course in Co-operation with the Government of Italy. Rome, Italy, 10-28 September 1984. RSC SER., No. 27. Rome, FAO. 301 pp.

Travaglia, C., Profeti, G., Aguilar-Manjarrez, J. & Lopez, N. A. 2004. *Mapping Coastal Aquaculture and Fisheries Structures by Satellite Imaging Radar: Case Study of the Lingayen Gulf, the Philippines*. FAO Fisheries Technical Paper. No. 459. Rome, FAO. 45 pp. (also available at http://www.fao.org/docrep/007/y5319e/y5319e00.htm).

Valvanis, V.D. 2002. Geographic Information Systems in Oceanography and Fisheries. Taylor and Francis, London.

van der Woerd, H.J., Blauw, A., Pasterkamp, R., Tatman, S., Laanem, S. & Peperzak, L. 2005. Integrated spatial and spectral characterization of harmful algal blooms in Dutch coastal waters. Report 05/09. Institute for Environmental Studies, Amsterdam, The Netherlands. 59 pp.

Vincenzi S., Caramori, G., Rossi, R. & De Leo, G.A. 2006. A GIS-based habitat suitability model for commercial yield estimation of *Tapes philippinarum* in a Mediterranean coastal lagoon (Sacca di Goro, Italy). *Ecological Modelling* 193 (2006) 90–104.

Vincenzi S., Caramori, G., Rossi, R. & De Leo, G.A. (in press). Estimating clam yield potential in the Sacca di Goro lagoon (Italy) by using a two-part conditional model. Aquaculture.

Vincenzi S., Caramori, G., Rossi, R. & De Leo, G.A. (in prep). Implications of three habitat 1suitability models for commercial yield estimation of *Tapes philippinarum* in a North Adriatic coastal lagoon (Sacca di Goro, Italy).

Ueng, Ping-Sheng, Yu, Shyi-Liang, Tzeng, Jiann-Jang, & Ou, Ching-Hsiewn. 2001. The effect of water temperature on growth rate of cobia *Rachycentron canadum* in Penghu, Taiwan. 6th Asian Fisheries Forum Book of Abstracts. 252 pp.

Wright, D.J., ed. 2002. Undersea with GIS. ESRI Press, Redlands, California, USA. 253 pp.

Wright, D.J. & Bartlett, D.J., Eds. 2000, Marine and Coastal Geographical Information Systems, Research Monographs in Geographical Information Science, Taylor and Francis, London. 320 pp.

Young, L., Helsley, C. , Ummoto, K., Merrifield, M., Tasaka, C., Kaiokamale, L., Takahashi, K., Pichaya, V. & Shen, C. 2003. Aquaculture site identification in Hawaii using GIS. *INFOFISH International* (6): 13-16.

The objective of this document is to illustrate the ways in which Geographic Information Systems (GIS), remote sensing and mapping can play a role in the development and management of marine aquaculture. 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 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.

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. A case study is included that illustrates how freely downloadable data can be used to estimate marine aquaculture potential. Because the ultimate purpose of GIS is to aid decision-making, a section on decision support tools is included.

ISBN 978-92-5-105646-2 ISSN 0429-9345

9 789251 056462

TC/M/A0906E/1/02.07/2050