

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

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8.1 INTRODUCTION

Aquaculture is a very broad endeavour when considered by environment, techniques, administration and economics, i.e. just to mention a few of its many facets. For example, aquaculture statistics are compiled by FAO by production and value, by environment (marine, brackish water, freshwater), by organisms cultured including fishes, shellfishes, reptiles, amphibians and plants (scientific and common names), and geographically by nation and continent. Additionally, aquaculture cannot be considered as an activity unto itself. For example, it is often associated with fisheries not only in terms of the species that are both fished and cultured, but more closely in terms of fisheries that are aquaculture dependent for most of their stock, i.e. historically a variety of salmon and trout species.

The rapid growth of aquaculture, already referred to in Chapter 1, has brought with it a great variety of environmental, social and economic issues. It is important to note that issues in aquaculture have two main sources: those stemming from aquaculture itself and those that affect aquaculture owing to external activities or events. No matter what the origin, each of these issues possess a number of components that vary by location and, therefore, can be addressed by spatial analyses. In this regard, GIS and remote sensing have been used to address the “what, where and how?” of aquaculture production activities since the early 1980s, but there is now considerable impetus to use spatial analyses to expand coverage of issues to “for whom, and with what social, environmental and economic consequences?” as obligatory, additional questions to be investigated in conjunction with the development and management of aquaculture.

The main thrust of this chapter is to provide measures of the status of GIS as it is employed to address spatial issues in the development and management of aquaculture. Because remote sensing and mapping are very closely associated with GIS, they are implicitly included when reference is made to GIS herein. This chapter covers GIS applications to aquaculture in a general way, i.e. as there is easy access to the details of the applications themselves, or to the abstracts of them, through FAO’s GISFish portal.¹⁹⁰ The breadth of GIS applications is measured in relation to the spatial issues being addressed and by the geographic distribution of applications. Several approaches are taken for this purpose. The first approach summarizes recent reviews of GIS applications in aquaculture followed by an account of the main spatial issues being addressed, i.e. based on the GISFish aquaculture database. A second approach, closely associated with the first, summarizes the status of GIS applications to aquaculture in terms of the geographic distribution of the applications based records in the GISFish aquaculture database and on the Aquatic Sciences and Fisheries Abstracts (ASFA). The final approach illustrates, via selected in-depth case studies, a range of applications and their associated issues.

¹⁹⁰ GISFish: www.fao.org/fishery/gisfish.

8.2 RECENT REVIEWS DEALING WITH SPATIAL ISSUES IN AQUACULTURE

The spatial issues in aquaculture to which GIS has been applied can be classified as: (i) development of aquaculture; (ii) aquaculture practice and management; (iii) training and the promotion of GIS; and (iv) multisectoral development and management that includes aquaculture. Each of these main categories has subcategories of issues associated with them, and GISFish provides a continuously updated count on the numbers of applications relating to each of the sub-issues (Table 8.1).

TABLE 8.1

Number and percent of main issues and sub-issues addressed among 391 GIS applications to aquaculture in the GISFish database (1985–2012)

Issue	Number	Percent
Development of aquaculture	209	53
Suitability of site and zoning	111	28
Strategic planning for development	79	20
Anticipating the consequences of aquaculture	15	4
Economics	4	1
Aquaculture practice and management	124	32
Inventory and monitoring of aquaculture and the environment	83	21
Environmental impacts of aquaculture	27	7
Restoration of aquaculture habitats	8	2
Web-based aquaculture information system	6	2
Training and the promotion of GIS	32	8
Training	9	2
Promotion	23	6
Multisectoral development and management that includes aquaculture	26	7
Management of aquaculture together with fisheries	9	2
Planning for aquaculture among other uses of land and water	17	4
Total	391	

Note: The "Web-based aquaculture information system" sub-issue could be a sub-issue of any of the main issue headings. However, most of the applications using Web-based information were focused on aquaculture practice and management per se.

Source: FAO (2012d).

The earliest reviews of GIS applications in aquaculture were conducted by Meaden (2001), Kapetsky (2004) and Kapetsky and Aguilar-Manjarrez (2004), with the latter covering the time period from 1985 (when such GIS applications first appeared) to 2002. Reviews of spatially related issues of GIS applications in aquaculture have been made in several contexts. Mapping, remote sensing and GIS applications applied to marine aquaculture, organized by the main spatial issues listed in Table 8.1, were covered by Kapetsky and Aguilar-Manjarrez (2007) with example applications being described. GIS applications and their related issues as described by Kapetsky and Aguilar-Manjarrez (op. cit.) were separately tabulated according to those pertaining to finfish cage culture (13 applications) and to shellfish culture (24 applications). By handling mapping, remote sensing and GIS applications separately, the important role of each in spatial analysis for development and management of aquaculture was emphasized.

More recently, the status of GIS, remote sensing and mapping applications in aquaculture was reviewed from an ecosystems viewpoint by Kapetsky, Aguilar-Manjarrez and Soto (2010). The purpose of the review was to gauge the spatial analytical experience that could be brought to bear on the ecosystem approach to aquaculture (EAA) and to draw attention to technical and geographic gaps. The indicators used to evaluate spatial experience were the number of applications associated with each spatial issue (identical to those in Table 8.1), the kinds of ecosystems being studied by the applications, or in which they were carried out (e.g. ponds, river basins) and the

scales encompassed by the applications (local to global) in the three main environments of brackish water, inland and marine. Regarding the issues addressed, it was concluded that GIS applications in the development of aquaculture and the aquaculture practice and management domains were fairly common, but that the economics sub-issue was rarely addressed. Also, applications in the main issue of multisectoral planning and management were infrequent, possibly reflecting the poor integration of aquaculture into land and water use planning. An important gap was found in the lack of experience in dealing spatially with the social and economic components of ecosystems. It was emphasized that promotion and training are issues aimed at increasing the capacity to use spatial tools, particularly with the purpose of more broadly promoting and propagating the spatial awareness that goes beyond the usual technical scope of training. Regarding the spatial scales that GIS addressed, it was recognized that, although GIS has the built-in capability to accommodate any scale, most of the applications in all three environments were carried out at the large scale, i.e. in relatively small areas, corresponding to local activities or to farm and aquaculture zone scales in EAA terms.

8.2.1 The development of aquaculture

Altogether, GIS aimed at development of aquaculture accounted for more than 50 percent of all applications, and the sub-issues most frequently addressed were: (i) suitability of the site and zoning and (ii) strategic planning for development (Table 8.1). GIS applications in this main issue category are carried out as a prelude to aquaculture development. Recent new thinking (Kapetsky and Aguilar-Manjarrez, 2013) conceives of aquaculture potential, zoning and siting, together with an estimation of carrying capacity, as development activities that follow a temporal and spatial hierarchical progression beginning with estimating potential and ending with siting (Table 8.2). In terms of spatial scope and the number of factors considered, estimating aquaculture potential has the broadest reach, but it includes only the more general factors. Zoning is intermediate, and site selection is the narrowest in spatial scope. Carrying capacity estimation has to be considered at all stages of development and management. Estimating potential, zoning and siting will need to be repeated as culture systems are developed for new species or as culture systems are modified for species already under culture.

The siting and zoning sub-issues of Table 8.1 relate directly to the concepts of Table 8.2. The sub-issue of “Strategic planning for development” closely corresponds to estimating the potential for aquaculture. Likewise, the sub-issues “Anticipating the consequences of aquaculture” and “Economics” relate to carrying capacity when carrying capacity is broadly interpreted in environmental, social and economic terms. The low number of applications addressing the economics sub-issue calls attention to a very serious gap when it is considered that all development activities in the commercial sector are driven by economics, including many of those that are government subsidized.

An example of estimating potential at the global level is the spatial analysis of offshore mariculture potential by Kapetsky, Aguilar-Manjarrez and Jenness (2013). The main objective was to assess the potential for the expansion of mariculture from present nearshore locations to offshore areas. An underlying objective was to identify countries with no mariculture but that appear to have high offshore mariculture potential. The study was comprehensive of all maritime nations and the results were comparable among them. The analytical approach located and spatially integrated those environmental factors that are essential to sustain offshore mariculture: (i) areas in which it is technically and economically feasible to place culture installations; (ii) areas that promote fast growth of fish and molluscs; and (iii) locations that minimize competing and conflicting uses while taking advantage of possible complementary uses of adjacent space. The culture systems were sea cages and longlines and the corresponding

TABLE 8.2
Sequential steps for the development of aquaculture

Steps	Estimating potential	Zoning	Siting	Estimating carrying capacity
Main purpose	Plan strategically for development and eventual management	Regulate development; minimize competing and conflicting uses; maximize complementary uses of land and water	Reduce risk; optimize production	Sustain culture; protect environment/ecosystem
Spatial scope: administration	Global to national	Levels 1 and 2 subnational	Farm or farm clusters	Farm or farm clusters
Spatial scope: ecosystems	Main environments (freshwater, brackish, marine)	Ecosystem	Portion of ecosystem	Aquaculture ecosystem
Ecosystem approach to aquaculture (EAA) scale	Global	Watershed or waterbody	Farm	Farm to watershed or waterbody
Executing entity	Organizations operating globally; national aquaculture departments	National, state/provincial/ municipal governments with aquaculture responsibilities	Commercial entities	Regulating agencies
Data needs	Basic, relating to technical and economic feasibility, growth and other uses	Basic environmental, social and economic sets	All available	Data to drive models
Resolution	Low	Moderate	High	High
Results obtained	Broad, indicative	Directed, moderately detailed	Specific, fully detailed	Moderately to fully detailed

Source: Kapetsky and Aguilar-Manjarrez (2013).

technical criteria were depth and current speed. The economic criterion considered the area within 25 nautical miles of a harbour, and implicitly took into account time and travel costs between an onshore support facility and an offshore grow-out installation having reliable access to the sea. Three species were used to indicate potential: cobia (*Rachycentron canadum*), Atlantic salmon (*Salmo salar*) and blue mussel (*Mytilus edulis*). Additionally, areas for integrated multitrophic aquaculture (IMTA)¹⁹¹ of Atlantic salmon and blue mussel were located. These species were selected as indicative of offshore mariculture potential because of their commercial importance and well-established culture practices. Also, the two fish species represent “fed” aquaculture while the mussel is an example of “extractive” culture. Taken together, the production of these species spans all the climate zones in which mariculture is currently practised. Areas favourable for growout of all three species were identified using temperature ranges from mariculture research and practice, and chlorophyll-*a*

¹⁹¹ For a detailed description of integrated multitrophic aquaculture, see Soto (2009).

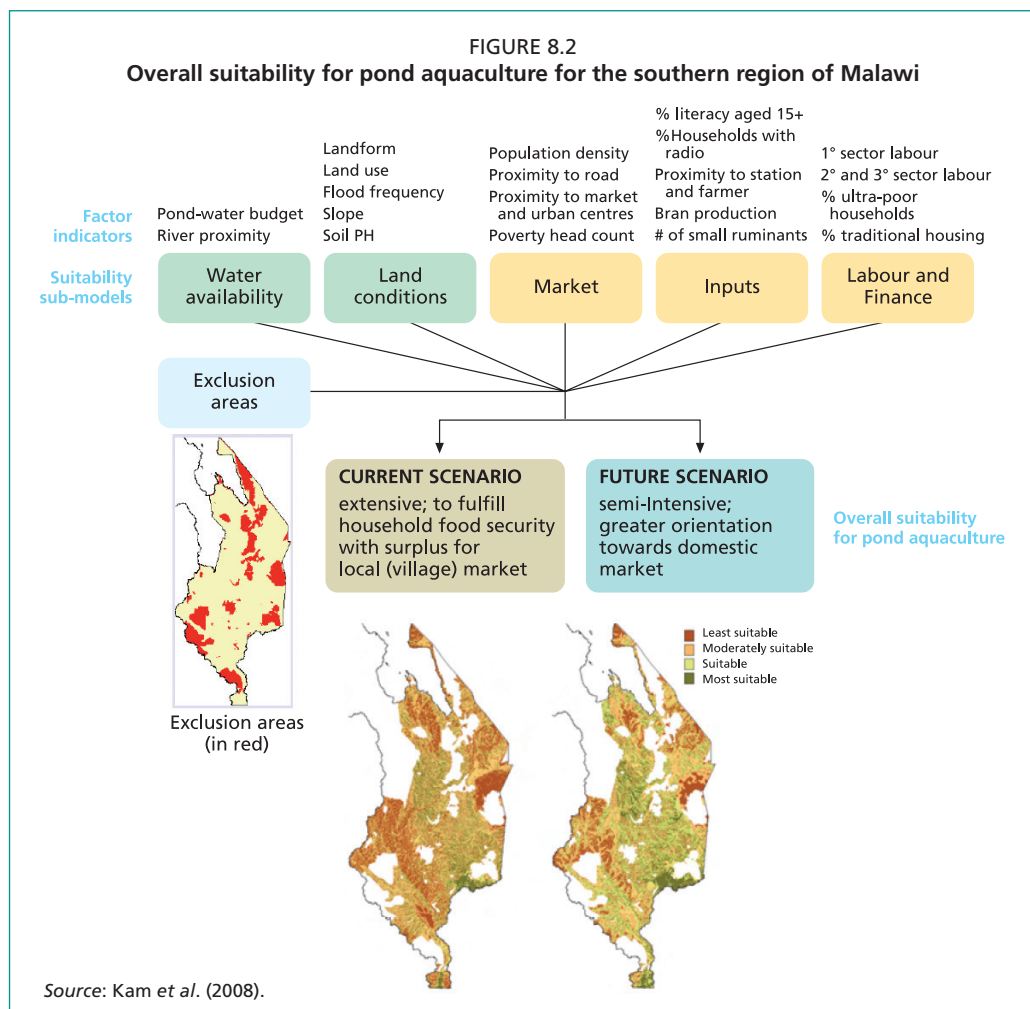
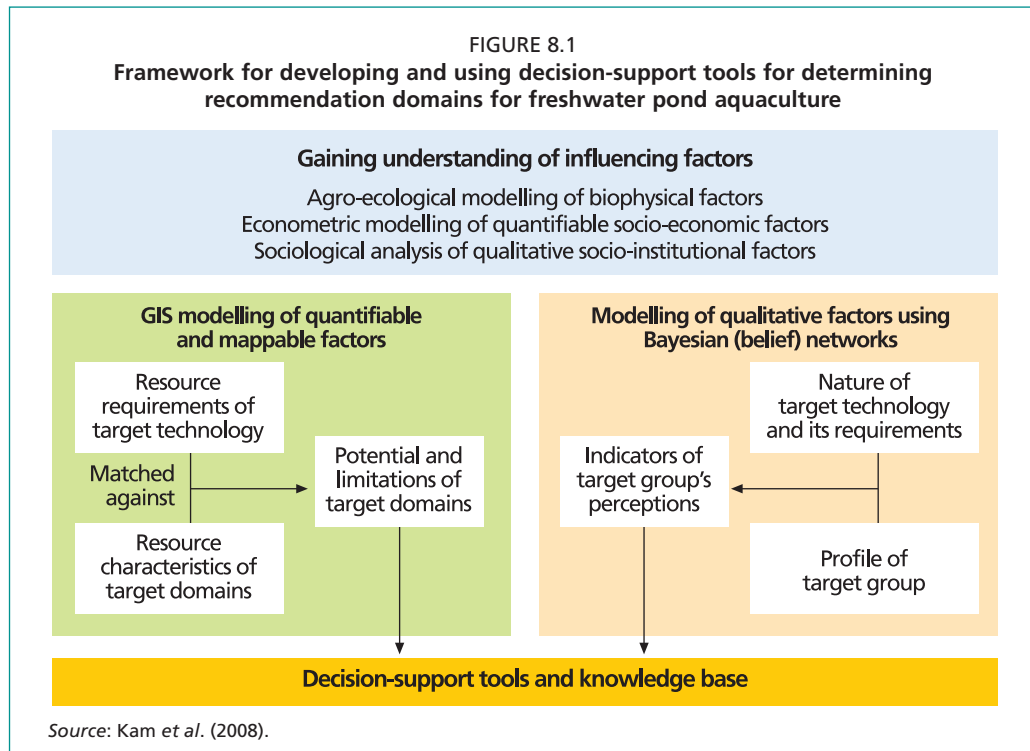
concentrations were also used to indicate areas with adequate food availability for the mussel. Marine protected areas (MPAs) were used in the modelling process to draw attention to competing, conflicting and complimentary uses. MPAs vis-à-vis mariculture may fall into any of these use categories. MPAs provide a relevant illustration of uses of marine space other than for mariculture because of their global coverage in international and national waters. Mariculture potential was estimated in terms of the surface areas meeting the criteria for successful fish production. The results indicated that there is much unrealized mariculture potential both among nations already practising mariculture and among those yet to develop it.

Another example of a study with a global reach is an assessment of the vulnerability of aquaculture-related livelihoods to climate change (Handisyde *et al.*, 2006). The study used a range of national scale and higher-resolution raster data in combination with a hierarchical modelling approach to assess the climate-induced vulnerability of aquaculture-related livelihoods. The assumption was that vulnerability is a function of sensitivity to climate change, exposure to climate change and adaptive capacity. In total, eight different assessments of vulnerability were produced at the country level: (i) general vulnerability; (ii) vulnerability in terms of food security; (iii) vulnerability based on economic importance of aquaculture; (iv) vulnerability with emphasis on adaptive capacity; (v) vulnerability of freshwater aquaculture to inland flooding; (vi) vulnerability of freshwater aquaculture to drought; (vii) vulnerability of brackish-water aquaculture to cyclones; and (viii) vulnerability of mariculture to cyclones. GIS was used to highlight areas where livelihoods are most likely to be affected. Rather than aiming for a single final output, a range of models was produced with the objective of addressing production in freshwater, brackish and marine environments in relation to a number of potentially changing climate trends and extremes. Results pointed to high vulnerabilities among countries in Asia where most of aquaculture production takes place. A follow-up study with methodological improvements is under way.

An example of estimating potential for aquaculture at the national level is the four-country research project (detailed in Kam *et al.*, 2008) to determine recommendation domains¹⁹² for promoting the development of freshwater pond aquaculture aimed at improving household food security and the livelihoods of smallholder farmers. The results of this work have been summarized as a case study by Kapetsky, Aguilar-Manjarrez and Soto (2010). The research project adopted an analytical framework, as depicted in Figure 8.1, that integrates the various multidisciplinary components into a knowledge-based analytical and decision-support system to provide an informed basis for recommending particular aquaculture practices and technologies. The framework served as the basis for using the GIS and Bayesian network¹⁹³ modelling techniques developed by the project to analyse the data collected on the quantitative and qualitative influencing factors. The combination of the GIS and Bayesian network tools identify places and sets of conditions for which a particular target aquaculture technology is considered feasible and advantageous to promote, while also identifying the nature of constraints to aquaculture development and thereby shedding light on appropriate interventions to realize the potential of the target areas (Figure 8.2).

¹⁹² Recommendation domains are places having sets of conditions for which a particular target aquaculture technology is considered feasible and therefore advantageous to support.

¹⁹³ Many factors that determine whether a particular aquaculture technology is sustainably adopted – particularly social, cultural and institutional factors – are not readily quantifiable, let alone mapped. In many situations, these “soft” factors have an overriding influence on technology adoption yet are excluded from GIS analysis and modelling. GIS modelling was therefore complemented in the project with another set of modelling tools based on Bayesian networks, which can incorporate factors of a qualitative nature that influence farmers’ perceptions about a particular aquaculture technology (for detailed information, see Kam *et al.* (2008) at www.worldfishcenter.org/resource_centre/WF_1047.pdf).



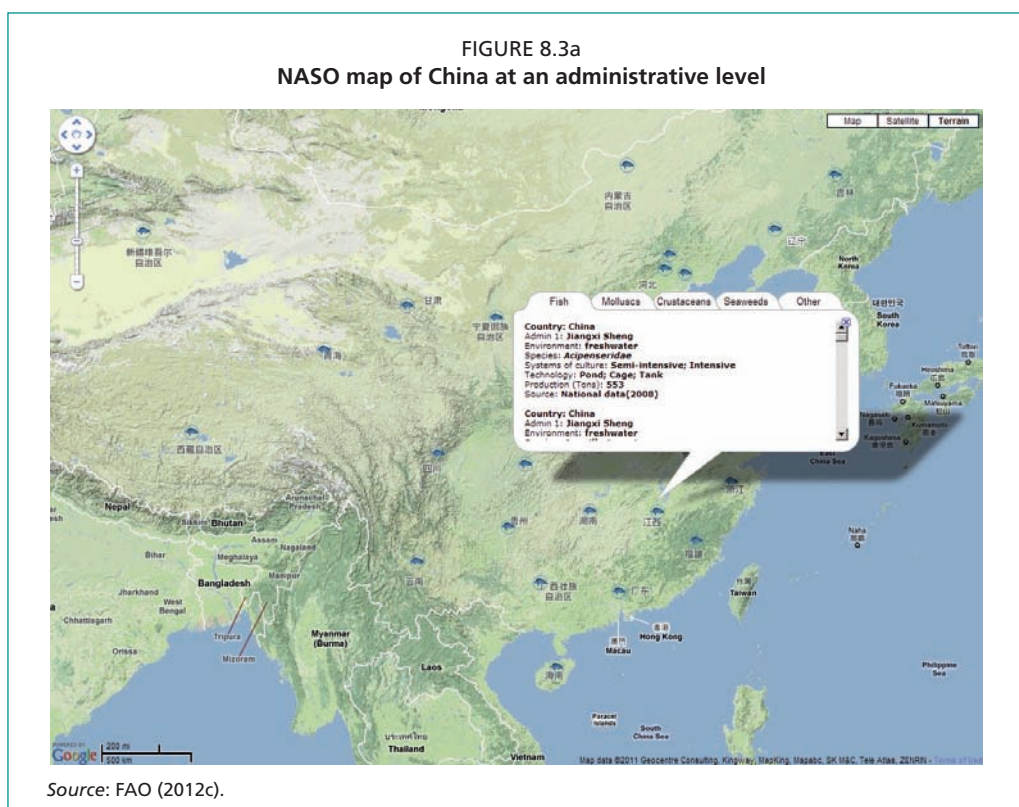
Note: How the "suitability submodels" are derived and modelled so as to arrive at both a current scenario and a future scenario are described in detail in Kam et al. (2008).

8.2.2 Aquaculture practice and management

Applications of GIS aimed at aquaculture practice and management accounted for about one-third of the total applications in GISFish, and “inventory and monitoring of aquaculture and the environment” was the most frequently addressed sub-issue (Table 8.1).

An inventory assessment of existing aquaculture facilities in an area is an indispensable component for the management and regulation of aquaculture and for its further spatial expansion, and the periodic monitoring of land-use developments is essential where aquaculture and other development activities are occurring at a rapid rate. Both inventory and monitoring activities are required in order to address the other sub-issues of “environmental impacts of aquaculture” and “restoration of aquaculture habitats”. Inexpensive opportunities for inventory and monitoring have been greatly advanced by relatively high-resolution imagery from earth browsers such as Google Earth. FAO’s FIRA has created a Web site, the National Aquaculture Sector Overview (NASO) map collection¹⁹⁴, which is a collection of Google maps for a selection of countries showing the location of existing aquaculture sites and their characteristics mainly at an administrative level (state, province, district) and in some cases at an individual farm level depending on the degree of aquaculture development.

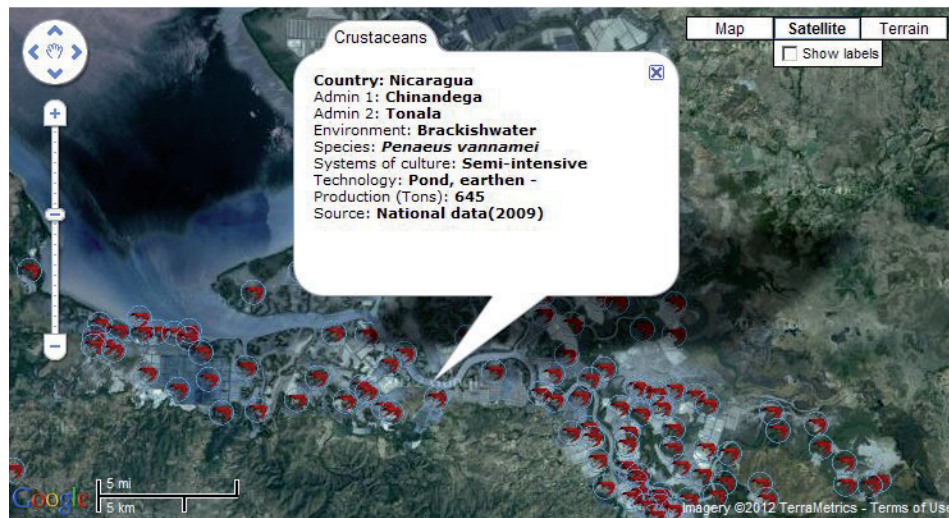
Aquaculture data for the NASO maps is collected using a Microsoft Excel submission form. The completed forms, once validated by FAO, are then used to create the NASO maps. The form allows for rapid data entry from compilers and easy data retrieval by users, and maps are accessible online through a browse map page or through a “Search by Country” page; an “Advanced Search” is also available. The NASO map collection currently consists of maps for 18 countries and new maps are added as they become available. The collection is important because it places aquaculture in a spatial domain that is easily accessible to nearly everyone, and it is a development that could have huge positive effects on the flow of reliable statistics and information about aquaculture for its improved development and management. The



¹⁹⁴ National Aquaculture Sector Overview (NASO) map collection: www.fao.org/fishery/naso-maps/naso-home/en.

NASO collection is in its early stages, but it clearly provides potential for monitoring the status and trends of aquaculture development, addressing site selection and zoning issues, and improving the operational management of aquaculture. The NASO map for the People's Republic of China is illustrated in Figure 8.3a. The map illustrates information that has been aggregated at an administrative level. Figure 8.3b illustrates a NASO map for the Republic of Nicaragua at an individual farm level showing the locations of shrimp ponds.

FIGURE 8.3b
NASO map for part of Nicaragua at an individual farm level



Note: Icons presented in red colour represent individual shrimp farms.

Source: FAO (2012c).

Fish farming cages are also clearly visible through Google Earth's satellite images (Figure 8.4). University of British Columbia, Canada, researchers have used them to estimate the amount of fish being cultivated in the Mediterranean. In the Mediterranean Sea, ocean fish farming is prevalent, and using satellite imagery available through Google Earth, stationary cages can be seen off the coasts of 16 countries. Using this tool, the University of British Columbia researchers demonstrated that a few trained scientists now have the capacity to ground truth farmed fish production data reported by the Mediterranean countries. With Google Earth, they could examine 91 percent of the Mediterranean coast and counted 248 tuna cages (circular cages 0.40 m diameter) and 20 976 other fish cages within 10 km of the shore, the majority of which were off the Hellenic Republic (49 percent) and the Republic of Turkey (31 percent). Combining satellite imagery with assumptions about cage volume, fish density, harvest rates and seasonal capacity, they made a conservative approximation of ocean-farmed finfish production for 16 Mediterranean countries. Their overall estimate of 225 736 tonnes of farmed finfish (not including tuna) in the Mediterranean Sea in 2006 is only slightly more than the FAO reports. The results demonstrate the reliability of recent FAO farmed fish production statistics for the Mediterranean as well as the promise of Google Earth to collect and ground truth data (Trujillo, Piroddi and Jacquet, 2012).

Environmental impacts of aquaculture have many facets as spatial issues. One of them is the public perception of the consequences of aquaculture development. Another spatial issue is the environmental impact of one or many aquaculture installations on other land or water users in the same area. An example is an environmental impact

FIGURE 8.4
Example image from Google Earth showing a fish farm off the coast of Greece



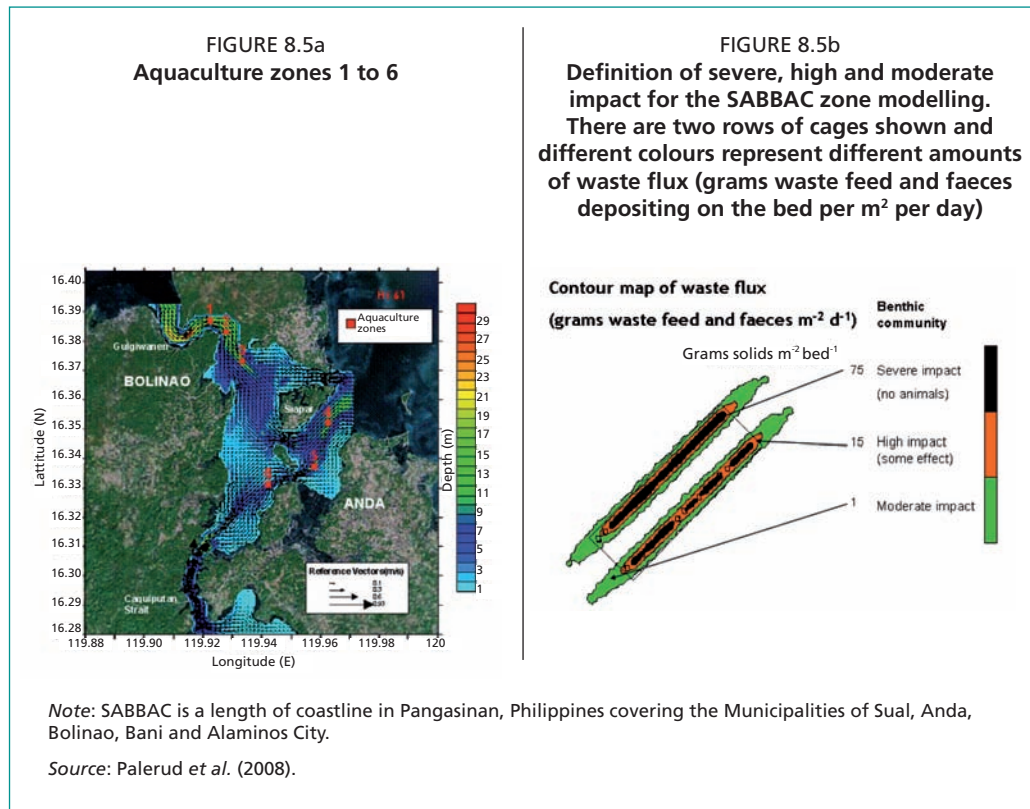
Note: Location: 38°19'19.21"N; 24° 3'14.33"E

Source: Image © 2012 DigitalGlobe, © 2012 Google

assessment project conducted in the Republic of the Philippines in Bolinao Bay to increase the organization and representation of farmers so that “clusters” of farms could be effectively monitored and managed, thus helping to avoid the classic boom and bust cycle prevalent in small-scale aquaculture. This project, based on work by Palerud *et al.* (2008), Legovic *et al.* (2008) and White (2009), has also been encapsulated as a case study in Kapetsky, Aguilar-Manjarrez and Soto (2010). The fundamental problem addressed by this project was that there was little planning, management and control of aquaculture development in Bolinao Bay. The solution involved a range of activities including GIS use and an assessment of carrying capacity, plus zoning along with the development of zone committees, cluster-level environmental assessment and monitoring, training/awareness, capacity building and institutional strengthening. The environmental impact assessment was addressed by proposing three types of surveys for monitoring the impact of aquaculture, i.e. low cost through intermediate to fully scientific surveys that differed in terms of cost, complexity and accuracy, but all of which might give a good indication of the level of aquaculture impact. Using a depositional model TROPOMOD¹⁹⁵, two and three rows of cages were tested and compared for each of the six aquaculture zones (Figure 8.5a). The area of high and severe impact was found to occupy the majority of the zone area and little room was available between rows for remediation of impacts (Figure 8.5b). Thus, in all aquaculture zones except zone 4, two rows of 18 cages were found to be optimum. As larger cages were present in zone 4, two rows of 12 cages were recommended.

From a GIS viewpoint, this study shows how a number of models can be coupled with GIS to identify zones, estimate the maximum number of cages in a zone, estimate the minimum distance between zones, and undertake scenario testing to identify management options for minimizing the impact of aquaculture.

¹⁹⁵ TROPOMOD is a particle tracking model used for predicting output, movement and deposition of particulate waste material (with resuspension) and the associated benthic impact of fish farms.



Regarding the Web-based aquaculture information system sub-issue of “aquaculture practice and management” (Table 8.1), traditionally inventories of aquaculture facilities have been confined to production installations. However, for a holistic understanding of the industry and for planning for development and regulation, all of the commercial components of aquaculture require inventories and monitoring, including transporting, processing and marketing facilities as well as seed production. One specific need for a Web-based aquaculture information system is for the comprehensive identification and characterization of existing production areas and individual sites in order to track production from the producer through the chain of processing, transporting and marketing to the consumer. More generally, all of these components need to be spatially placed in their respective administrative jurisdictions, as well as in their social, economic and ecological contexts. Additionally, aquaculture support services, whether commercial or governmental, need to be accounted for spatially in terms of their areas of operations and specific services so that delivery of services and feedback are rapid and are properly channelled. These functions are within the domain of an “Aquaculture Management Information System”, of which a Web-based GIS could be the backbone. FAO currently has a Technical Cooperation Programme project under way in the Kingdom of Thailand that encompasses a number of these functions (Aguilar-Manjarrez and Miao, 2011), and AkvaVis (see Section 8.4.2) also embodies other functions of a Web-based aquaculture information system particularly with regard to transparency of information and public participation in management via the Internet.

8.2.3 Training and the promotion of GIS

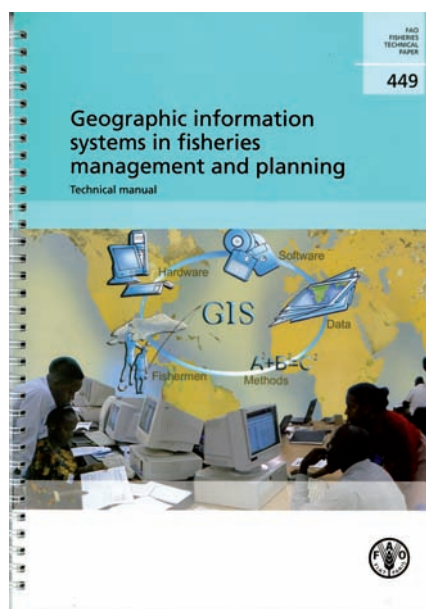
A lack of appreciation of the importance of spatial matters by aquaculturists and other practitioners has been identified as a problem and/or issue that GIS training and the promotion of GIS can help to address. Altogether, GIS training and promotion made up 8 percent of the current applications in GISFish with “promotion” receiving the most attention (Table 8.1).

GIS training and the promotion of GIS in one sense can be seen as one and the same issue in that promotion of the various applications of GIS in aquaculture can be considered as a training exercise aimed at managers and decision-makers as well as at technical staff. Indeed, an important mission of this technical paper is to promote GIS by engendering an interest in its applications to a wide range of problems in aquaculture faced by managers and decision-makers. To this end, Section 4.8 devotes significant advice on where further guidance and training can be obtained.

Both the FAO Fisheries and Aquaculture Department Aquaculture Branch (FIRA) and the Institute of Aquaculture at the University of Stirling, Scotland,¹⁹⁶ have been active in promoting the use of GIS and remote sensing as applied to aquaculture since 1985. Promotional activities at FIRA have been carried out through training, projects, field missions and oral presentations and publications. The Fishery-Aquatic GIS Research Group, established in Japan in 1997, also promotes GIS and spatial analyses in fishery and aquatic sciences, with its primary activity being to organize the triannual “International Symposium on GIS/Spatial Analyses in Fishery and Aquatic Sciences”, which includes aquaculture, and to publish its proceedings.

A training manual by de Graaf *et al.* (2003) provides “hands-on” step-by-step guidance on the use of GIS software for inland fisheries management and planning, and aquaculture is also included (Figure 8.6). The manual is aimed at fisheries biologists, aquatic resource managers and decision-makers in developing countries who do not have any knowledge of GIS. It by no means covers all possibilities of GIS; it merely touches upon some of the most important features for fisheries management and planning, but it is useful for a broad range of fishery and aquaculture applications. The manual was written for use with the Environmental Systems Research Institute’s (ESRI) ArcView 3.x and Spatial Analyst software¹⁹⁷; it includes two CD-ROMs with spatial data for exercises and has been tested in the Republic of Uganda, the Republic of Namibia, and the Republic of India.

FIGURE 8.6
Technical manual on GIS in fisheries
management and planning



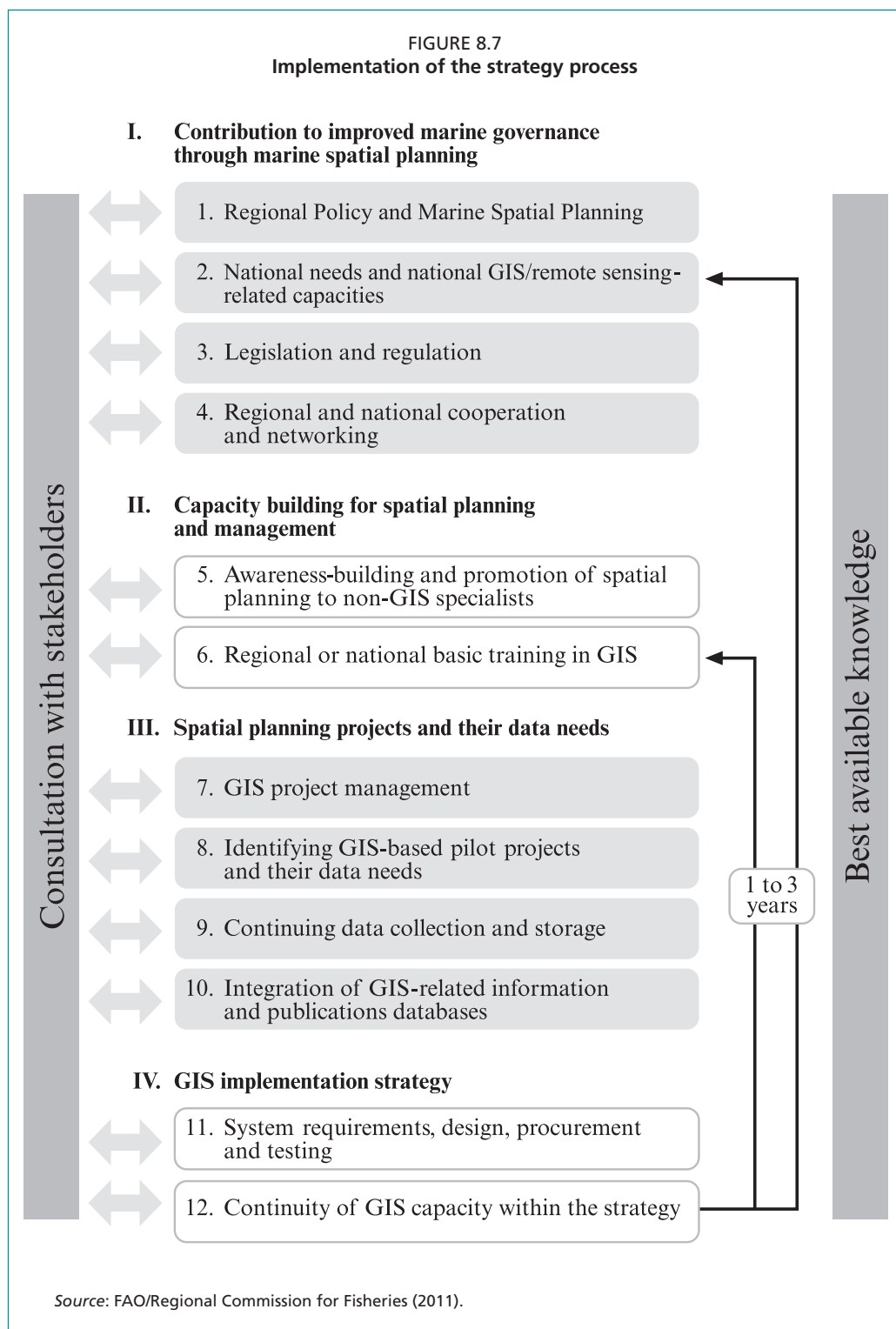
Source: de Graaf *et al.* (2003).

¹⁹⁶ Institute of Aquaculture at the University of Stirling: www.aqua.stir.ac.uk/GISAP/gis-group.

¹⁹⁷ ArcView 3.x is now discontinued. However, the examples provided in this manual could be replicated using the most recent ArcGIS software.

8.2.4 GIS for multisectoral development and management that includes aquaculture

This main issue addresses the role of GIS in establishing aquaculture in the context of competing, conflicting and complementary uses of land and water space. The attention this issue has received relative to other issues, only 7 percent of the total (Table 8.1), is an indication of the minimal extent to which planners and decision-makers have taken aquaculture into account in the general context of development.



In many cases, especially in the coastal zone or in estuaries or larger bodies of inland water, aquaculture and fisheries use the same resources and are practised in the same or adjacent space. Additionally, both pursuits have many interests and needs in common, not the least of which is an environment having ecological, social and economic components that allows both activities to remain sustainable. This sub-issue can be illustrated comprehensively by a proposal for a regional programme to implement a spatial strategy for the simultaneous management of marine fisheries and aquaculture in the Middle East Gulf Region, as detailed by FAO/Regional Commission for Fisheries (2011). Although the approach is regional, elements of the spatial strategy pertain to individual nations and their government institutions and commercial entities, i.e. to the extent that the strategy could be used as a framework for a combined national strategy for spatial planning for marine fisheries and for aquaculture development. Indeed, elements of the strategy could contribute to the wider regional marine spatial planning that will be necessary in the future for many of the more “congested” marine areas. Figure 8.7 shows a schematic diagram of the strategy illustrating that it consists of four programme components and 12 elements. Two actions are fundamental throughout the strategy process: (i) to collect and use the best available information; and (ii) to have broad stakeholder participation. The process, steps and potential starting points are described in this figure.

The sub-issue of “Planning for aquaculture among other uses of land and water” (Table 8.1) addresses the place of aquaculture among other users of land and water, and it goes beyond those considerations necessarily required collectively by fisheries and aquaculture. Ideally, there are several important roles for GIS relating to this sub-issue. One role is to establish where aquaculture can best be established while taking a detailed account of other uses of the land and water, i.e. so that conflicts are eliminated, competition is minimized, and complementary uses of the aquaculture space are thoroughly explored. A second role is to effectively communicate these results to high-level decision-makers.

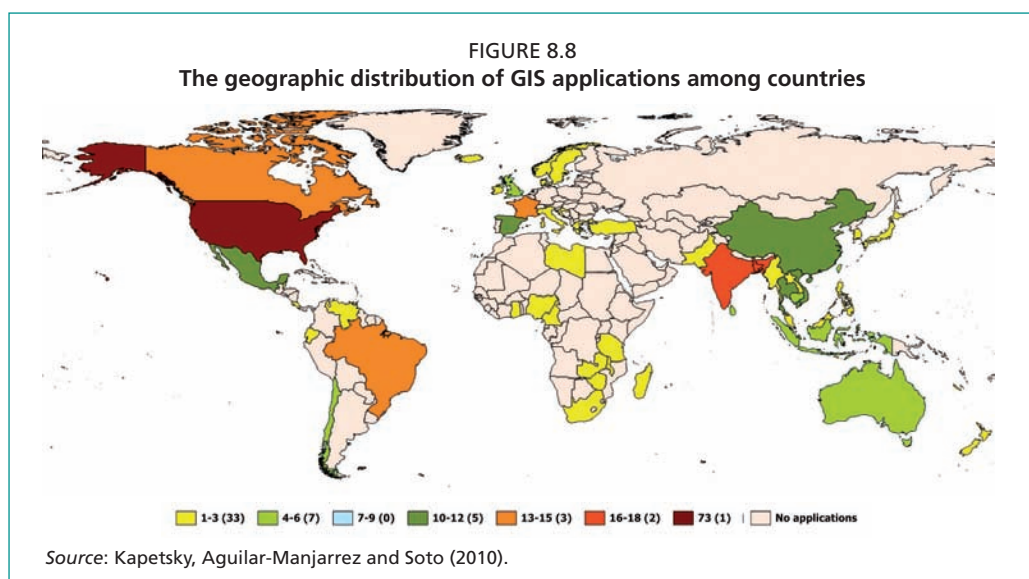
8.2.5 Trends in addressing aquaculture issues using GIS

A positive trend in addressing aquaculture spatial issues is that it is becoming more difficult to associate any one GIS application in aquaculture with any one issue or sub-issue. This means that spatial analyses for aquaculture are becoming broader in scope to the point that multiple issues are more frequently being addressed by any single project. In a recent review (Kapetsky and Aguilar-Manjarrez, 2013), attention was called to applications that incorporate multiple species, multiple models at different scales, including economic models, varied temporal scales for the simulation of consequences of management options, and the possibility that they could be adapted to address issues at different scales in other countries. GIS is used to provide the spatial components for the modelling of key variables by providing input values via a spreadsheet or database, as a platform for communication between different models, in the verification of data and of model results, for visualization and for spatial analyses. Despite such progress, there is a need for a greater focus on spatially defining and integrating the environmental, economic, and social components of aquaculture development, practice and management.

8.3 THE GEOGRAPHIC DISTRIBUTION OF GIS APPLICATIONS TO AQUACULTURE

Along with the types of spatial issues in aquaculture addressed by GIS, the geographic distribution of the applications is also of interest. For example, it is important to know the level of experience with GIS on a country basis so that technical assistance and training can be allocated in a way that might be appropriate to country needs and capacities. One such indicative measure was the number of applications to aquaculture by country in the GISFish aquaculture database in December 2009, and this was

depicted as a thematic map by Kapetsky, Aguilar-Manjarrez and Soto (2010) (Figure 8.8). The results were quite skewed, with more than half of the countries having only one to three recorded GIS applications but with very few countries having many applications, i.e. indicating that the GIS experience is far from evenly distributed. Moreover, although 51 countries were represented among the 298 GIS applications, at that time there were 163 countries having some recorded aquaculture production. This result suggests that there are many aquaculture practising countries that are not employing GIS to address aquaculture issues even when taking into account the bias toward the English language inherent in the GISFish aquaculture database and/or that many countries are simply not writing about and publishing their aquaculture GIS work. Even countries with a high aquaculture production, such as Japan, the Kingdom of Norway, and the Republic of the Philippines, publish very few studies relating to aquaculture where GIS has been a significant input.



A similar measure of the extent to which GIS applications in aquaculture are spatially distributed is based on the number of records from ASFA using “GIS” and “geographic information systems” together with “aquaculture” and “mariculture” as search commands for the period 1996 to 2010 (Table 8.3). In comparison with the GISFish analysis, fewer applications were found in ASFA, but the relative rankings among countries is similar. This is not surprising as ASFA focuses on scientific literature that has appeared in books, journals and conference proceedings while GISFish includes the grey literature from technical reports and trade publications as well as ASFA records.

An additional background area indicating the status of GIS applications to aquaculture is that of where much of the major and innovative work in aquaculture GIS (in terms of the institutions) is being conducted. Box 8.1 gives a general overview of some of the major organizations that are pursuing work in aquaculture GIS. The main institutions are in Europe; however, there are now institutions in the Republic of Chile, the Republic of Ecuador, the Republic of Ghana, the Republic of India, the Sultanate of Oman, the Republic of Peru and the Republic of South Africa where applications of GIS to aquaculture research projects and to management are innovative.¹⁹⁸ It is worthwhile visiting the Web sites of the institutions periodically to learn about work in progress or to view technical reports that may contain innovations not yet published in journals.

¹⁹⁸ See “Country initiatives” in NASO maps collection (www.fao.org/fishery/naso-maps/country-initiatives/en), and Kapetsky, Aguilar-Manjarrez and Soto (2010), Box 7.1, p. 115.

TABLE 8.3
Country or marine area of application for 350 literature records on papers covering GIS + geographic information systems + aquaculture + mariculture in FAOs ASFA database (1996–2010)

Region	Country of application	Number of applications
North America	United States of America	107
	Canada	12
	Mexico	3
Latin America and Caribbean	Brazil	3
	Peru	2
	Chile	2
Caribbean Sea + Gulf of Mexico		17
Asia and Pacific	China	24
	India	17
	Sri Lanka	9
	Viet Nam	8
	Bangladesh	7
	Indonesia	6
	Thailand	6
	Australia	6
	New Zealand	4
	Japan	4
Philippines	2	
Indian Ocean		1
Africa	South Africa	2
	France	8
Europe	Spain	4
	Baltic Sea	3
	Norway	3
	Italy	2
	Portugal	1
	Denmark	1
	Finland	1
North Atlantic		1
North Sea		1
No specific area		74
Total		350

Source: FAO (2012b).

BOX 8.1

Overview of major organizations carrying out aquaculture-related GIS research and projects

Clearly this box can only be illustrative and it is beyond the scope of this publication to give the exact range or number of institutions carrying out aquaculture-based GIS work.

- **Brazil.** The Universidade Santa Úrsula conducts aquaculture and GIS research in the marine and coastal environment. Different types of GIS projects include studies for aquaculture site selection (tilapia, *Litopenaeus vannamei*, bivalves), habitat suitability (marine turtles), stock evaluation (sea cucumbers – *Isostichopus badionotus*). Also species fragility in environments undergoing rapid changes, such as coastal areas and wetland homes to the annual freshwater killifish (*Rivulidae* – *Sympternichthys*).
- **Brazil.** The Universidade Federal de Santa Catarina, Centro de Filosofia e Ciências Humanas, Programa de Pós-graduação em Geografia conducts PhD work related to GIS e.g. use of GIS for the management of mariculture
- **Canada.** Hatfield Consultants Partnership (Hatfield) was established in 1974. The company capitalizes on its remote sensing and GIS group capabilities to provide a range of remote sensing and GIS products and services that complement and support traditional environmental assessment and monitoring services. Since its inception, the company has focused in particular on providing innovative and cost-effective environmental management solutions to the fisheries and aquaculture sectors.
- **France.** The Institut français de recherche pour l'exploitation de la mer (IFREMER) – French Research Institute for Exploitation of the Sea – carries out projects relating to remote sensing and GIS in the coastal zone.
- **Italy.** The FAO Fisheries and Aquaculture Department Aquaculture Branch (FIRA) develops methodologies, technical guidelines, technical papers, reviews, training materials, georeferenced information systems such as GISFish and GIS applications to aquaculture.
- **Japan.** The Fishery-Aquatic GIS Research Group was established in 1997, and is a non-profit organization located at the Environmental Simulation Laboratory Inc., Kawagoe, Saitama, Japan. The objectives of this group's activity is to promote GIS and spatial analyses in fishery and aquatic sciences through developing marine GIS software and organizing the triannual International Symposium on GIS/Spatial Analyses in Fishery and Aquatic Sciences and to publish its proceedings. The Graduate School of Fisheries Science at the Hokkaido University also carries out much innovative GIS work on fisheries and aquaculture.
- **Malaysia.** The World Fish Center has developed methodologies that apply remote sensing and GIS techniques, linked to environmental and socio-economic modelling, to support aquaculture and fisheries research, planning and management. Applications have included developing GIS-based decision support tools for identifying recommendation domains for small-scale aquaculture, and using remote sensing and GIS for community-based participatory planning of coastal livelihoods rehabilitation in post-tsunami coastal areas of Aceh province in Sumatra.
- **Spain.** The Dirección General de Pesca y Acuicultura, Consejería de Agricultura y Pesca conducts studies on integrated coastal zone management for the Andalucía region in the Kingdom of Spain.
- **Thailand.** The Fishery Information Technology Center at the Department of Fisheries, Thailand, develops and maintains computer networking, GIS, management information systems, and fisheries data collection and statistics reports for end users in Thailand. Current projects are: inventories of aquaculture and fisheries structures; fish cage identification and inventory; vessel monitoring systems; fishing gear detection; and flood management
- **United Kingdom.** The Institute of Aquaculture, University of Stirling, Scotland, has a small GIS group working on GIS and remote sensing applications in aquaculture. Its programme has taken two directions: the strategic evaluation of large regions for aquaculture exploitation and development, and the use of GIS in detailed facility location within a site. GIS-based environmental impact modelling is also being developed, with special emphasis on coastal zone management. GIS and remote sensing are incorporated into their M.Sc. programmes and GIS and remote sensing have been provided for a range of overseas institutions.
- **The United States of America.** There are a number of entities that use GIS for aquaculture including the Office of Aquaculture, National Oceanic and Atmospheric Administration, as well as regional fisheries bodies such as the Gulf States Marine Fisheries Commission. In addition, many of the states have their own fishery-aquaculture GIS units (e.g., North Carolina) and there are companies dedicated to the application of GIS and remote sensing in aquaculture (e.g., Consultants in Fisheries and Aquaculture Sciences and Technologies (C-FAST, Inc.).

8.4 CASE STUDIES

Case studies allow for the easy comprehension of what are often advanced and detailed research activities with practical applications. They are also a valuable complement to journal articles and technical publications because not only do they call attention to a wide variety of applications that have contributed to solving important issues that affect the sustainability of aquaculture, but they also provide information usually lacking from scientific papers and reports, namely, in what ways, and with what commitments of time and specialized personnel the work has been completed, as well as lessons learned that are helpful to assess the time and resources required to undertake similar investigations.

A source of case studies of GIS, remote sensing and mapping applications in aquaculture is the published case studies page of GISFish¹⁹⁹. There are currently 14 case studies and new ones are added as innovative material becomes available. In addition to the presentation of the application in the case study format, there are links to the publications upon which the case study was based. Another source for case studies are those assembled and interpreted from an ecosystems viewpoint by Kapetsky, Aguilar-Manjarrez and Soto (2010). The purpose of these case studies was twofold, the first being to show the relevance of GIS capabilities to the EAA principles and the second was to illustrate by actual application examples ways in which GIS, remote sensing and mapping can contribute to the implementation of the EAA.

The following case studies were selected from a number of different sources including those described above. These case studies not only illustrate the technical capacity of GIS applications in aquaculture, but they also address issues that are of global to local importance and that span environmental, social and economic considerations.

The four case studies selected also needed to be as varied as possible and therefore include a variety of GIS-based techniques and degrees of complexity. The studies provide:

- a sophisticated and holistic example from a developed world area where a fairly large group of research workers were deployed (Sections 8.4.1);
- a sophisticated example also from a developed world area involving the use of a Web-based decision-support system (Section 8.4.2);
- a less sophisticated study also in a developed world area involving the use of remote sensing data (section 8.4.3);
- a fairly basic study carried out by a Ph.D. level student using precollected data and looking at defining aquaculture potential in Ghana (Section 8.4.4).

8.4.1 Sustainable options for People, catchment and Aquatic Resources (SPEAR)

Original publication reference: Ferreira, J.G., Andersson, H.C., Corner, R.A., Desmit, X., Fang, Q., de Goede, E.D., Groom, S.B., Gu, H., Gustafsson, B.G., Hawkins, A.J.S., Hutson, R., Jiao, H., Lan, D., Lencart-Silva, J., Li, R., Liu, X., Luo, Q., Musango, J.K., Nobre, A.M., Nunes, J.P., Pascoe, P.L., Smits, J.G.C., Stigebrandt, A., Telfer, T.C., de Wit, M.P., Yan, X., Zhang, X.L., Zhang, Z., Zhu, M.Y., Bricker, S.B., Xiao, Y., Xu, S., Nauen, C.E. & Scalet, M. 2008. SPEAR: *Sustainable options for People, catchment and Aquatic Resources: the SPEAR project, an international collaboration on integrated coastal zone management*. 180 pp.

Spatial tools: GIS, remote sensing, models.

Main issue addressed: Environmental impacts of aquaculture.

Duration of study: 2004–2007.

Personnel involved: The SPEAR team consisted of 35 experts from different countries around the world with a wide range of expertise ranging from tools, systems, aquaculture, ecosystem modelling, screening modelling and management.

Target audience: Coastal zone water managers, planners and licensing authorities.

¹⁹⁹ Case studies page of GISFish: www.fao.org/fishery/gisfish/id/1014.

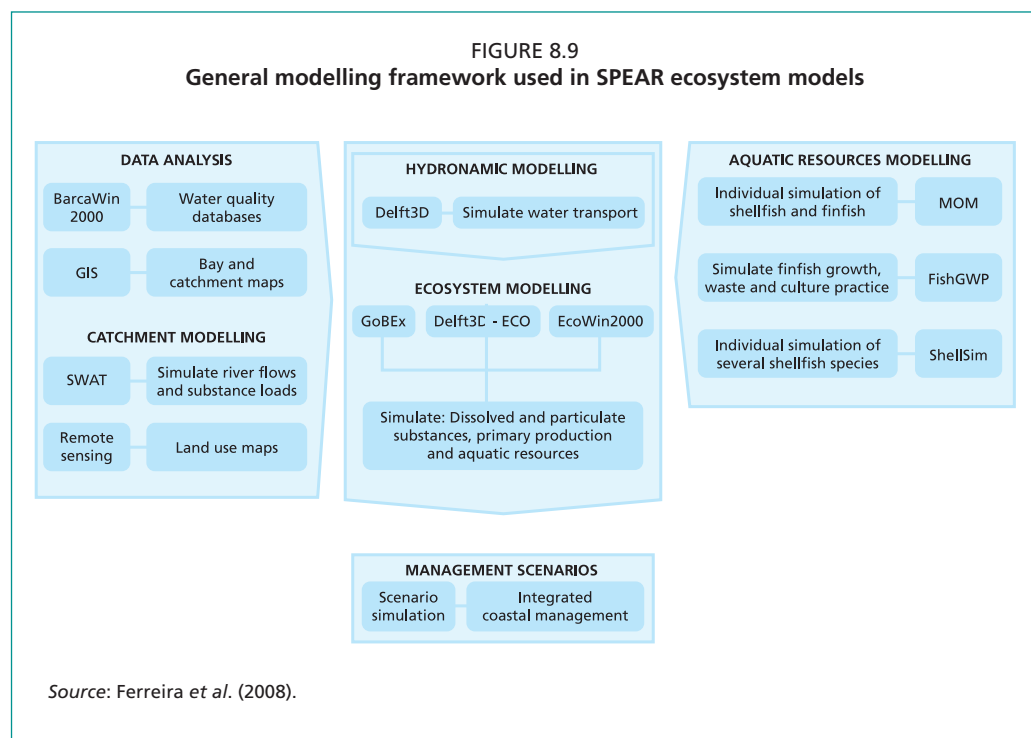
Introduction and objectives: The SPEAR project was financed by the European Union INCO-DEV programme (www.biaoqiang.org). It was a follow-up to the experiences gained in the Sustainable Mariculture in Northern Irish Loughs Ecosystems (SMILE) project (2004–2006) for determining environmentally sustainable carrying capacity for shellfish aquaculture for Irish loughs (Ferreira *et al.*, 2007).

The general objective of SPEAR was to develop and test an integrated framework for management of the coastal zone, using two test cases where communities depend primarily upon marine resources of which a large component is aquaculture of finfish, shellfish and seaweeds, often in integrated multitrophic aquaculture (IMTA).

This case study does not aim to provide an exhaustive account of all the research executed in SPEAR, and the reader is directed to the official project Web site (available in English at www.biaoqiang.org and in Chinese at www.spear.cn). A digital copy of the SPEAR book is available on the site, together with links to databases, models, reports and all other resources made available by this research.

Methods and equipment: Two contrasting coastal systems in the People's Republic of China were used as study areas. Sanggou Bay is in a rural area in the north, and Huangdun Bay is an industrialized area south of Shanghai that is subject to substantial human pressure at both local and regional levels.

The overall SPEAR framework accounted for watershed interactions, ecological structure and human activities. The interdisciplinary study used combined natural and social science approaches and addressed the complex scaling issues inherent in integrated management. The main objectives of model development at the ecosystem scale were to: simulate the ecosystem processes on a multi-year scale for each bay; simulate the aquatic resources produced in the bays; develop the socio-economic components to dynamically integrate this framework; and to calibrate and validate the research model suite. A key feature of the general modelling approach was to integrate the various models in order to develop a robust ecosystem modelling framework where GIS and remote sensing play an integral part (Figure 8.9).



Results: SPEAR focused on both research and screening models. The latter, useful for a fish farmer, farm manager or coastal manager, are employed to support decisions and are featured herein. For example, at the local scale, screening models²⁰⁰ may be used to look at aquaculture yields, local impacts of fish farming and water quality. A good illustration is the particulate waste distribution model developed for fish culture in Huangdun Bay (Figure 8.10) using GIS, which provides a footprint of the organic enrichment beneath fish farms. The footprint can be used to predict changes to benthic biodiversity through empirically derived calibration curves. Such enrichment footprints are used for the environmental regulation of cage fish farming in many countries.

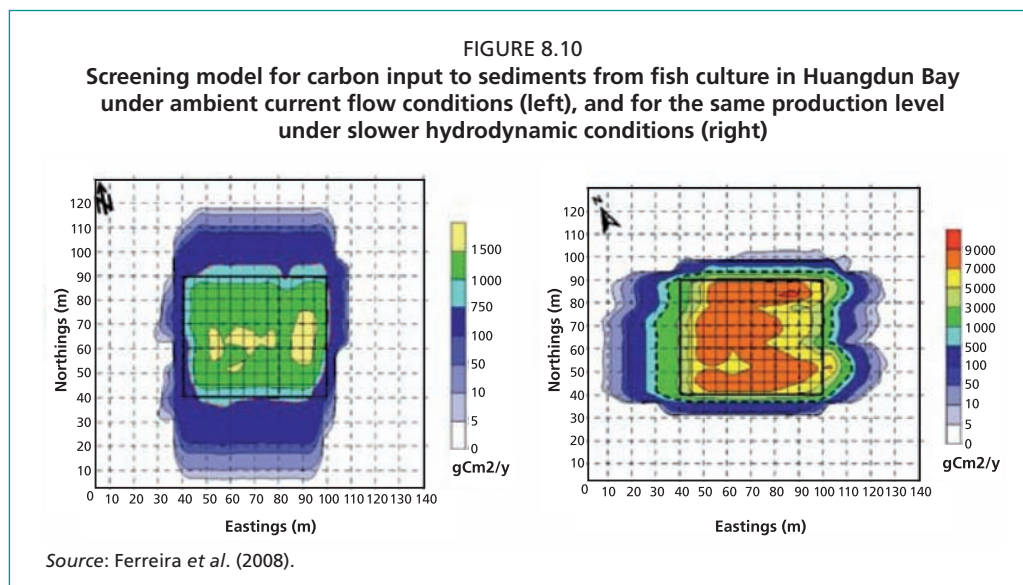
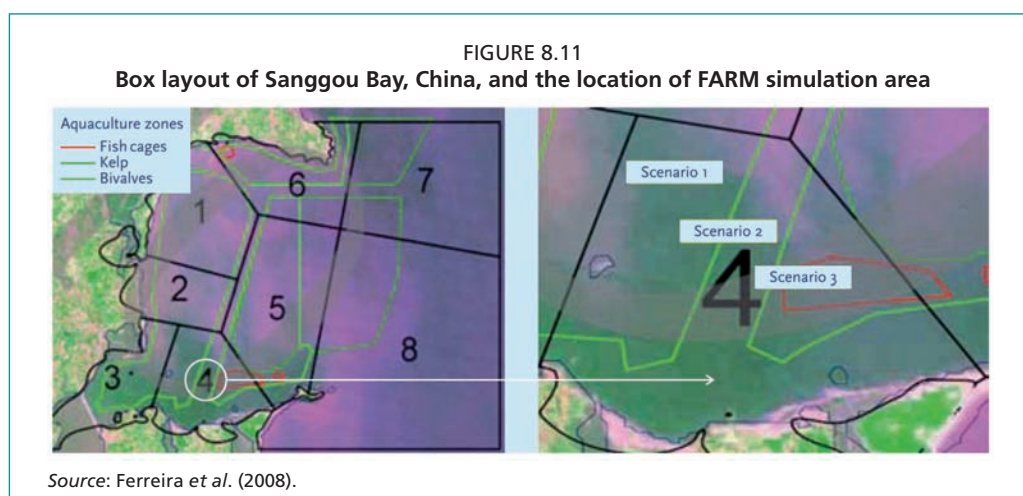


Figure 8.11 illustrates one of the management scenarios from the project. The farm selected as a demonstration site is located in Box 4 of Sanggou Bay, where Pacific oyster (*Crassostrea gigas*) raft culture, Japanese flounder (*Paralichthys olivaceus*) and pufferfish (*Fugu rubripes*) cage culture coexist. There, three scenarios were posed all of which concern different ways to spatially distribute oyster culture among the other



²⁰⁰ The distinction between research models and screening models is related to the data requirements, complexity of use, difficulty/ease in interpreting the results, runtime and post-processing required, and target audience. Research models are considerably more costly to build and run, require inputs from multiple users, are useful for detailed analytical work, and tend to be used by scientists or others who are experts in the particular issue and model. While screening models are less costly, they consist of rapid assessments and should in principle be usable by anyone with a working knowledge of the issue at hand.

cultures and the effects of these distributions. Overall, scenario 3 provided both the highest profit from production activities and the highest potential income when also considering the environmental costs of nutrient treatment, or (alternatively) the resale value of nitrogen credits as a catchment management option.

Discussion, conclusions and recommendations: From a technical standpoint, outputs from the SPEAR project represent the state-of-the-art in coastal management, featuring Web-based models, hybrid ecological-economic approaches, and management tools that can be used at a variety of scales. Technological developments will mean that the tools themselves will evolve fairly rapidly, but the underlying scientific paradigms are expected to change more slowly.

In summary, GIS was used throughout the project in several key roles:

- In decision support as the geographic component of key variables and results to support the decision-making process.
- In modelling, by providing input values relevant for parameterization and calibration, by serving as a platform for communication between different models and by allowing a first approach at 2D validation processes, for allowing the use of spatialized assessment of model results.
- In visualization at several stages of the project for basic mapping purposes to facilitate the understanding and interpretation of relevant inputs and results, and by performing spatial analysis of model results. However, most models used in this project were not fully integrated within the GIS software. This was done in a follow-up project, “Understanding Irish Shellfish Culture Environments”, on the carrying capacity in Ireland, where an application in ArcGIS was used to run the various models (J.G. Ferreira, personal communication, 2011).

Challenges and benefits from the case study: This project is valuable because it is a holistic assessment of aquaculture on the basis of people, planet (i.e. environment) and profit. The challenge of bringing the various components of the people-planet-profit equation together as a holistic indicator of sustainable carrying capacity in coastal areas appears both achievable and appropriate for integrated coastal management. From a GIS viewpoint, this project is noteworthy in a number of ways: (i) it represents a good example of integration of spatial data across different scientific disciplines; (ii) it is novel because it combines models running at widely different time and space scales for different ecosystem components as a requirement for scaling and as co-validators of each other, lending confidence to the outcomes; and (iii) it included a socio-economic viewpoint using the MARKET model. Also valuable are the set of management scenarios proposed by the project team, including the stakeholders, that clearly illustrate the role and value of GIS.

As a follow-up to SMILE and SPEAR, the Institute of Marine Research (IMAR) has been working with others on individual shellfish modelling over the past two years. In particular, IMAR has developed a new model called AquaShell, which aims to include the minimum set of equations required to successfully simulate bivalve growth, and it has implemented it for the blue mussel, grooved carpet shell clam and Pacific oyster (J.G. Ferreira, personal communication, 2011). The model has been applied to oyster cultivation in the Republic of Chile using the following approach: (i) a coastal system was screened for potential shellfish aquaculture areas using GIS; (ii) the FARM model, using AquaShell to simulate individual growth, was applied to examine the feasibility of production in those areas and at appropriate sites; and (iii) an optimization analysis was carried out for production, profit and environmental effects (Silva *et al.*, 2011).

At the system scale, the AquaShell model is also being used in the CoExist project (www.coexistproject.eu) for the analysis of the offshore culture of finfish and shellfish in integrated multitrophic aquaculture.

8.4.2 AkvaVis decision support system

Original publication reference:

Ervik, A., Agnalt, A.-L., Asplin, L., Aure, J., Bekkvik, T.C., Døskeland, I., Hageberg, A.A., Hansen, T., Karlsen, Ø., Oppedal, F. & Strand, Ø. 2008. AkvaVis – dynamisk GIS-verktøy for lokalisering av oppdrettsanlegg for nye oppdrettsarter – Miljøkrav for nye oppdrettsarter og laks. *Fisken og Havet*, nr 10/2008. 90 pp.

Ervik, A., Døskeland, I., Hageberg, A.A., Strand, Ø. & Hansen, P.K. (forthcoming). *Virtual decision support tool (AkvaVis) for integrated planning and management in aquaculture*.

Publication/date:

Ervik *et al.* (forthcoming) is being prepared for submission.

Spatial tools: GIS.

Main issues addressed: Inventory and monitoring of aquaculture and the environment; environmental impacts of aquaculture; Web-based aquaculture information system.

Duration of study: Five years

Personnel involved: Eight aquaculture research experts and three GIS/virtual technology experts, all members of academic and governmental groups.

Target audience: Stakeholders in the fields of aquaculture production, aquaculture and coastal zone management and policy implementation.

Introduction and objectives: Aquaculture is a major coastal activity in the Kingdom of Norway. Total aquaculture production in 2010 was 1 008 010 tonnes at a value of US\$5 020 275 000 (FAO Statistics and Information Branch of the Fisheries and Aquaculture Department, 2012). The industry contributes substantially to employment and rural economies. Fish are produced in fjord-based farms using net cages for Atlantic salmon (*Salmo salar*) and rainbow trout (*Oncorhynchus mykiss*), and they occupy more than 1 000 sites. Diversification of the industry is being encouraged by research and development, which seeks new aquaculture species, i.e. marine fish: cod (*Gadus morhua*), halibut (*Hippoglossus hippoglossus*); shellfish: mussels (*Mytilus edulis*), scallops (*Pecten maximus*), flat oyster (*Ostrea edulis*); and lobster (*Homarus gammarus*). Aquaculture production of seafood continues to grow; however, this continued growth has also brought concerns about environmental impacts.

As in other parts of the world, the exploitation of the Norwegian coastal zone is increasing, with new activities, stakeholders and interests facing a complexity of environmental and social interactions. New, comprehensive and more holistic approaches for coastal zone management are being applied such as the ecosystem approach and long-term maintenance of biodiversity. This is a challenge for the developing aquaculture industry. The development of new decision-support systems that can handle the variety of interests and that can transfer scientific-based knowledge to the targeted user is urgent. There is also an increasing mismatch between the rather static coastal area development plans prepared by local municipalities and the rapidly changing and dynamic nature of the aquaculture industry. This further emphasizes the need to provide planners and managers with up-to-date data, knowledge and advice.

AkvaVis is a Web-based interactive site selection, coastal zone area planning, carrying capacity, management and monitoring, decision-support system. Although the system is currently under development (Ervik *et al.*, forthcoming), it is aiming to provide a Web-based interface that will be transparent to public users and dynamic, in the sense that it is adaptable to new knowledge and new regulatory frameworks, and that it addresses the demands from the industry, including public and private stakeholders. AkvaVis aims to cover all main aquaculture species in the Kingdom of Norway and also to integrate other activities as part of marine spatial planning so as to make informed and coordinated decisions about how to use marine resources sustainably. The challenges for integrated planning and management for aquaculture

in the Norwegian coastal zone have prompted the launching of a new cohesive management system called MOLO (Environmental adaption and efficient area usage for the aquaculture industry)²⁰¹ (Anonymous, 2009), under which AkvaVis is intended to be developed as the virtual decision support tool.

Methods and equipment: AkvaVis makes use of “intelligent objects”²⁰² and integrated data models. The system creates a virtual reality²⁰³ for aquaculture site selection and carrying capacity.

AkvaVis consists of three modules:

1. The management module compiles the best available information needed by the authorities for aquaculture management. It provides thematic maps, i.e. adopted area management plans and other geographic information of relevance regarding the conflicting use of the coastal area, and information on mandatory environmental monitoring and environmental quality standards.
2. The siting module identifies and evaluates the suitability of areas for specified aquaculture activities and provides simulations of their carrying capacities.
3. The application module aids in an efficient application procedure for aquaculture licences and ensures that all relevant information is provided.

The AkvaVis siting module divides the study area into grid cells containing quantitative information on several relevant location factors (e.g. depth, current velocity, etc.). The user can insert on the map of the study area an intelligent object (e.g. a virtual mussel farm) to communicate dynamically with information provided by databases and mathematical models simulating aspects of the physical, production and ecological carrying capacities, as well as with information on other conflicting objects such as sewage outlets, fisheries, conservation areas, etc. Once a virtual farm is inserted in a given site (or grid cell) on the map, AkvaVis will immediately report back on how suitable the site would be for the cultured species by giving a suitability score for each parameter (depth, wave exposure, carrying capacity, etc.) and a calculated total score on how all requirements are met. Databases and information are both shared between national data providers and internally between the three system modules.

Results: As part of the ongoing development of the AkvaVis tool, demonstration versions are available at www.akvavis.no for the blue mussel (*Mytilus edulis*) and Atlantic salmon (*Salmo salar*) in the Hardangerfjord. This area was chosen for testing AkvaVis owing to the availability of environmental data, such as current velocity conditions (Figure 8.12), the availability of an already tested hydrodynamic model and a very active aquaculture scene.

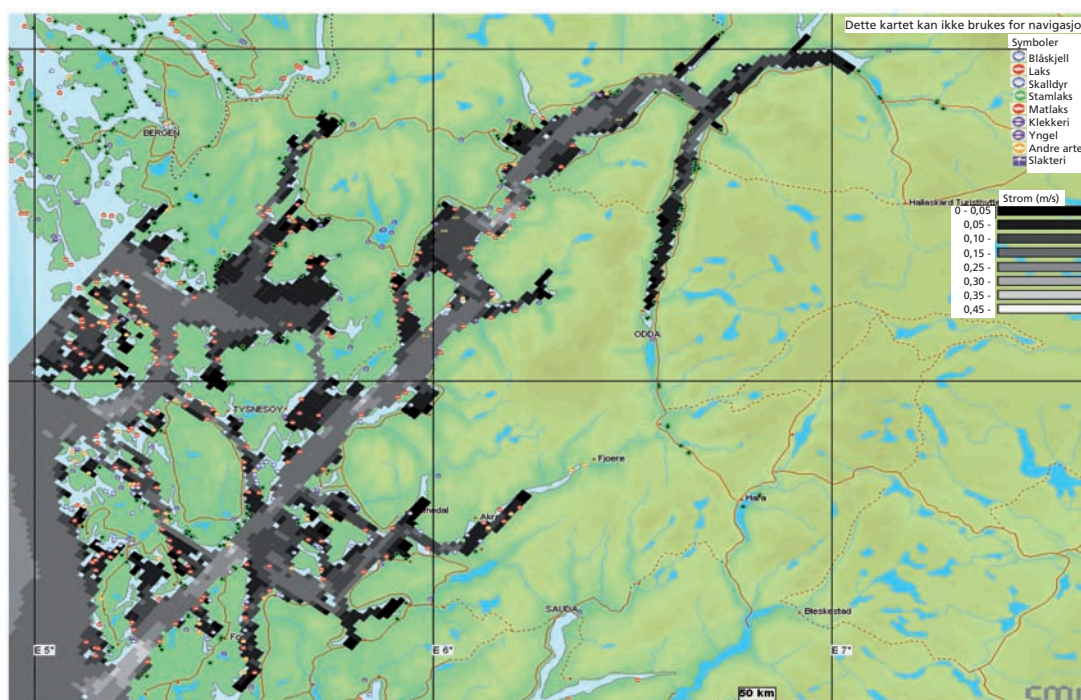
The simulation of a specific siting of a salmon farm will interact with an industry compliant and/or adopted version of the Modelling-Ongrowing fish farms-Monitoring (MOM) model (Ervik *et al.*, 1997; Hansen *et al.*, 2001; Stigebrandt *et al.*, 2004), assessing the potential effects on the bottom and on benthic fauna, and reporting a suitability score according to accepted environmental impact standards. Figure 8.13 shows a part of the Hardangerfjord with contour depth information displayed and

²⁰¹ Environmental effects and access to areas will be crucial factors in the Norwegian aquaculture industry's development and growth. The Minister of Fisheries and Coastal Affairs has asked the Institute of Marine Research to prioritize the work on developing a total system for the regulation of environmental effects and adaption of areas for aquaculture. The system is called MOLO and the development work will take place in cooperation with other institutions. It will cover both the planning and operation phases for aquaculture and combines the use of geographic information systems with calculations of the carrying capacity and the monitoring of environmental effects (Institute of Marine Research: http://www.imr.no/english/_data/page/6540/Coast_and_Aquaculture_2007.pdf).

²⁰² Intelligent objects are virtual representations of a spatial or non-spatial entity (object).

²⁰³ Virtual reality is a technology that allows a user to interact with a computer simulated environment.

FIGURE 8.12
The AkvaVis – Hardangerfjord grid for simulating current velocity



Source: Ervik *et al.* (forthcoming).

Map legends:

Top-right symbols (from top to bottom): Mussels, salmon, shellfish, broodstock of salmon, cage farming, hatchery, fry, other species, processing.

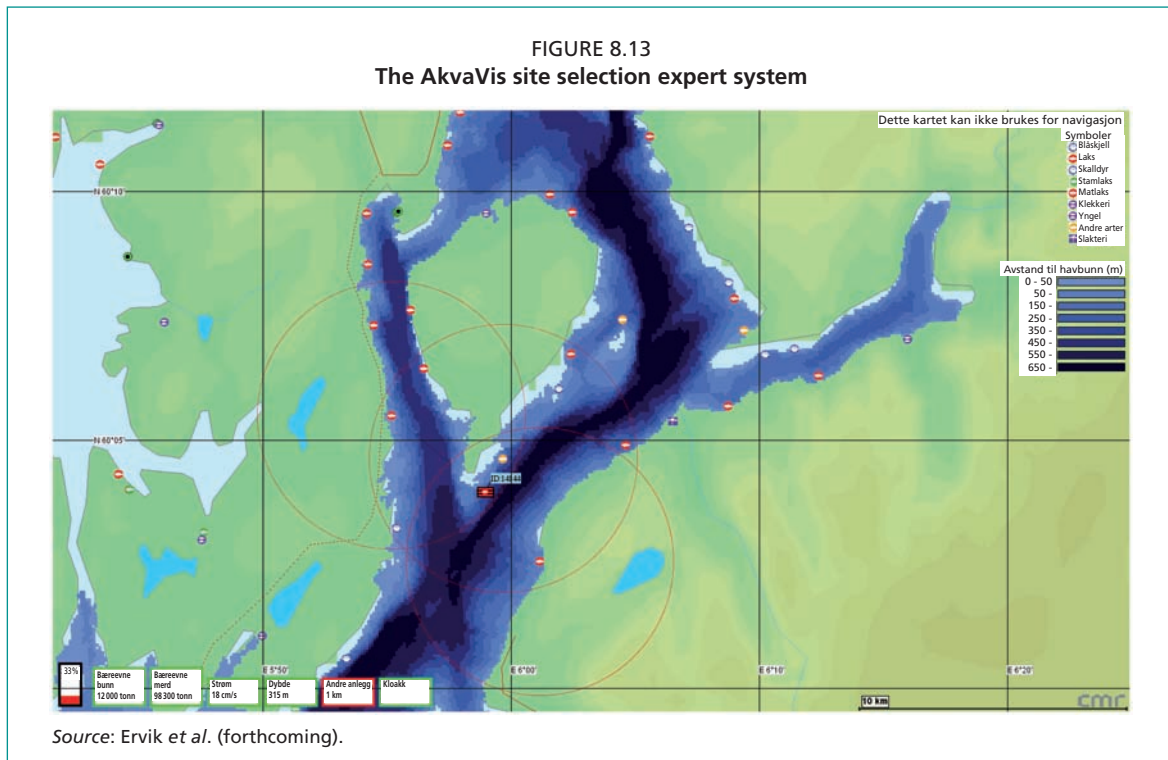
Mid-right symbols: Current (m/s).

the locations of different types of existing aquaculture. The red-squared location (ID 14144) at the centre of the figure is the virtual fish farm presented with suitability indicators in the form of coded results (traffic lights) at the bottom left corner. In this case, all indicators (i.e. carrying capacity to benthic impact, carrying capacity to cage environment, current velocity, depth, distance to sewage outlet) are acceptable (green code) except for the distance to the nearest existing aquaculture location (red code), for which minimum distance is indicated by the red circles on the map.²⁰⁴

For the current development of the demonstration version, models such as MOM that are already adopted as guidelines and are regarded as partially implemented in the management of aquaculture in the Kingdom of Norway are proposed for implementation. Examples are exposure to currents and waves, risk of eutrophication on regional scale, and risk of oxygen depletion in fjord basins.

The AkvaVis demonstration tool integrates: (i) data on a range of parameters (e.g. currents, aquaculture sites and waste outlets); (ii) data based on expertise (e.g. growth models, rules for weighting selection factors and boundary values); (iii) legislation, regulations and directives (e.g. distance to other aquaculture sites); (iv) calculations, visualizations and interactivity between the tool and the user; and (v) basic topographic and thematic maps. The interactive feature allows the users to immediately see the consequences of their choices. A user survey (Hageberg, 2008) has been conducted as part of the current development of the system.

²⁰⁴ Farm sites fallow on a rotational basis to prevent disease transmission to the stock. Compliance to minimum distance between farms may also vary over time. The minimum distance used is adopted as the standard. At present, AkvaVis is still under development; therefore, suitability indicators are not fully developed.



Map legends:

Top-right symbols (from top to bottom): Mussels, salmon, shellfish, broodstock of salmon, cage farming, hatchery, fry, other species, processing.

Mid-right symbols: Depth (m).

Bottom-left symbols (from left to right): Carrying capacity benthic, carrying capacity cage, current, depth, other farms, sewage.

Discussion, conclusions and recommendations: The AkvaVis decision-support system will provide a hands-on Web-based aquaculture simulator and data management tool that will give the user immediate feedback on site selection choices. The management, siting and application modules are purpose-designed to meet some of the prime needs in aquaculture management by authorities and industry. The transparency to public users and dynamism to accept new knowledge, new regulatory frameworks and the demands from industry and public and private stakeholders are regarded as important for development of an efficient and trustworthy tool.

Challenges and lessons from the case study: Several challenges have characterized the development work and demonstration presentations of the AkvaVis system. Some of the challenges and lessons learned are summarized as follows:

- In order to be totally effective, AkvaVis will probably need long-term experience in practical management to be realized, even for the most important species (e.g. Atlantic salmon). However, some of the subcomponents suggested for the siting module, such as the MOM-model, environmental quality standards and others, are regarded as already being partially implemented for the management of aquaculture in the Kingdom of Norway. This inclusion of established subcomponents will ease the process of developing AkvaVis towards a full operational application.
- Factors important to site suitability when represented in a spatial domain require high-quality data, both from measurements and models, and these are currently only available for a few areas.
- Current velocity data are crucial for estimating most of the factors affecting site suitability. The hydrodynamic models, from which the currents were obtained,

are also used in other simulation models, and these will need to be implemented for the whole Norwegian coastal system. (i.e. the models will need to use average current conditions, derived from model simulations, and not only average values, for example, variability is needed for some indicators and this process of producing a catalogue of extracted data is ongoing).

- Involvement of stakeholders is complicated because the target audience consists of industry, management and policy-makers. The process of integrating user-friendly aspects as part of the decision-making procedure is ambitious.
- The simplification of information that is used and presented as indicators and simple codes causes a risk of both loss of information and misinterpretation of it.
- The dynamic nature of the aquaculture industry and the expected challenges to meet environmental and socio-economic issues related to sustainable production sets specific requirements on how regulatory frameworks can adapt and the types of decision-support tools that are needed. The need for adaptation to these changes requires a transparent system, but there are limitations that need to be resolved to make it fully transparent and operational, such as access to some of the functions of the system, databases, models and Web tools.

8.4.3 Environmentally sustainable offshore aquaculture: an eco-physical perspective

Original publication reference:

Longdill, P.C., Healy, T.R., Black, K.P. & Mead, S.T. 2007. Integrated sediment habitat mapping for aquaculture zoning. *Journal of Coastal Research*, Special Issue 50, 173–179.

Longdill, P.C. 2008. Environmentally sustainable aquaculture: an eco-physical perspective. Waikato University. 280 pp. (PhD dissertation)

Longdill, P.C., Healy, T.R. & Black, K.P. 2008a. GIS-based models for sustainable open-coast shellfish aquaculture management area site selection. *Ocean and Coastal Management* (51), 612–624.

Longdill, P.C., Healy, T.R. & Black, K.P. 2008b. Transient wind-driven coastal upwelling on a shelf with varying width and orientation. *New Zealand Journal of Marine and Freshwater Research* (42), 181–196.

Spatial tools: GIS.

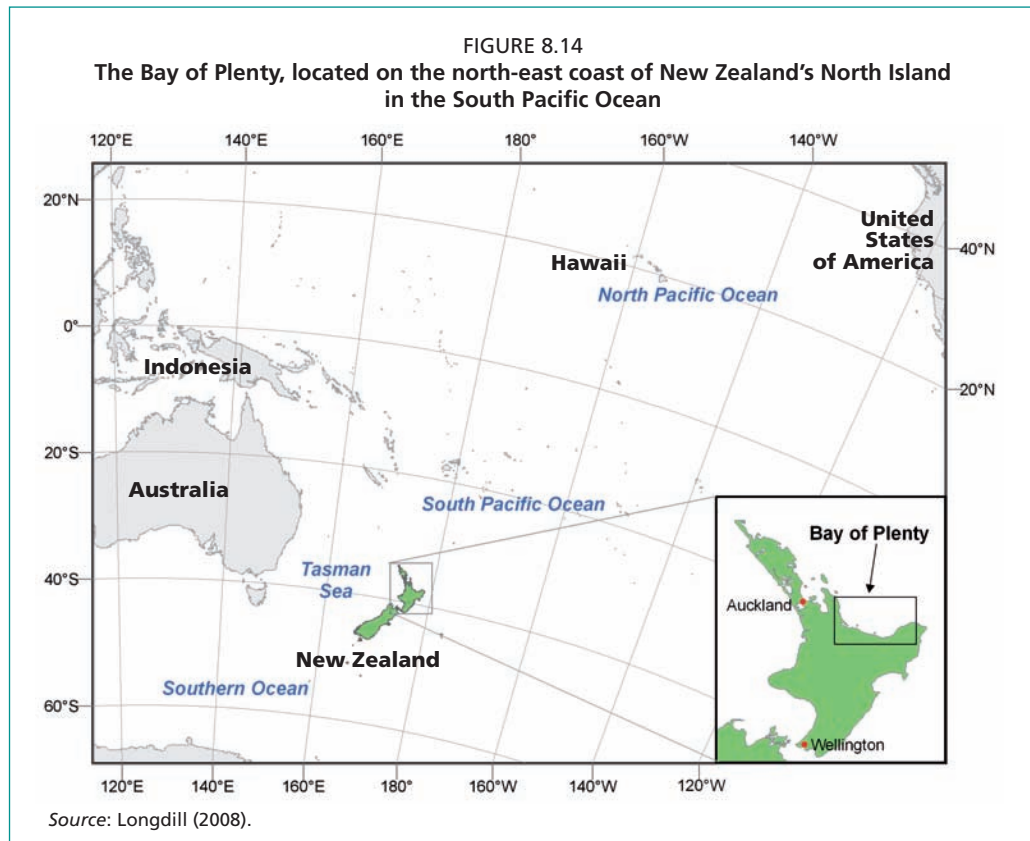
Main issues addressed: Strategic planning for development; anticipating the consequences of aquaculture.

Duration of study: Four years: 2004–2008.

Personnel involved: 1 full time Ph.D. student. Advice and assistance as required during the study.

Target audience: Local government, aquaculture industry groups, aquaculture researchers, marine scientists, local interest groups and the general public interested in marine resources.

Introduction and objectives: The study stemmed from the growth of the New Zealand Greenshell mussel (*Perna canaliculus*) industry during the 1990s and early 2000s. Traditional methods of mussel aquaculture within New Zealand have been longline techniques located in sheltered enclosed embayments. A near saturation of the predominant culturing locations led to interest in offshore, open coast locations. This case study summarizes the results of investigations to determine the suitability of offshore open coast locations (from the coast to 100 m water depth) for commercial bivalve aquaculture within the Bay of Plenty, New Zealand (Figure 8.14). The study was funded both by local government (Environment Bay of Plenty Council, EBOP) and the New Zealand Tertiary Education Commission.



The study implemented a framework to collect and analyse data sets relating to the environmental effects of bivalve culture, competing uses of the marine environment, and also the productive capacity for aquaculture. To achieve this framework, a network of factors that aid the development of a sustainable and viable industry were identified and examined (Figure 8.15).

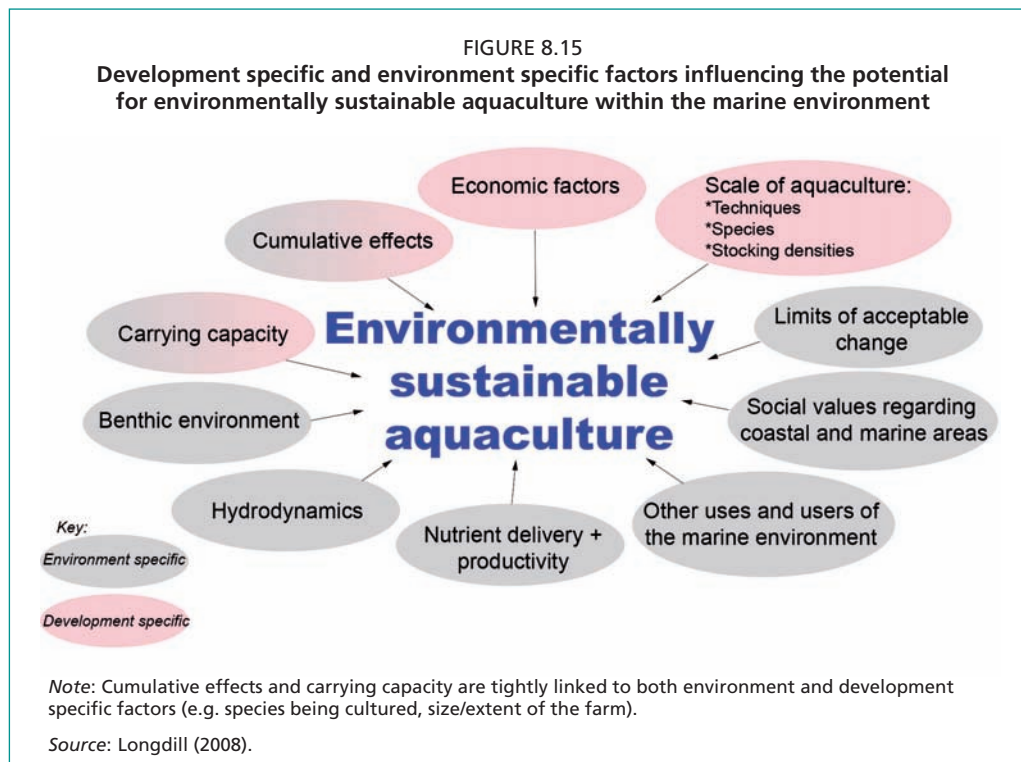
Methods and equipment: Key existing spatial data sets were obtained from government agencies and research institutions, e.g. bathymetry, fishing density, existing ocean zoning areas, shipping areas, climatology, remotely sensed data that includes sea surface temperature and ocean colour time series. Other essential data sets were collected specifically for this study, e.g. benthic habitats, sediment character, water quality, water current data, calibration data for remotely sensed data sets, calibration data for numerical physical and ecological models. Fieldwork was performed in a cooperative engagement between the local environment agency (EBOP), a local university specializing in marine and coastal studies (University of Waikato), and a marine consulting firm (ASR Ltd).

The analysis was divided into three separate steps:

- (i) GIS analysis of benthic environments and their ability to assimilate the inputs from aquaculture;
- (ii) GIS analysis of other factors influencing the potential zoning of open coast aquaculture farms (environmental, institutional²⁰⁵ and productive capacity);
- (iii) Numerical analysis of physical marine processes (tides, currents, temperatures etc.), along with ecological processes (nutrient and plankton dynamics) and analysis of the model output within a GIS to assess the impact of aquaculture development on water quality and phytoplankton dynamics.

All GIS work was performed using ESRI's ArcGIS v9.2.

²⁰⁵ Institutional factors relate to other users and uses (e.g. access ways, protected areas, existing shipping routes and anchorage areas) of the coastal marine environment (See Fridley, 1995).



The collected benthic data (bathymetry, habitat type, sediment grain size, sediment organic content and benthic fauna assemblages) were classified into discrete categories depending upon its suitability for culturing infrastructure (bathymetry) and for its ability to assimilate the inputs resulting from a mussel culture operation, e.g. increased deposition of organic material on the seabed. This classification then allowed for these data sets to be included within the raster-based GIS analysis.

The determining factors that were included in order to identify suitable or optimal locations for open coast aquaculture were the growth and quality of the cultured shellfish, the magnitudes of potential environmental impacts, and existing uses and users of the marine area (including societal values). These factors were considered in a spatial framework using raster-based GIS analysis.

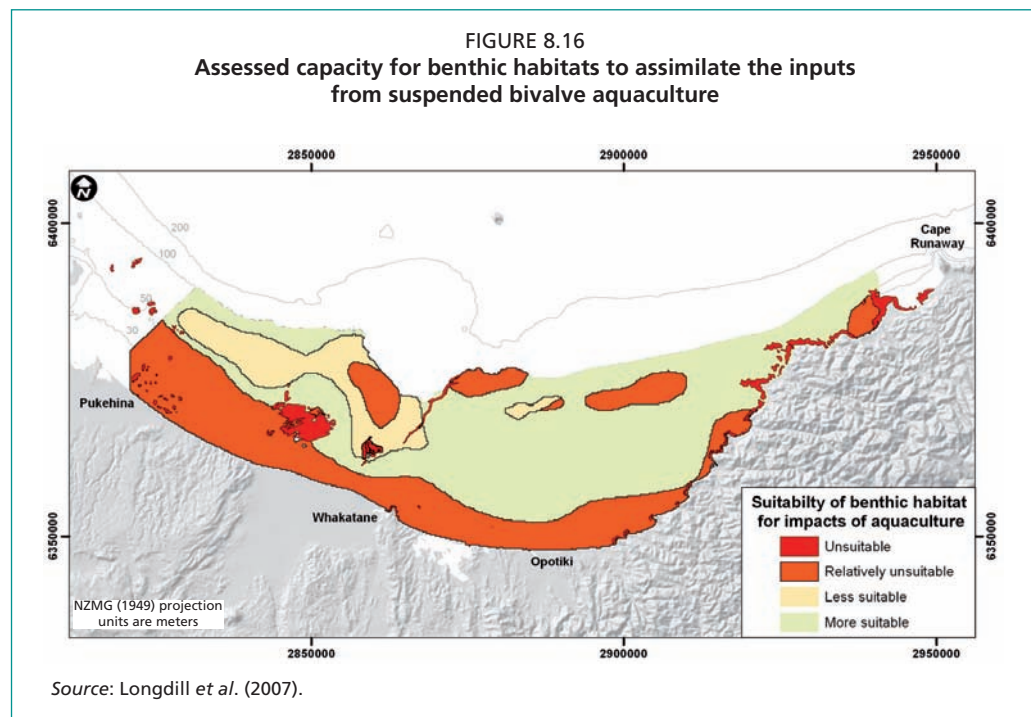
Data layers employed included:

- the visibility of farm-related infrastructure, e.g. buoys and barges, from the coastline;
- access ways;
- culturally significant areas, e.g. traditional fishing zones;
- protected areas;
- legally constrained areas;
- recreational use;
- commercial fishing;
- shipping zones;
- residual current directions;
- mean current speeds;
- benthic habitats;
- relative productivity (chlorophyll-*a* and sea surface temperature climatology);²⁰⁶
- water depth.

²⁰⁶ In this case study, monthly means over a ten-year period were utilized for both remotely sensed chlorophyll-*a* and sea surface temperature to define the climatology.

Combining these selected data sets requires that each parameter be transformed to comparable and consistent units. For this purpose, parameter-specific suitability functions (PSSFs – e.g. see Vincenzi *et al.*, 2006) were defined to assess the suitability of a given site with respect to biogeochemical and physical parameters. These PSSFs convert the raw data set to bivalve aquaculture suitability scores, e.g. a score of 1 for a highly productive area ranging to close to 0 (i.e. 0.001) for a very low productivity area.²⁰⁷ Individual data sets were converted to either continuous suitability scores (e.g. productivity) or to discrete groups, e.g. culturally significant areas – score of 0 if present, or 1 if not present, as applicable. The subsequent raster layers were then subjected to the multi-criteria evaluation technique (see, for example, Nath *et al.*, 2000) whereby they were combined using an unweighted geometric mean type approach. The use of the geometric mean type formulation allows a “0” score in any of the layers to be reflected in the final result (i.e. a score of 0). This provides an advantage over more simplistic summation or arithmetic mean type techniques where the final result for any raster cell could still be greater than 0, despite constraints (i.e. scores of 0) being present at that cell in one or more of the data layers²⁰⁸.

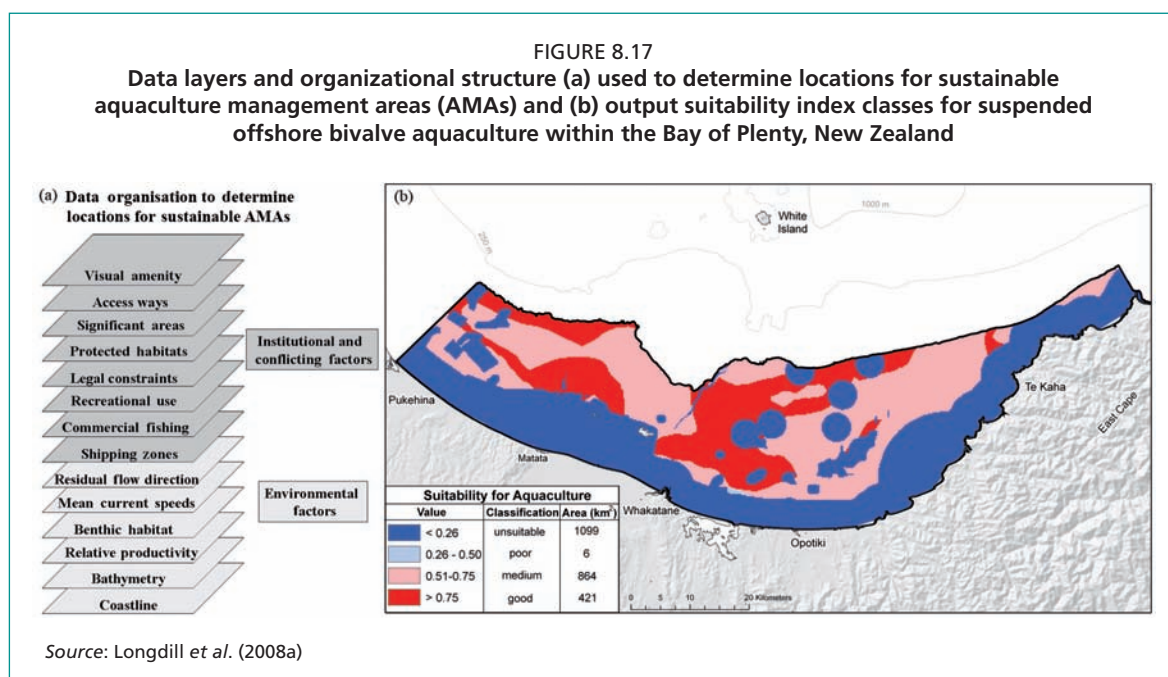
Physical process modelling utilized the 3DD modelling suite and entailed calibrating and applying a 3-dimensional numerical model simulating tidal dynamics, wind driven influences, and regional current systems. A dedicated 3-dimensional numerical ecological model (3DD Life) was developed in both MATLAB and FORTRAN environments and superimposed on the physical process model to simulate nutrient-phytoplankton-zooplankton-detritus interactions. This ecological model also comprised an aquaculture submodel to simulate the effects of bivalve aquaculture.



²⁰⁷ A value of “0” would represent a “zero productive area”. In implementing the model, it was ensured that there were no “0” values in specific relevant data sets, such as productivity potential. This was performed as it would be incorrect to categorize areas as of “zero productivity potential”, i.e. there would always be some level of productivity (or this productivity could be obtained at a high cost).

²⁰⁸ If data layers have values of 0.5, 0.5, 1, 0, the geometric mean is 0 and the arithmetic mean is 0.5. As one of the layers is a constraint (score of 0), then with the geometric approach the final result is 0.

Results: Benthic habitats have varying abilities to assimilate inputs from intensive aquaculture. The discrete benthic data sets (habitat type, sediment size, sediment organic content and potential for aquaculture-induced change) were combined to create a benthic suitability index²⁰⁹ (Figure 8.16), which was subsequently used for further GIS assessments (Figure 8.17). The analysis of benthic data indicated that soft-sediment habitats, comprised of fine silty and muddy sediments with low organic contents, as the most suitable benthic environment (within the Bay of Plenty continental shelf) above which to site bivalve aquaculture. An integrated GIS assessment of selected factors influencing environmental, institutional and productivity aspects of aquaculture zoning resulted in 18 percent (or 421 km²) of the 2 390 km² Bay of Plenty continental shelf being classified as “good” or “most suitable”(Figure 8.17).

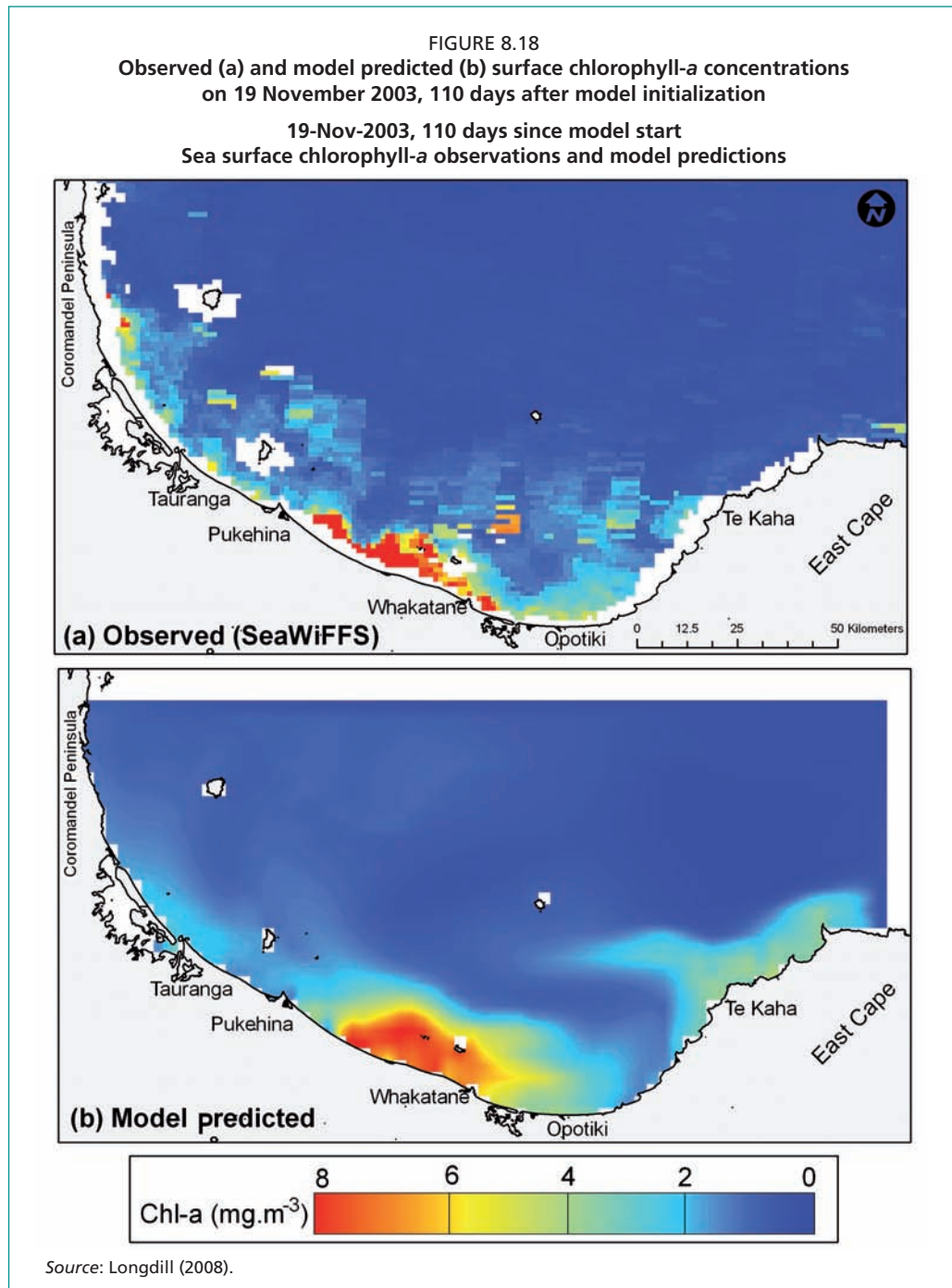


Taking the analysis further, 3-dimensional numerical modelling of both physical processes (tide and wind currents, etc.) and ecological processes (nutrients and phytoplankton, etc.) was calibrated against measured data to ensure replication accuracy. Figure 8.18 shows a comparison of observed (SeaWiFS) and model-predicted surface layer²¹⁰ (0–15 m) chlorophyll-*a* concentrations on 19 November 2003.²¹¹ Chlorophyll-*a* concentrations in deeper layers within the 3-dimensional model were calibrated against field data collected from alongshore normal transects made during four separate seasonal survey campaigns (Longdill, Healy and Black, 2008a). With the model predicting accurately, a mussel feeding submodel could be implemented to predict the influence of substantial offshore bivalve mussel culture (two farms were proposed by the industry of 4 000–4 500 hectares each located from 5–15 m below the sea surface) on the modelled ecological parameters.

²⁰⁹ This index comprised a classification of benthic environments into four broad categories. The basis for the suitability categories is described in detail in Longdill *et al.* (2007).

²¹⁰ The 3-dimensional model attempted to replicate both the horizontal and vertical distributions of chlorophyll-*a*. Remote sensing provided surface layer calibration data while the results of field survey campaigns (four surveys spaced throughout the year) provided calibration data for deeper model layers (to 80 m depth), as described in Longdill (2008a).

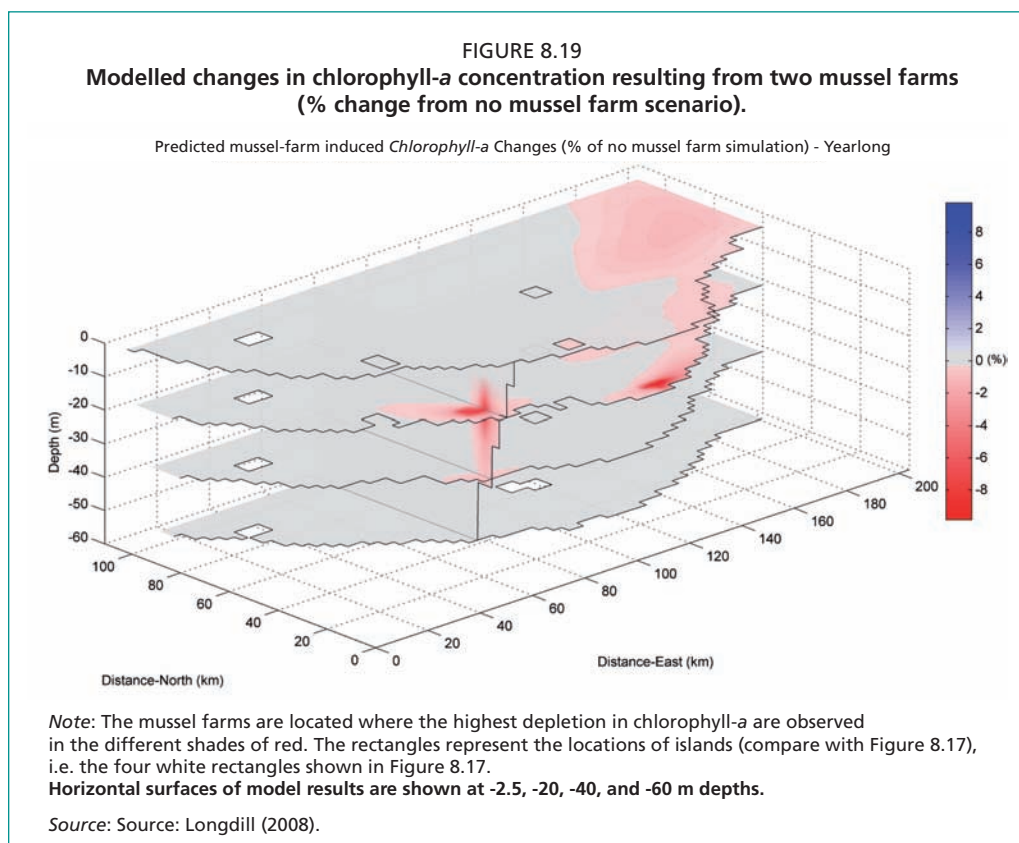
²¹¹ The date of 19 November 2003 was selected for display in Figure 8.19 because of the relative cloud-free remote sensing data available at this time, along with the date corresponding to 110 days into the model run, thereby indicating model stability.



Results from this testing were valuable and indicated that maximal depletions of chlorophyll-*a* (≥ 5 percent of background) were restricted in spatial extent to scales similar to those of the farms themselves (Figure 8.19). At lesser chlorophyll-*a* depletion magnitudes (< 5 percent of background), the modelled depletion halos of the two farms are largely influenced by local hydrodynamics. In particular, the westernmost farm shows a depletion zone extending both horizontally and vertically while the easternmost farm shows a more vertically restricted (and horizontally extensive) depletion halo (Figure 8.19).²¹² The greater vertical extent of the westernmost farm's depletion halo is related to the vertical mixing caused by upwelling and downwelling processes occurring at this location (and not at the location of the easternmost farm),

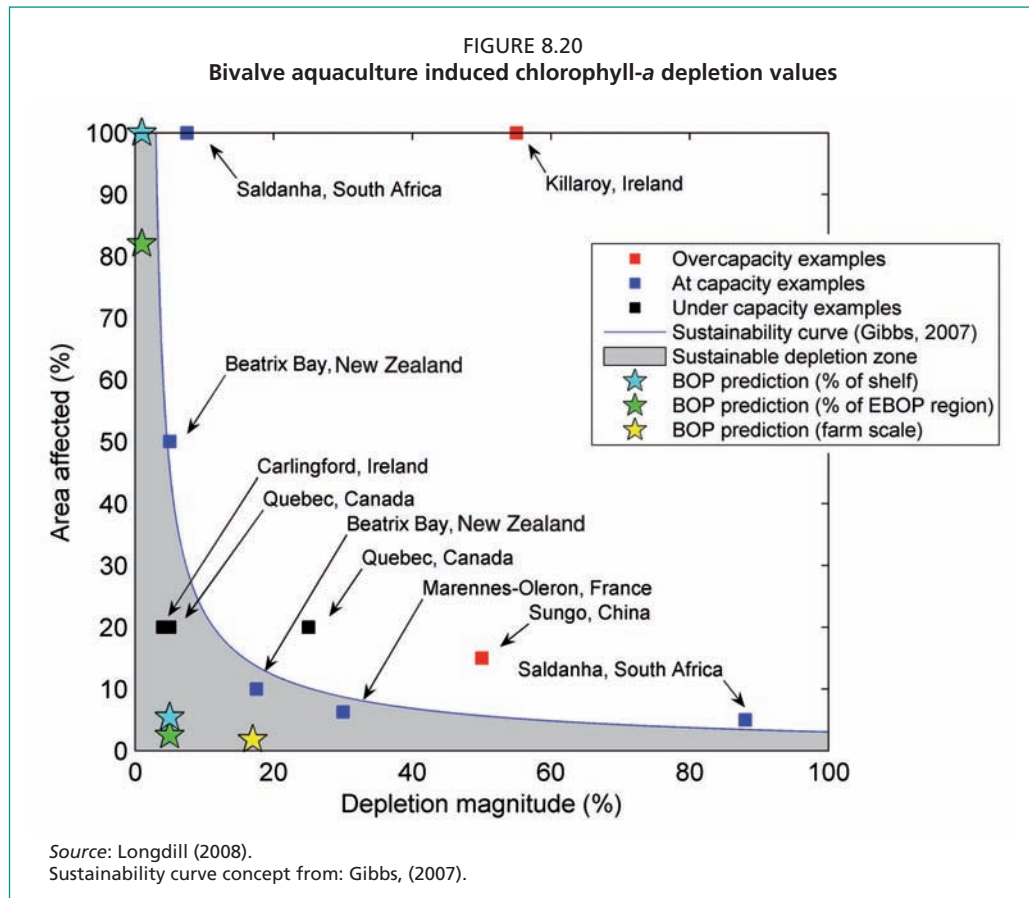
²¹² It is important to note the large-scale variation shown in this figure between the vertical and the horizontal axes.

Longdill, Healy and Black (2008b). Magnitudes and extents of these depletion halos were summarized within the GIS. Simulated interactions between the mussel farm and the surrounding waters (such as mussel-farm-related chlorophyll-*a* and ammonium concentration changes) varied substantially throughout the year owing to seasonal environmental stressors.



Discussion, conclusions and recommendations: The applied method can effectively identify the most suitable areas (based on the predefined input criteria), and indicate the potential level of impact (on basic ecological variables and based on a predefined farm size/type). However, difficulty arises when attempting to answer the final question of “What level of aquaculture is acceptable or sustainable?” i.e. What is the ecological carrying capacity? The study attempted to provide some response to this question by placing the magnitude and spatial extent of chlorophyll-*a* change (used as a proxy for phytoplankton) into a global context. A promising methodology for assessing the limits of “acceptable” depletion magnitudes and spatial extents is that of depletion limits. This methodology requires that consideration be given to both the magnitude of depletion and the spatial scale over which it occurs. Specific definitions and the application of “acceptable depletion limits” or “trigger values” are currently only in the initial stages of implementation with respect to aquaculture (e.g. Gibbs, 2007). Through a review of other studies and their authors’ assessments of carrying capacities, an “acceptable depletion curve” was generated and results from the Bay of Plenty model included (Figure 8.20).

For the simulated farms within the Bay of Plenty, the predicted extent of the 5 percent chlorophyll-*a* depletion halo reached a maximal value of 243 km² (during autumn), while the 1 percent depletion halo reached a maximal value of 7 821 km² (during winter). Converting the extent of these depletion halos to a percentage-based value (required for depletion magnitude-extent values) presents a problem on open



coast sites because a “total area” must be defined in a location where boundaries can be difficult to define. Suitable boundaries within the Bay of Plenty might be the continental shelf (extending to 200 m water depth) and the marine administrative area of the regional council (EBOP). The use of both these areas results in multiple potential depletion magnitude-extent combinations, i.e. blue and green stars respectively in Figure 8.20, rather than single point estimates. Predicted depletion magnitude-extent combinations using both of these boundaries, along with the maximal extents of the 1 and 5 percent depletion halos and the maximal depletion at farm scales (17 percent over ~85 km² and the yellow star in Figure 8.20) all result in combinations well within the “sustainable zone” of the inferred “sustainable depletion curve” (Figure 8.20).

Challenges and benefits from the case study: The application of the GIS to identify the most suitable sites for aquaculture in an open coast location appears to be beneficial. However, several challenges were met during the study and they must be either overcome or acknowledged for the study to be useful. These include the costs of data collection and a focus on a predefined aquaculture system and species. By using such a predefined system and species, however, the analysis can be taken further to include preliminary productivity estimates and economic aspects for a future aquaculture lease as demonstrated by some of the data layers employed in this study. There should be no doubt that the identified areas cannot, on the sole outcome of such a GIS analysis, be assigned as aquaculture areas. The analysis can be used to indicate suitable (and unsuitable) locations, though much more consultation and many agreements would of course be required prior to implementation.

This study and others of its type also fail to allow for the future changes in existing uses and/or users, legal settings and culturing techniques. Such changes could of course lead to fundamentally different outcomes. If these are real and key concerns

for the study, the application of the described approach should be kept in perspective. Additionally, the technique favours existing uses of the marine area as it does not consider that aquaculture may have as much of a “right” to an area as a pre-existing use. The use of an ecological model to simulate potential farms and the corresponding GIS analysis represent a valuable and exciting future direction for the use of GIS and aquaculture.

8.4.4 Development of potential and financial viability of fish farming in the Republic of Ghana

Original publication reference: Asmah, R. 2008. *Development of potential and financial viability of fish farming in Ghana*. Institute of Aquaculture. University of Stirling. 289 pp. (PhD dissertation)

Spatial tools: The primary software tools used were IDRISI Andes and Cartalinx.

Main issues addressed: Strategic planning for development.

Duration of study: 1 year.

Personnel involved: Ruby Asmah (PhD student), James Muir (principal supervisor) and Lindsay G. Ross (additional supervisor).

Target audience: Water Research Institute of the Council for Scientific and Industrial Research, Accra, Ghana. Fisheries Commission of the Ministry of Food and Agriculture, Ghana, and aquaculturists.

Introduction and objectives: The Republic of Ghana is located in West Africa, a few degrees north of the equator. It has a total land area of 238 540 km² and a coastline length of 550 km. Aquaculture has been practised in Ghana since the 1950s, but until about a decade ago fish culture was largely undertaken in earthen ponds, primarily at the small-scale level and where rudimentary tools were employed. From about 1998, the sector has transformed with the introduction of commercial cage fish farming in Lake Volta. Vigorous campaigns and promotions of the sector by government agencies over the years have further enhanced commercial interests of both foreign and local investors. A number of farms, with targeted production capacities ranging from 700 to 5 000 tonnes per annum, have been established within the last five years and are operating at various levels of their full capacities. Several other small-scale production facilities or farms, mainly operated by locals, have also sprung up and their numbers continue to grow. The main cultured species is Nile tilapia (*Oreochromis niloticus*). Other cultured species are African catfish (*Clarias gariepinus*), African Arowana (*Heterobranchus spp.*), striped snakehead (*Channa striata*), grey mullet and *Heterotis* sp. (Asmah, 2008).

Decreased fish production from wild capture coupled with increasing human population in the Republic of Ghana has led to a shortfall in domestic fish supply with current annual supplies being about 40 percent less than the required 735 000 tonnes. With aquaculture being a more reliable way of increasing fish production than management of wild stocks, the Government of the Republic of Ghana has enhanced its focus on aquaculture with a goal of increasing production from 1 150 tonnes per annum (2006 annual production figure) to 15 000 tonnes in about five years. A key issue in aquaculture development is that of defining its potential location and scale. This conventionally involves site selection, and requires definition of conditions and strategic locations where appropriate farming systems can be developed, although this can be complicated by conflicting economic, social and environmental interests and the requirement for the activity to be commercially viable (McLeod, Pantus and Preston, 2002). With an adequate database, however, GIS can be used to organize and present spatial data to allow effective environmental management planning, and GIS can thus serve as a powerful analytic and decision-making tool (Nath *et al.*, 2000).

The first assessment of the country's fish farming opportunities using GIS was undertaken by Kapetsky *et al.* (1990) to identify the districts with the best prospects for farming Nile tilapia (*Oreochromis niloticus*) and African catfish (*Clarias gariepinus*) in ponds with manure and rice bran as the main inputs. Other assessments involving the Republic of Ghana and other countries in the African region were those by Kapetsky (1994) and Aguilar-Manjarrez and Nath (1998).

The objective of this study was to use a GIS approach to reassess the potential for small-scale and commercial aquaculture development in the Republic of Ghana in the light of the expected expansion in the sector, using data of higher resolution compared with previous studies and incorporating recommendations for improved assessment methods mentioned in the previous studies. The study focused on freshwater aquaculture, considered to be the primary area of sectoral development at this stage, with particular but not exclusive focus on tilapia. It incorporates primary definers²¹³ of water, climate, soils and feed/fertilizer sources, together with more specific issues such as market access and other social and economic factors. This case study is a summary of Chapter 5 from Asmah (2008).

Methods and equipment: Data were obtained from secondary sources, primarily from the Ghana Country At a Glance (G-CAG) database, which was developed in 1999 as an additional resource to the Environmental Information System Development component of the Ghana Environmental Resource Management Project (GERMP). Fifty-one geographical, referenced and harmonized data sets covering 12 geographical themes are presented in the database. The themes are: national and international boundaries, conservation areas, climate information (temperature, rainfall and evapotranspiration), geology, hydrology, land cover, land ownership, soils, topography, infrastructure, transportation and population information.

Digital elevation models used in the slope submodel were obtained from the Shuttle Radar Topography Mission (SRTM) Web site (<http://srtm.usgs.gov/index.php>). Updated information on district populations and growth rates used in the market submodel were obtained from the Ghana Statistical Services 2000 population and housing census report (Ghana Statistical Service, 2002) and the Ghana Districts Web pages (www.ghanadistrict.com). Information on road density for each of the districts was obtained from online reports at the Ministry of Roads and Highways (www.mrt.gov.gh).

The suitability of areas for aquaculture development in the Republic of Ghana was assessed by identifying important factors and constraints. A factor (or production function) is defined as a criterion that adds to the suitability of the specific alternative area under consideration, while a constraint serves to limit alternatives under consideration (Eastman, 2001), such as forest and game reserves, road networks, river courses and large waterbodies (in relation to pond construction). Factors considered basic for aquaculture development in the study were: water availability and quality, terrain and soil suitability, infrastructure in the form of roads, support in the form of extension services and supply of fingerlings, availability of inputs (manure, agriculture by-products and other feed types) and markets.

²¹³ "Primary definers" are the basic physical and biological factors that control the possibility of (in this case) fish production taking place.

The factors were classified in four suitability rankings i.e. very suitable (VS), suitable (S) fairly suitable (FS) and unsuitable (US). The VS level provides a situation in which minimum time or investment is likely to be required in order to develop fish farming, an S classification implies that modest time and investment are required, FS level implies that significant interventions may be required before fish farming operations can be conducted, while US implies that the time or cost, or both, are too great to be worthwhile for fish farming (Aguilar-Manjarrez and Nath, 1998). Criteria classifications for the various factors are summarized in Table 8.4. Classification was primarily based on the literature and on prevailing practices in the Republic of Ghana (referred to as local practices).

To develop a decision-making model, the selected and classified criteria were developed into a series of submodels that can logically group certain factors together within a general model. For example, some factors were grouped to form submodels naturally, e.g. in a soil classification, soil texture, soil pH and slope were grouped into a submodel called soils and terrain, while some others factors were grouped into submodels to enable a better understanding, e.g. research centres and fisheries offices were grouped to form a support submodel. Aguilar-Manjarrez (1992, 1996) and Aguilar-Manjarrez and Ross (1995b) noted that the creation of submodels may be divided into stages within the general model, i.e. primary, secondary, tertiary, etc. The number of stages will vary according to the application, but the overall approach is the same and contains the following steps:

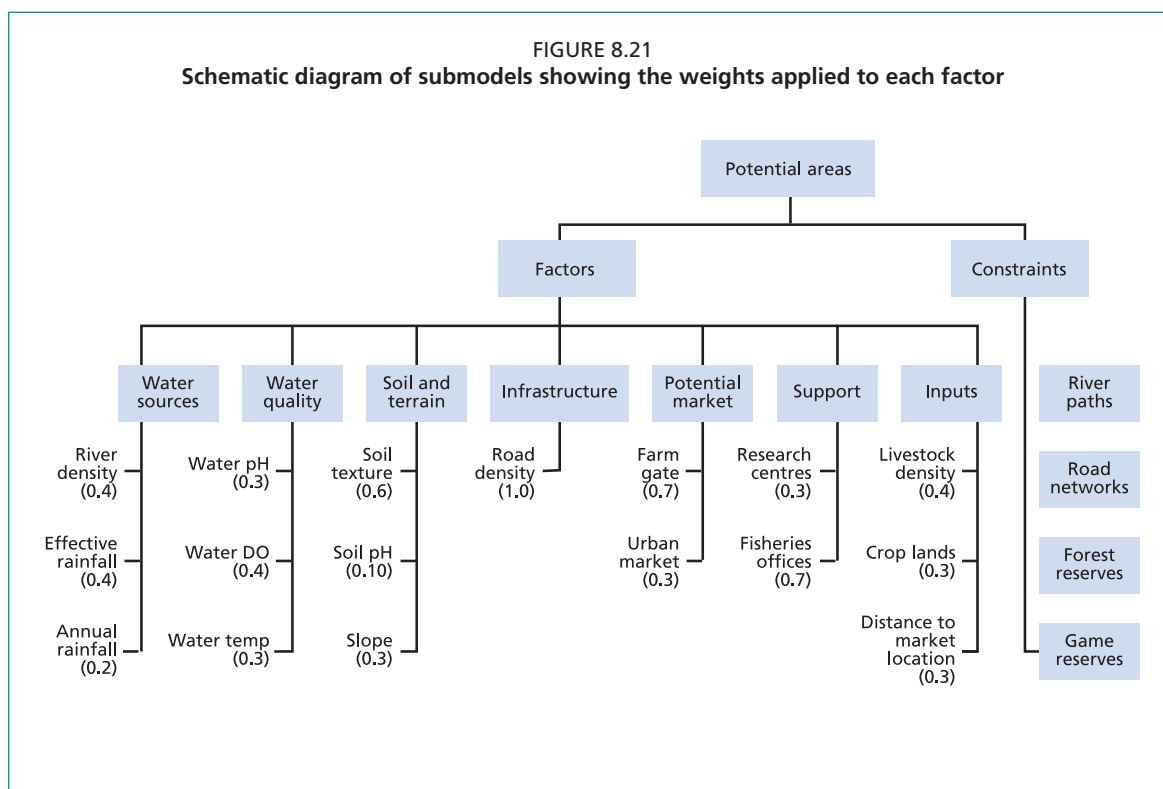
- (i) The primary stage of the models constitutes its foundation and is represented by the collection of original data, i.e. thematic maps, statistical data and data available in computer format.
- (ii) In the second stage, factors are grouped naturally, i.e. river density, effective rainfall and annual rainfall were associated to a water sources group, and as nonspecifically as possible (Table 8.4).
- (iii) As the model develops, more submodels are created in a more specifically orientated way so as to develop specific responses required by the user, e.g. construction constraints for pond construction.
- (iv) Only at the very end of the modelling process do the groupings become application-specific in order to solve a particular problem/issue, e.g. suitability for commercial farming of Nile tilapia.

To illustrate the approach used, Figure 8.21 is a schematic diagram of the integration of the submodels showing the weights applied to each submodel.

TABLE 8.4
Criteria classification

Land characteristics	Classification criteria				References
	Very suitable	Suitable	Fairly suitable	Unsuitable	
Water sources submodel					
Annual rainfall (mm)	> 1 200	1 000–1 200	700–1 000	> 700	Kapetsky, 1994
Effective rainfall (mm)	≥ 0	1 to -2000	-2000 to 3499	< -3500	Aguilar-Manjarrez and Nath, 1998
Perennial river density (km/km ²)	≥ 0.36	0.2–0.35	0.04–0.20	< 0.04	Kapetsky, 1994
Water quality submodel					
pH	6.0–8.0	5.0–6.0	4.0–6.0	< 4.0	Salam, 2000
Dissolved oxygen (mg/l)	5.0–10.0	4.0–5.0	3.0–4.0	< 3.0	Salam, 2000
Water temperature (°C)	25–32	22–25	18–22	0–18	Salam, 2000
Soil quality and terrain submodel					
Soil texture (%)	> 80	50–80	20–50	0–20	Coche and Laughlin, 1985
Soil pH	6.5–8.5	5.5–6.5	4–5.5	1.0–4.0	Coche and Laughlin, 1985
Soil slope (%)	0.2	2 – 5	5–8	> 8	Coche and Laughlin, 1985
Infrastructure submodel					
Road density (km/km ²)	≥ 0.36	0.20 – 0.36	0.04 – 0.19	< 0.04	Kapetsky, 1994
Market submodel					
Farmgate (inhabitants/km ²)	150–310	25–150	1–25	< 1 and > 31	Kapetsky and Nath, 1997; Aguilar-Manjarrez and Nath, 1998
Urban market (inhabitants/km ²)	> 1 000 000	250 000 – 1 000 000	50 000 – 250 000	< 50 000	Aguilar-Manjarrez and Nath, 1998
Proximity to urban market (km)	0–165	165–330	330–499	> 500	Based on local practices
Inputs submodel					
Crop lands (suitability index)	80– 00	50–79	20–49	< 20	Boateng <i>et al.</i> , 2001
Proximity to urban market locations (km)	0–166	167–333	334–499	> 499	Based on local practices
Support submodel					
Proximity to institutions and commercial farms (km)	100	200	300	> 300	Based on local practices

Note: The suitability index refers to the suitability of an area for growing particular crops whose by-products (e.g. rice bran, waste crops etc) were used as fish feed by farmers. Soil type and other environmental factors were considered for this index.



Results: Results of the submodels showing the size (km²) and percentage of total land area identified as very suitable, suitable, fairly suitable and unsuitable are summarized in Table 8.5, and are presented pictorially in Figure 8.22. Included in Table 8.5 are the results of the integrated models in which size and percentage suitabilities of land for small-scale and commercial farming are indicated.

Integrated models

The submodels were integrated using the weights shown in Table 8.6. Maps of the integrated submodels are presented in Figure 8.23 a and b. About 80 percent (191 854 km²) of the country's land area, excluding forest and game reserves (47 017 km² in size), were found to be suitable for small-scale fish farming. Of this, close to 2 percent (3 692 km²) was very suitable, 97.4 percent was suitable, and less than 1 percent was fairly suitable (Figure 8.23a). The very suitable areas for small-scale farming were largely in the Ashanti and eastern regions, and these were areas where a number of the relevant variables overlapped each other favourably.

The area of land found to be very suitable for commercial farming (Figure 8.23b) was about ten times smaller (314 km²) than that for small-scale farming, and this may be attributed to the greater emphasis placed on market and infrastructure. These areas were again in the Ashanti and eastern regions. A much larger area (161 943 km²) of the country was, however, found to be suitable for commercial farming, which based on the definition of suitability given in the methodology overview, implies that modest time and investment may be required to implement such projects. Similar to that for small-scale aquaculture, the fairly suitable sites were largely in the northern-most part of the country, more precisely in the upper east and upper west regions (Figure 8.23b).

The weights derived for each culture system submodel were based on feedback from aquaculture and development specialists in the Republic of Ghana and the United Kingdom of Great Britain and Northern Ireland between 2004 and 2008. Weights assigned for each submodel ranged from 0–1.

TABLE 8.5
Areas (km²) and percent suitabilities of lands for the factors, submodels and integrated models for small-scale and commercial farming

Land characteristics	Very suitable		Suitable		Fairly suitable		Unsuitable	
	Km ²	%	Km ²	%	Km ²	%	Km ²	%
Inputs submodel								
Effective rainfall	-*	-	184 102	77.1	54 769	22.9	-	-
Perennial river density	4 661	2.0	126 916	53.1	91 357	38.2	15 936	6.7
Annual rainfall	128 257	53.7	70 770	29.6	39 842	16.7	-	-
Overall	4 113	1.7	194 856	81.6	39 901	16.7	0.36	0.0
Water quality submodel								
Water temperature	238 872	100	-	-	-	-	-	-
pH	238 872	100	-	-	-	-	-	-
Dissolved oxygen	194 101	81.3	44 770	18.7	-	-	-	-
Overall	238 872	100	-	-	-	-	-	-
Soil quality and terrain submodel								
Soil texture	34 546	14.4	41 790	17.5	52 610	22.0	110 305	46.1
Soil pH	42 555	17.8	156 122	65.3	25 140	10.5	15 436	6.5
Slope	62 042	27.9	99 634	44.8	29 924	13.4	30 901	13.9
Overall	21 709	9.1	62 516	26.1	130 468	54.4	24 876	10.4
Infrastructure submodel								
Road density	28 106	11.8	70 883	29.7	131 712	55.1	8 170	3.4
Market submodels								
Farmgate	16 482	6.9	146 426	61.3	65 185	27.3	10 777	4.5
Urban market and proximity	480	0.2	35 927	15.0	202 463	84.8	-	0.0
Inputs submodel								
Crop lands	2 790	1.2	47 707	20.0	67 887	28.4	120 489	50.4
Animal density	2 015	0.8	13 266	5.5	141 267	59.0	82 904	34.6
Proximity to urban market locations**								
Over all	260	0.1	41 458	17.2	158 858	66.0	40 103	16.7
Support submodel								
Proximity to institutions	96 760	40.5	98 009	41.0	44 101	18.5	-	0.0
Integrated models								
Final model – small-scale	3 692	1.9	186 880	97.4	1 278	0.7	-	-
Final model – commercial	314	0.2	161 943	84.4	29 597	15.4	-	-

* The area is less than 1 km². ** Physical locations.

Note: The data in Table 8.5, represented by Figure 8.22 include the reserved areas. These areas were only taken out in the final integrated models in Figure 8.23 a and b, as they show areas where one can supposedly site a pond.

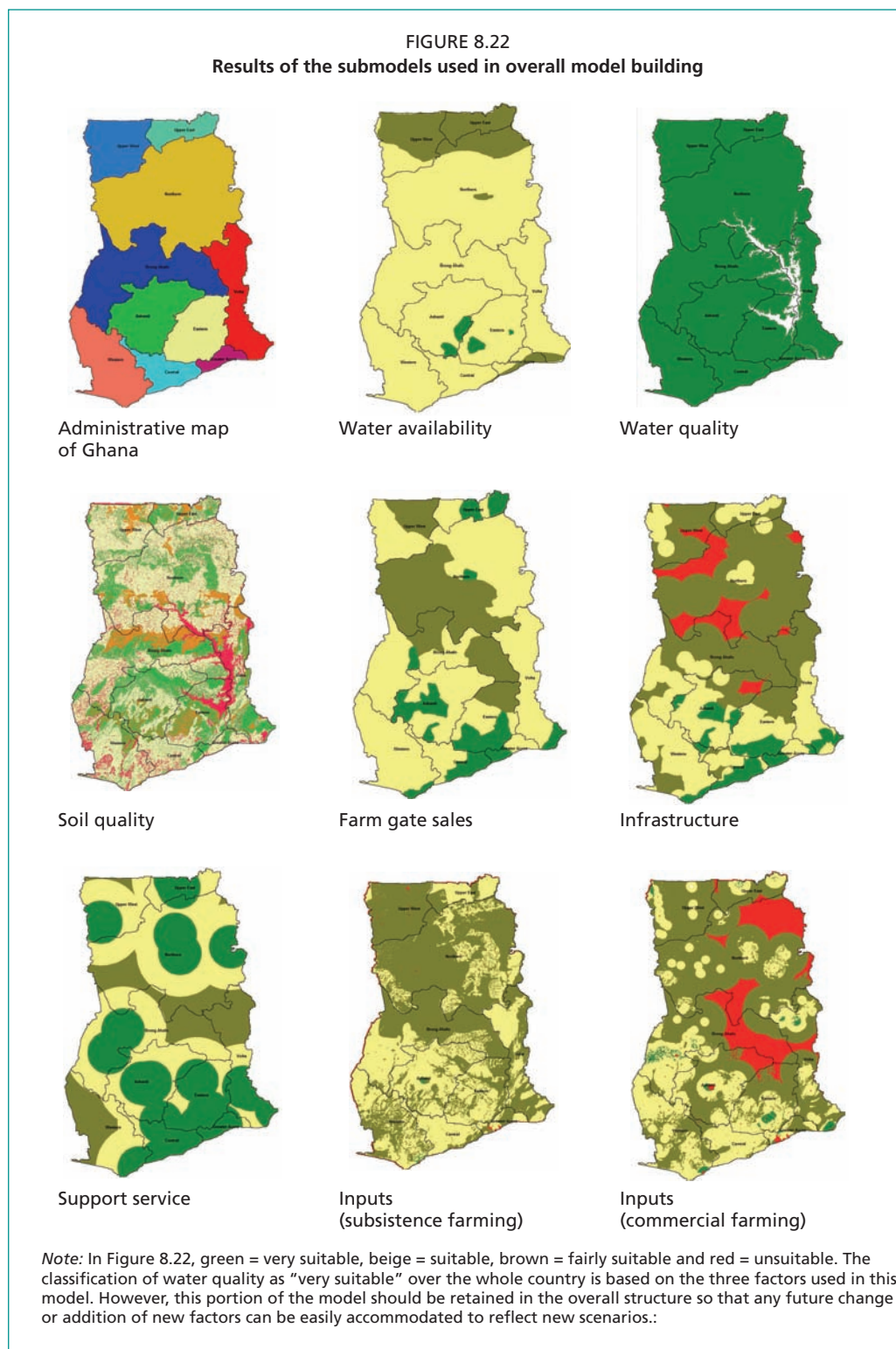
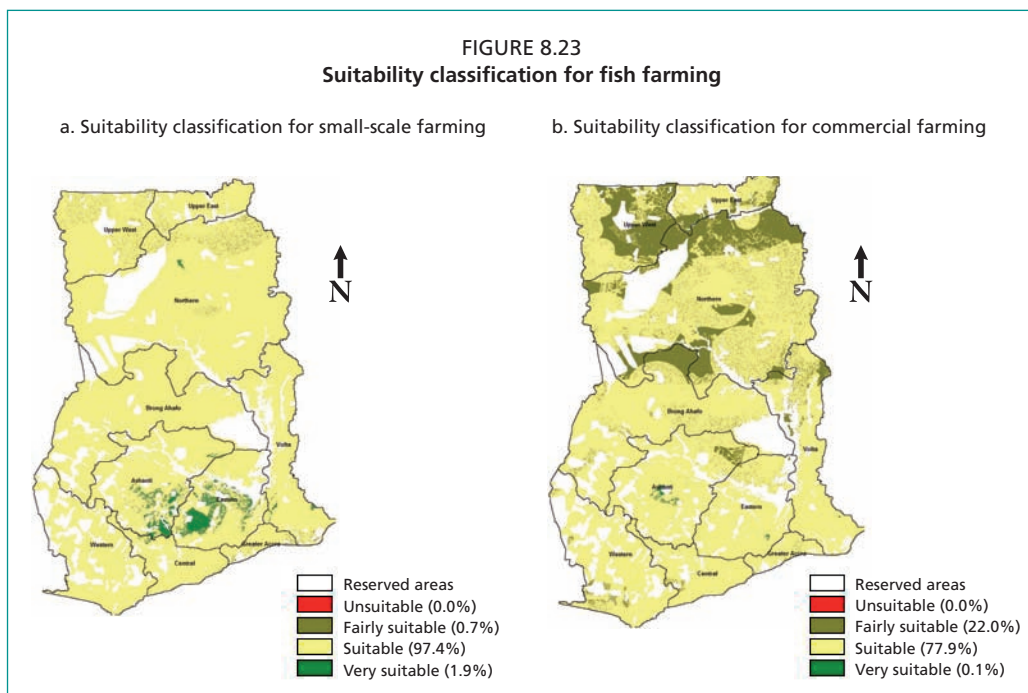


TABLE 8.6
Weights derived for the submodels

Submodels/ models	Water resources	Water quality	Soil quality and terrain	Infrastructure	Markets	Inputs	Support	Total weight
Small scale	0.41	0.18	0.21	0.06	0.01	0.07	0.06	1.0
Commercial	0.27	0.15	0.12	0.08	0.25	0.08	0.05	1.0

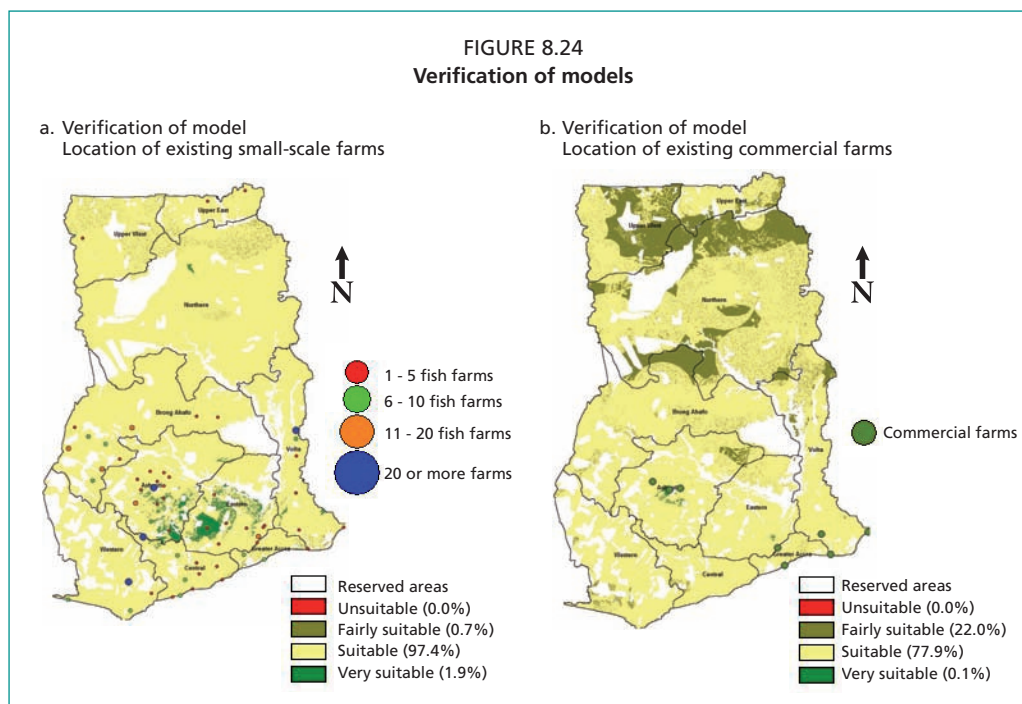
The inputs submodel was given a low rating for both small-scale and commercial farming because most fish farmers obtained ingredients from the market and produced their own feed on the farm so availability was not an issue. On-farm feed production was only abandoned in recent times as people have realized that imported extruded feed gave better growth rates and that the quality of inputs is very important. Markets had a high rating for commercial farming as it served two purposes: (i) selling of product; and (ii) buying of feed components. Farmed fish did not have the market that it has now and there were times when farmers could not sell their produce, so identifying a good market in the early to mid-2000s was very important. The commercial farmers also produced their own fingerlings on-farm from broodstock that were sometimes obtained from the wild.



The key differences in factor rankings for small-scale compared with commercial farming were in the relative importance placed on urban markets and infrastructure with respect to likely commercial farming success. Harvests from commercial farming will be expected to sell beyond the farmgate where proximity to urban markets and infrastructure becomes very important, whereas in small-scale farming farmers consume part of the harvest, use some as compensation for labour and sell the surplus locally. Water availability, water and soil quality, and terrain models were given the highest importance in small-scale farming, as farmers in this category may not be in a position to incorporate expensive technologies.

Verification of integrated models

The verification process simply compares the extent to which current fish farms are located in the optimum areas predicted by the models. Outcomes of the verifications are presented in Figure 8.24 a and b for small-scale and commercial farming, respectively. Most of the fish farms in both cases were located in areas classified as either very suitable or suitable and largely concentrated in the southern and middle belts of the country. The concentration of pond farms within particular areas is depicted on the map by the colours red, green, orange and blue for areas with 5 farms or less, 6 to 10 farms, 11 to 20 farms, and more than 20 farms, respectively.



Discussion, conclusions and recommendations: In general, the very suitable areas for both levels of production were all in the southern parts of the country, specifically the Ashanti and eastern regions. Kapetsky *et al.* (1990) also identified the southern part of the country as having the best opportunities for fish farming.

Based on an overview of fish farming in the Republic of Ghana undertaken by Asmah (2008), mean fish yield/ha by small-scale farming was found to be 2.3 tonnes/annum. Yields by commercial farmers were varied ranging from 4.4 tonnes/ha per annum to 45 tonnes/ha per annum depending on scale and intensity of production. Commercial farming currently accounts for about 60 percent of the country's annual aquaculture production. Meeting the government's target of 200 000 tonnes of fish production from aquaculture per annum in five years, based primarily on pond culture and current production practices and trends, may require developing about 13 978 ha (14 km²) of land for commercial farming and 34 783 ha (347.8 km²) of land for small-scale fish farming, which, based primarily on the availability of land, is certainly feasible. Aquaculture production of 1 150 tonnes in 2006 and an annual mean farm development growth rate of 16 percent (Asmah, 2008), however, makes the target unachievable in the time scale given. Achieving this target, in addition to considering the availability of land, may require a growth rate of both commercial and small-scale farming of not less than 60 percent per annum over five years.

Challenges and lessons from the case study: This study uses data available from public sources to generate a holistic overview of aquaculture opportunities in the Republic of Ghana in order to support broad-scale strategic planning decisions. A multi-criteria evaluation (MCE) technique was used to generate logical submodels and MCE was used again in order to combine submodels to achieve the overall project objectives. The model structure and the assignment of weights used were based on expert opinion from United Kingdom and Ghanaian aquaculture and development specialists. Model structure and weight assignment are an important stage and is what distinguishes simple cartography from more advanced use of such systems to form expert models. While further data refinement and model adjustment could be achieved, the outcome is nevertheless a powerful illustration of the integrative use of GISs and their ability to work with and model from widely disparate data sets.

This study is based on a relatively simple model structure and, consequently, is easily replicated for other countries (assuming that the data are available), for example, to support the preparation of national aquaculture strategies and national development plans. Having identified potential areas within the Republic of Ghana, more detailed studies would follow using data sets at a greater resolution to allocate zones for aquaculture and to conduct site selection and carrying capacity assessments and to establish monitoring programmes.