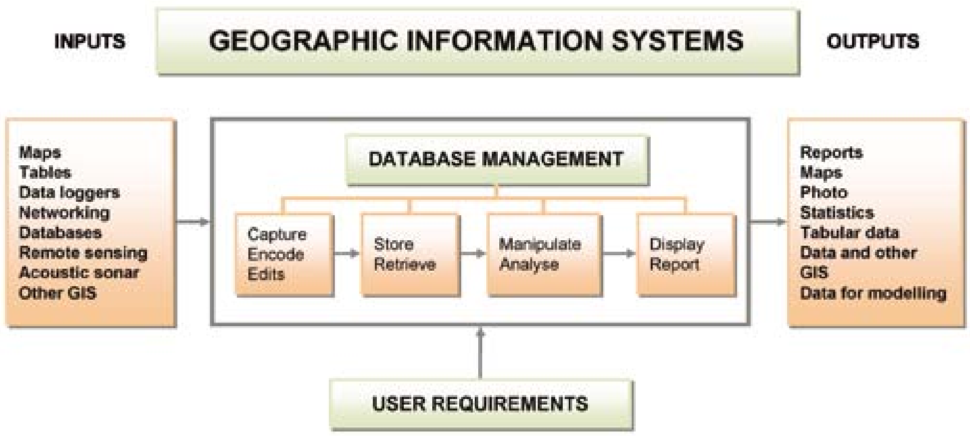
3. The current status of GIS in marine fisheries

3.1 GIS AS A TOOL

A GIS may be defined as a collection of computer hardware, software, data and personnel designed to collect, store, update, manipulate, analyse and display geographically referenced information (Rahel, 2004) (Figure 3.1). There is no single GIS; systems can be assembled in an infinite number of ways. Hardware can refer to desktop or laptop computers, plus other smaller mobile devices, and to technology designed to input or output data or information such as digitizers, scanners, printers and plotters. There are a many general commercial and free open-source GIS software packages and even more GIS applications that have been developed for specific purposes, such as for use by the military or utility companies. Data can be collected for specific projects in the field or can be obtained from commercial or governmental sources and data can be delivered via CD-ROMs, flash-drives or over the Internet or other such integrated server networks. Personnel are usually highly trained in both computer science and geographical analysis, though many specialists have moved from applied research areas to GIS when it has been advantageous.

FIGURE 3.1
A process diagram to conceptualize the functioning of GIS



Source: Modified from Rahel, 2004.

The importance of GIS is based on the fact that all earth processes and functions are inherently spatial. GIS are unique in their ability to conduct spatio-temporal analyses in order to understand complex earth processes. For any specific problem or area or time, data can be assembled and input to the system. GIS themselves are designed to perform a large array of spatio-temporal analyses and operations over multiple scales or resolutions. Output from a GIS is largely in the form of maps although it can also be in tabular, statistical or graphical form. The appeal and usefulness of a GIS lie in its capacity for problem solving in the spatial domain and for generating mapped representations of complex ecosystem interactions and processes in a way that managers can understand and make decisions from.

3.2 A BRIEF HISTORY OF GIS TECHNOLOGY AND DEVELOPMENTS

The history of the GIS began in the 1960s with the development of the Canada Geographic Information System. This first true GIS was designed to manage natural resources dispersed over a wide spatial area (Tomlinson *et al.*, 1976). At that time, a second impetus for computer generated mapping was provided by the Dual Independent Map Encoding project undertaken by the United States Bureau of the Census to produce spatially-based output from the 1970 United States census. The 1970s saw intensive work at universities such as Harvard, Minnesota, Edinburgh and the Royal College of Art in London to develop both vector- (line) and raster- (pixel) based mapping, so that by the end of the 1970s a large number of software packages for handling geographic information had been developed (Marble, 1980). Many of the early GIS were designed to meet specific needs and generally focused on improving basic mapping capability. Almost all the early work on GIS development was conducted by the public sector (government, universities and the military), mainly because very high costs were involved for acquiring and operating the requisite mainframe computers.

Following this innovative early period, the 1980s saw an era of commercialization (Longley *et al.,* 2001). This was made possible for a number of reasons, primarily the rapidly decreasing costs of computing, the development of cost-effective applications, the proliferation of data (largely through satellite remote sensing) and the emergence of smaller computing platforms (minicomputers and then personal computers), plus developments in parallel fields (see Box 3.1). The integration of these parallel technologies are extremely important for GIS because not only are many of them crucial to GIS but the existence of the GIS itself provides a rationale and spur for their own development. The 1980s saw the emergence of most of today's major software suppliers so that by the mid-1980s there were approximately 100 different commercial GIS packages available. Gradually the use of GIS spread into an increasing number of areas, though its major applications remained with the more traditional areas of land-use planning and resource management.

The 1990s saw continued though accelerating commercial development with expansion rates in the GIS sector as a whole of approximately 14 percent per annum (Payne, 1993; Frost & Sullivan, 1994). Along with the growth of GIS came the proliferation of associated activities such as the publication of dedicated books and journals, specialist conferences, the development of international standards through such organizations as the Open Geospatial Consortium (OGC), the establishment of GIS associations (e.g. the Association for Geographic Information in London) and a large expansion in GIS-oriented higher education. Towards the end of this period, some consolidation within the software development sector rationalized the number of commercial GIS packages available. It would be true to say that at the beginning of the 21st century we are now in an age of mass use and exploitation of GIS by a broad array of social, economic and environment sectors.

3.3 THE MAIN FUNCTIONALITIES OF GIS

The following is a brief overview of the main areas of functionality that GIS can provide.

- Data pre-processing and management. Before any GIS task can be performed, various editing or manipulation functions may be necessary to ensure that the data are in a suitable form and sufficiently accurate for subsequent analysis and representation. For example, data might need to be updated or corrected, or converted to an appropriate map projection. Scale changes might also be required.

BOX 3.1

Parallel technologies or disciplines that have assisted in the development of GIS

The Internet. It has allowed for information and data downloads and is now increasingly used for the development of interactive mapping engines.

Remote sensing. Satellite and aerial imagery are by far the largest source of data for GIS. Satellites also provide the basis for the global positioning system (GPS) and derived applications, e.g. vehicle navigation and VMS.

Environmental modelling. Outputs from models provide a source of data and modelling itself is often performed using a GIS environment.

Software developments. Not only are there many varied GIS packages but linkages between GIS and other specialized software are becoming increasingly common in many sectors.

Hardware. Hardware forms the computer-based platform for GIS operations and numerous other pieces of hardware may form part of a complete GIS, e.g. scanners, plotters, digitizers, data loggers, GPS and sonar.

Computer-aided design (CAD) and graphics. CAD represents a technology having similar input/output requisites to GIS and has thus contributed significantly to GIS development.

Digital cartography. While most cartography is not concerned with analysis *per se*, the output from digital cartography shares the exact requirements to those of GIS.

Geostatistics. Much of the output from a fisheries GIS depends upon the application of geostatistics to model various distributions or future projections.

Photogrammetry. It is a technique for measuring objects from photographs, electronic imagery, videos and satellite images, providing an important source of spatial information.

- Spatial and non-spatial data integration. Integration of geographic entities representing real location on the earth into non-spatial information is one of the strengths and prominent functionalities of a GIS. In this context, quantitative information (location, dimension, spatial relationships) can be combined with qualitative information (attributes, text, descriptions) to create a functional model of the real world.
- Measurement. This can be achieved in terms of not only distance, perimeter, volume and area but also in the sense of statistical measurements (sum, mean, mode, standard deviation).
- Distributions and relationships. Fundamental to geographic analyses are basic distributions and distributional patterns, e.g. do entities display clustered, random or uniform distributions? Are there spatial patterns showing contiguity, proximity or autocorrelation? What is the optimum location for any specific enterprise?
- Modelling. Models of geographic processes can be constructed to understand the world as it is now, as it has been in the past or how it might be in the future through "What if scenarios". They can range from relatively simple models, such as might be used by planners who seek optimum layouts for cities and their components, to more complex models that seek to discern optimum faunal habitats or to very complex models for processes such as climate change prediction.

- Network analyses. Networks can comprise extremely wide-scale geographic features such as transport routes, drainage networks, pipeline and cable networks, and other linear features. An array of cost and time analyses can be performed by GIS, including shortest path and optimum route analyses, time/cost efficiency routing and connectivity indices.
- Temporal analyses. An important area of interest is how natural and human processes change over time. GIS can, for example, be used to calculate rates of urban expansion, deforestation rates and crop-acreage changes over time. The long-term collection of remotely sensed data has greatly expedited time series analyses such as these changes.

To operationalize any of these functions, GIS applications are equipped with a range of functionalities which themselves are used in a programmed sequence in order to accomplish individual tasks. The commands must be directed towards spatially-referenced data to enable the GIS analyses to proceed. These data are held in files and databases that may be accessible locally or over a network and are held as individual files or as part of a wider data management system.

3.4 USE OF GIS IN MARINE FISHERIES

Although terrestrial applications of GIS had commenced by the late 1960s, it was another two decades before GIS was being applied in the marine environment. Meaden (2000) outlined a GIS Fisheries Task Conceptual Model that described why GIS was a complex task for early adoption by fishery researchers or scientists. In the mid-1980s, a seminal paper by Caddy and Garcia (1986) highlighted the importance of computer-based mapping and spatial analysis to fisheries. Around the same time, the GIS was being demonstrated as a valuable tool for aquaculture (FAO, 1985). Indeed the earliest applications of GIS to fish production were those applications utilized for locating sites for new marine aquaculture operations (e.g. Mooneyhan, 1985; Kapetsky *et al.*, 1987; FAO, 1989; Kam Suang Pheng, 1989).

These early examples of the application of GIS for location analysis were performed for the most part using remotely sensed imagery. Unlike the spatial complexities inherent in marine fisheries, aquaculture location deals with a nearshore static environment in simple 2D and costly surveys are not required to get a range of fisheries-related data. During the early phase of GIS adoption by fisheries, Simpson (1992) noted that remote sensing had the potential to generate much marine data of relevance to GIS applications, such as data for monitoring fishing effort, tracking pollutants, mapping bathymetry and sea-bed habitats, and providing measurements of physical and biological properties in the water column.

During the early 1990s, GIS slowly expanded its range of fishery applications (Meaden, 2001). One of the more popular uses of GIS was for constructing spatially-explicit models of fish-habitat suitability, particularly in inshore zones where, for instance, mangroves, estuaries, seagrass beds, bottom sediments and littoral environments could be mapped relatively easily. After the mid-1990s, the use of GIS for fishery-related work grew rapidly and by the time that the First International Symposium on GIS in Fisheries Science was held in 1999 (Nishida *et al.*, 2001), papers on GIS applications for marine fisheries were presented on various thematic areas (Table 3.1).

TABLE 3.1
Thematic areas of the papers on GIS marine fisheries presented at the First International Symposium on GIS in Fisheries Science in 1999

Thematic area	Number of papers
Fisheries oceanography/habitats	7
Fisheries resource analysis	5
Remote sensing and acoustics	3
Ecosystems/forecasting	2
Estuary and coastal management	2
General review	2
Concepts	1
Education	1
Research in progress	1
Software/database/computer systems	7

Source: The First International Symposium on GIS in Fisheries Science, 1999.

The accelerating rate and breadth of GIS-based, fisheries-related applications resulted from the same set of factors as outlined previously (decreasing costs of computing, better access to data). GIS technology has also been promoted through numerous publications, specialist conferences and workshops, and through the appearance of GIS-generated output in various fisheries journals and more general publications. For a more detailed description of the proliferation of fisheries GIS applications from the beginning of this century, see Meaden (2000), Meaden, (2001), Valavanis (2002) and Nishida *et al.* (2004). Despite this proliferation, it would be true to say that at the end of the last century the use of GIS for fisheries-related work was at an immature stage and this was a result of the very fragmented nature of the fisheries sector as a whole, i.e. much small-scale work was being pursued in isolated places, and because publications were mostly confined to the "grey" literature.

Fisher (2007) describes how applications of GIS to fisheries science and management came to be more sophisticated. Thus, in a survey of relevant publications issued before 2000, he found that a majority of the publications were concerned with qualitative studies that involved single parameters, a few publications reported multiple parameters and a very few publications contained studies that used quantitative (statistical and non-statistical) methods. However, when Fisher analysed recent fisheries publications, he found that the shift in publication content was markedly towards multiple parameter studies that embedded geostatistical techniques. The main thematic areas that presently utilize GIS with respect to fisheries can be categorized as follows.

- Habitat mapping. This is a process whereby sea-bed types are classified in terms of sediments, morphology, depth and benthos using data from various acoustic sonar devices and biological sampling equipment. Habitats can be portrayed in various means and categories, for example, by draping a map of sediment types or benthos over a 3D topographical image. Over the last decade, the importance of habitat mapping has increased markedly and in many ways habitat maps are now expected to form the basis upon which marine ecosystems are managed.
- Species distribution and abundance. The 2D mapping and modelling of the distribution and abundance of species of interest (resource analysis) has grown into a substantial area of research covering both terrestrial and marine domains. Marine species pose particular challenges as their populations are relatively dynamic in space and time. Mapping their distribution, therefore, presents a challenge to statisticians and ecological modellers.
- Fisheries oceanographic modelling. Research in this area is aimed at explaining the relationships between fish occurrence and oceanographic variables. This involves aggregating data from a wide variety of sources, with satellite remote sensing and fisheries surveys being of primary importance. Only a GIS has the functional capability of carrying out the necessary complex modelling.

- Fishers' activities. Knowledge of who is fishing where, who is catching what and by what means is a fundamental requirement for management to be effective. Many large-scale commercial fisheries are now subject to monitoring by satellite-based VMS. These systems are designed to augment existing logbook schemes and can potentially generate more accurate assessments of where fishing activities are taking place. Small-scale fisheries are required to submit logbook records of catch and effort, whereas subsistence fisheries are rarely subject to a formal reporting mechanism. Where spatially structured data for catch and effort exist, various GIS-based analyses are possible that seek relationships between fishing effort and marine ecosystem properties.
- Fisheries management. Managers have an overall responsibility to sustain fish stocks and to do this, they often work hand-in-hand with fishery scientists. Together they have access to a wide range of fisheries data. Use of GIS output allows better decisions to be made on factors such as closed areas, stock abundance, stock enhancement, marine reserve locations, fishing effort distribution and behaviour, and fish mortality rates. The capability for some management tasks will be greatly expedited with a move towards electronic fisheries logbooks.

It is interesting to note that Fisher (2007) does not include EAF as one of the thematic areas under which work in fisheries GIS might be classified. Despite this lack of explicit recognition, without a doubt much of the work now being carried out is moving in the direction of EAF, though perhaps this work is still taking a rather narrow view of what EAF implies. For overviews of recent GIS applications in fisheries management and research, the authors recommend Fisher and Rahel (2004), Nishida *et al.* (2004), Wright and Scholz (2005), Nishida *et al.* (2007) and Meaden (2009).

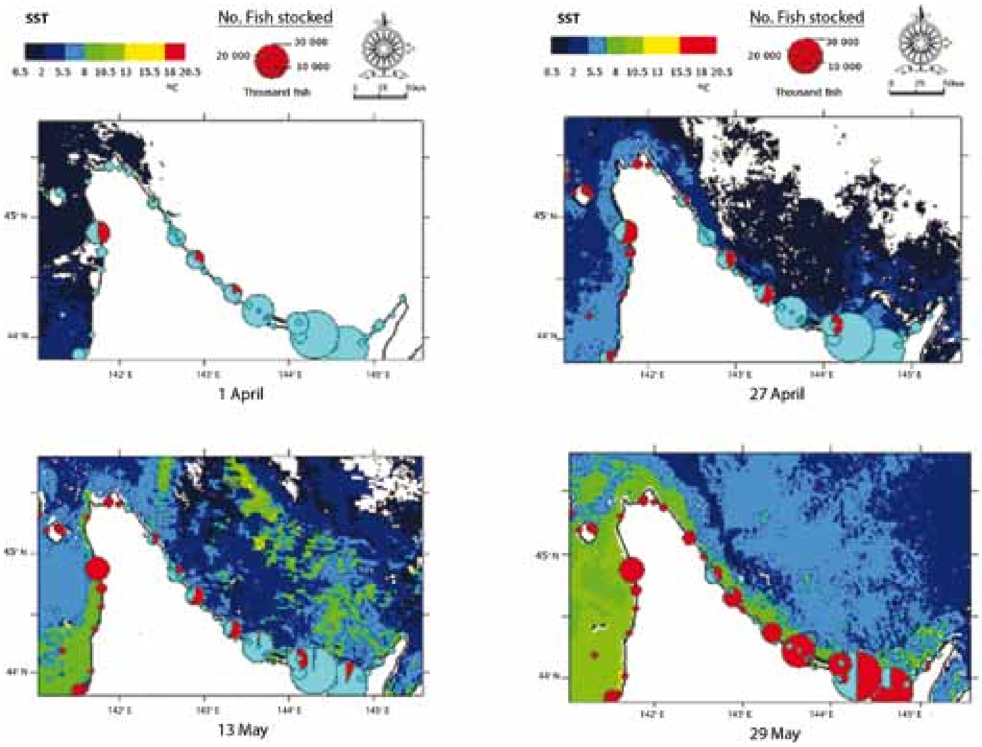
3.5 CASE STUDIES OF GIS APPLICATIONS TO FISHERY-BASED TOPICS

GIS applications in fisheries are increasing. The following four studies of some GIS applications were selected on the basis of the issues addressed, their ease of understanding, the variety of uses of GIS, the variety of data sources used in the study and the different geographic areas and spatial scales covered.

3.5.1 In search of the optimum time to release juvenile chum salmon into the coastal waters of northern Japan

With salmonid stocks rapidly declining worldwide and with salmon being an ideal species for large-scale hatchery rearing, the release of salmon directly into the coastal environment appears to be a sensible and economic strategy. In fact, this practice has long been followed in Japan. Miyakoshi *et al.* (2007) show how, for nearly a century, the quantitative release of chum salmon into the coastal waters around the northern Hokkaido region of Japan is closely mirrored by the return of chum salmon, especially since the 1970s when releases greatly increased. This is one of the most successful marine stock-enhancement programmes in the world. Nevertheless, the success rates could be greatly enhanced if an appropriate match could be made between a number of variables such as size of hatchlings, sea temperatures, food availability and stocking densities. Miyakoshi *et al.* used remote sensing data to establish sea-surface temperatures and this was related to the date of hatchling release and the release location for the period 1997 to 2001. Figure 3.2 shows the incremental buildup of chum salmon released during four time periods from the beginning of April to the end of May, 2000, with the red portion of the circles indicating the percentage of salmon released by the date shown. Also given are sea-surface temperatures. The GIS-based analyses showed that salmon production, as indicated by salmon returns, is more likely to be optimized where sea temperatures range from 8° C to 13° C, and when juveniles are > 5 cm in length. This information can potentially be used to maximize the benefits of future restocking operations.

FIGURE 3.2
The location of chum salmon release sites in the coastal waters of northern Hokkaido, Japan, 2000



Source: Reproduced with permission from Miyakoshi *et al.*, 2007.

Note: The red portions of the location circles indicate the proportion of total annual releases made by the date indicated.

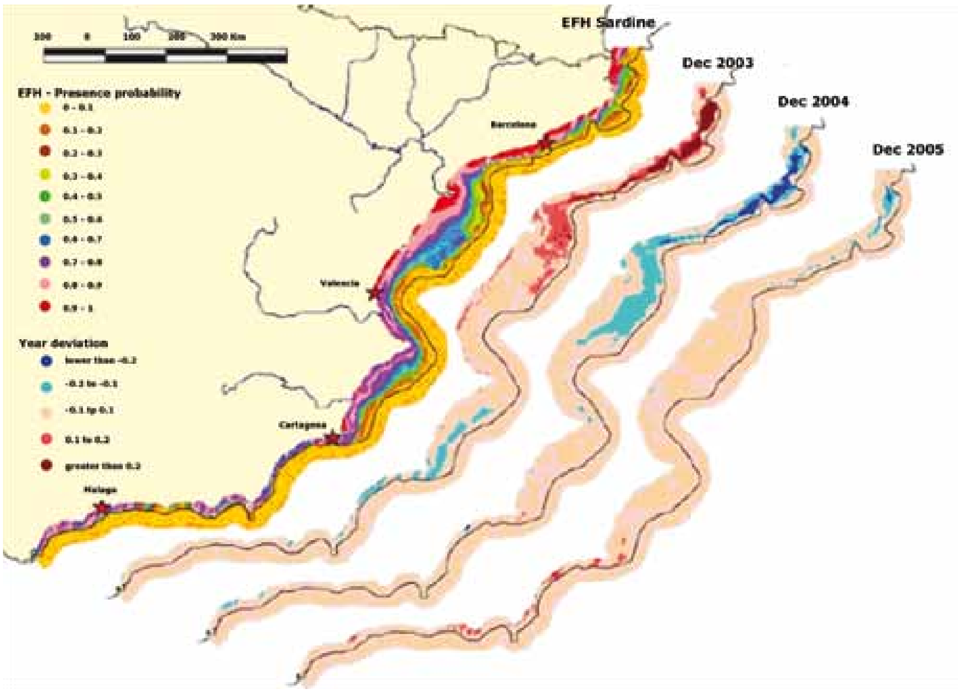
3.5.2 Identification of the essential fish habitat for small pelagic species in Spanish Mediterranean waters

Small pelagic fish such as sardines and anchovies provide an important fishery along Spain's Mediterranean coast. Spatial abundance data obtained from annual acoustic surveys were combined with environmental data in a GIS environment to generate a model that showed the likely optimum relationships between abundance and location for both anchovies and sardines. The model outcomes were then used to help define essential fish habitats (EFH) for these species. The statistical methods used to derive the EFH are described by Bellido *et al.* (2008). The environmental variables used were bathymetry, sea-surface chlorophyll-a and sea-surface temperatures. Bellido *et al.* noted substantial interannual variability in the distribution and quality of the EFH, particularly for anchovy, and they commented on the importance of assessing EFH for the management of the local marine resources. Figure 3.3 gives an example of the GIS output showing the EFH for sardines in the Spanish Mediterranean waters.

3.5.3 Development of a GIS for the marine resources of Rodrigues Island

Rodrigues Island, a small island in the Indian Ocean, is located about 600 km east of Mauritius, and like many similar islands in the tropics, it is under pressure from natural resource exploitation and increasing tourism. Until recently, there was a complete lack of structured information on marine resources and this hampered any attempts at management. Since 2000, a GIS (using MapInfo software) has been incrementally developed by the University of Wales with funding from various aid projects (Chapman and Turner, 2004). The intentions of the GIS were to integrate data on the distribution of biodiversity with environmental factors controlling distributions and with human

FIGURE 3.3
The essential fish habitat for sardines in the Spanish Mediterranean waters



Source: Reproduced with permission from Bellido *et al.,* 2008.

activities such as fishing and conservation planning measures. Biotope mapping based on satellite imagery and ground truthing was carried out for the entire lagoon area surrounding the island, which at 240 km^2 is the largest lagoon in the Indian Ocean. As a result of the mapping effort, 42 separate biotopes within four main habitat groups were described, i.e. coral, consolidated limestone, lagoon mud, and sand and rubble. Figure 3.4 shows a satellite image of the island and the distribution of main habitat types in the lagoon. The GIS is linked to a relational database to store and display site-based data, including biotope descriptions, photographs, species lists, illustrations and environmental data. A rich variety of GIS outputs was derived and the analysis of some of this output has helped to improve the designation of marine protected areas and other conservation measures. This GIS comes complete with a detailed user's guide plus a companion document that describes the GIS in detail, including the processes involved in developing the system and the research projects behind the data.

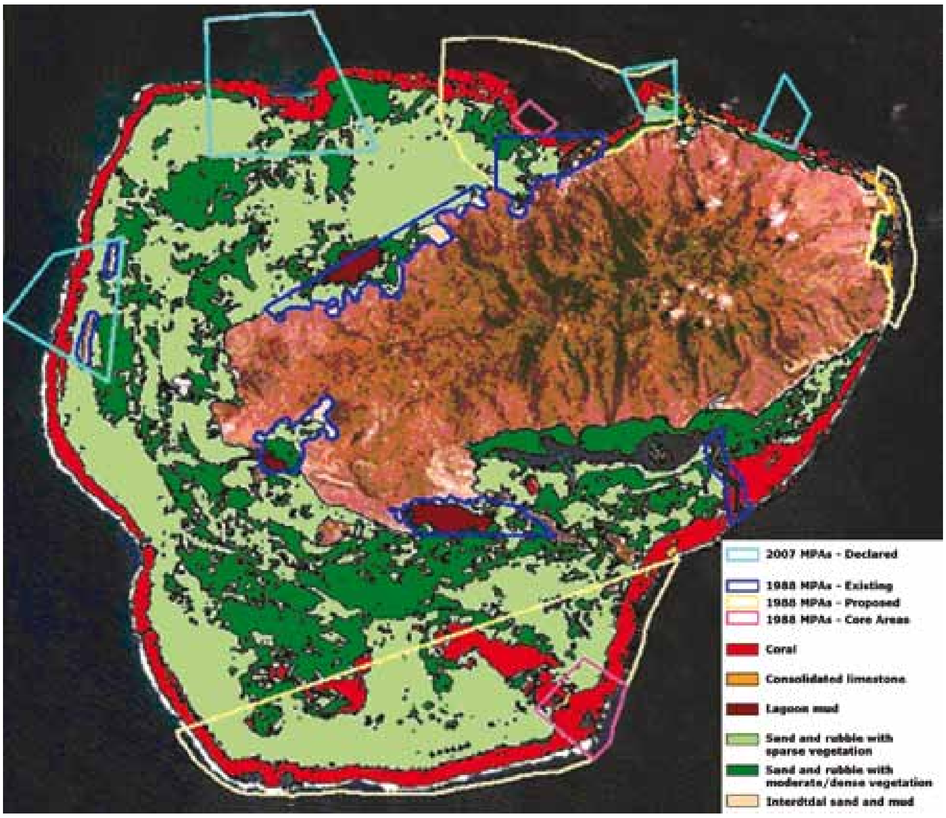
3.5.4 The influence of closed areas on fishing effort in the Gulf of Maine

It has long been suggested that problems likely to be associated with establishing closed areas to fishing are the so-called "boundary" and "displaced effort" effects. The boundary effect refers to the likely increase in fishing effort around the boundary of the closed area in response to the greater likelihood of catching fish that spill over from the closed area. The displaced effort effect refers to a natural concentration of fishing effort in the smaller available marine space, to the likely detriment of benthic habitats[2].

The Gulf of Maine is a large gulf of the Atlantic Ocean off the coasts of Maine, New Hampshire and Massachusetts in the United States of America. By comparing fishing effort distribution data for 1990–1993 (pre-area closure) with effort distribution data for 2003 (post-area closure), Murawski *et al.* (2005) found that, indeed, in 2003 effort

[2] For a more detailed account of the influences of areas that are closed to fishing see Hilborn *et al.* (2004).

FIGURE 3.4
A map of Rodrigues Island and lagoon showing combined habitat classes



Source: Reproduced with permission from Chapman and Turner, 2004.

Note: Shown on the map is an overlay of the reserve areas as identified in Pearson (1988) and of the northern reserve areas as proclaimed by the Rodrigues Regional Assembly in April 2007.

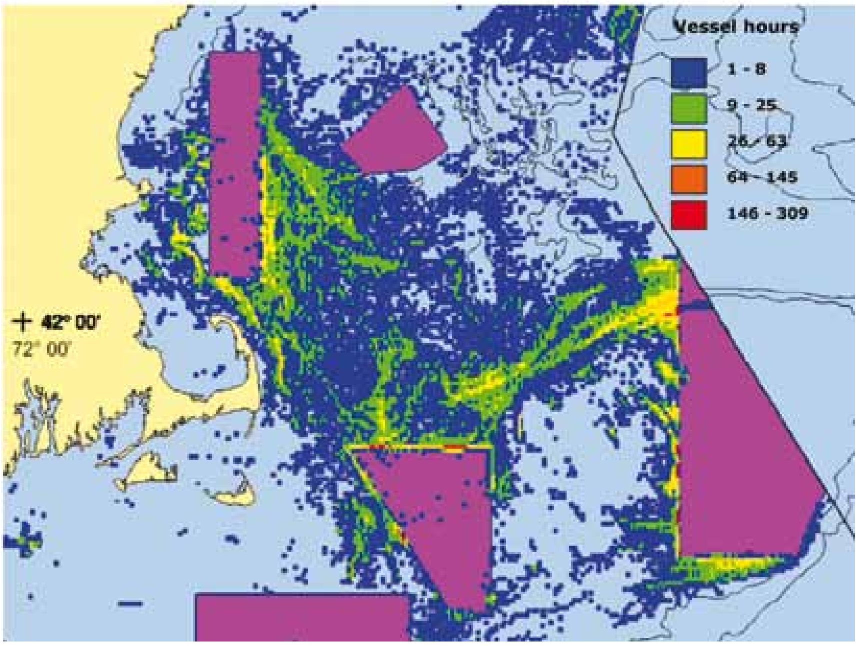
had been concentrated and nearly 10 percent of total effort was deployed within 1 km of the closed area boundaries. As is shown in Figure 3.5, this effort concentration varies significantly between the five closed areas, obviously reflecting different fish densities that relate to habitat suitability. An analysis of catch quantities and fishing location revealed that for some species some of the closed areas were having a positive effect and that the average revenue per hour trawled was about twice as high within 4 kms of a closed area than the revenue generated in more distant locations. Revenue generation was, however, highly variable among closed areas and along boundaries, reflecting overfishing in some areas and seasonal variations in fish distributions. It should be noted that the information demands to produce this type of GIS output are very high and VMS location data has contributed a large portion of the needed information. A major data problem for many fisheries and management authorities is the accuracy of catch locations, as is the case in most northern European fisheries where catches are only assigned to so-called ICES rectangles, which measure 1 degree longitude by 0.5 degrees latitude[3].

3.6 CONCLUSIONS

In the two decades since GIS was first used for spatial analyses or mapping of fisheries related themes, significant progress has been made. However, it is likely that progress has not been as significant as progress achieved in many terrestrial GIS applications because of the many challenges that face workers who try to apply mapping

[3] Approximately 5 000 km^2 in mid-latitudes.

FIGURE 3.5
Hours of fishing effort by otter trawls in the Gulf of Maine, 2003



Source: Reproduced with permission from Murawski *et al.*, 2005.

Note: Closed areas are shaded in purple.

technologies to an environment that functions in three dimensions, and where almost everything that can be mapped is constantly moving (see Section 6.4). Despite these and other challenges, the enthusiasm shown for GIS use by many fishery researchers, managers and organizations will ensure that GIS has a vibrant future. This future will be enhanced by the fact that fisheries are entering an era when the ecosystem approach to fisheries has come to the fore and the following section will illustrate how this is being achieved.