

Coastal GIS: Functionality Versus Applications

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Abstract

Despite the high appraisals of the potential of GIS application in the coastal/marine environment, the development of coastal GIS is still relatively slow. This is due to: i) the complexity of coastal/marine systems in the 3D environment, ii) lack of data, and iii) lack of communication between coastal experts and GIS professionals. As the result of these, the commercial GIS vendors have been hesitating to invest in developing coastal GIS. This paper addresses functionalities (both existing and potential) versus different coastal applications with an example of fisheries. A concept of levels of applications has been proposed with the identification of the three levels of applications and their corresponding requirements on GIS functions. The paper also provides potential GIS users with some examples of the GIS applications in coastal zone.

1 Introduction

Sustainable development in the coastal zone is vital to our society (Cicin-Sain 1993), given that many cities around the world are concentrated in the fringe of the coastline. The economic and comfort advantages of living in the coastal environment (e.g. the sea breeze and view) result in high population density (Zeng *et al.* 1998). The coastal zone contains 50 – 70% of the world population, and it is estimated that 78% of gross national product (GNP) worldwide is derived from activities that are directly or indirectly connected with coastal zones (IPCC, 1997). Human well-being is largely dependent upon the availability of environmental goods and services provided by marine and coastal systems.

GIS has proven to be indispensable for Coastal Zone Management (CZM) (Damoiseaux 1995). The role of GIS in CZM has been highly appraised by, e.g. Ellis (1972), Ader (1982), Fairfield (1987), Davis and Davis (1988), Townend (1990), Welch *et al.*, (1992), Riddel (1992), Ricketts (1992), Jones (1995), Mumby *et al.*, 1995; Bartlett (1990, 1994), Deakin and Miment (1994) and Nath, *et al.*, (2000). The reasons for using GIS in CZM have been well documented by Wright and Barllett (2000).

In recent years, the demands on applying GIS to CZM have been increasing. However, among the boarder spectrum of GIS applications in coastal zone, few have discussed coastal GIS in generic terms. There is growing realisation that the use of GIS should go beyond simple data display, reporting and management, so that it is necessary to gain a better understanding on more advanced forms of analysis and modelling (Raper and Maguire 1992, Walford 1999). This paper, therefore, attempts to categorise the current GIS applications in CZM followed by an example of fisheries industry. Then, it discusses some GIS functions in a generic sense and outlines GIS functionalities versus applications at different levels. Further needs in developing Coastal GIS are also discussed.

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2 Brief Review of Current Applications

The development of Coastal GIS began in the early 1970's (Ellis 1972), and its progress has been accelerated in the last decade. Many researchers have theoretically investigated different aspects of Coastal GIS, including data structure (Li, 1999; Lucas, 1999; Sherin, 1999), data model, data standardisation and analysis methods (Ricketts, 1992). There are numerous interest groups in coastal zone (Figure 1), each of which has its own focus on particular aspects of coastal environment. Examples of these include shipping and harbour facilities, sand and mineral mining, military manoeuvres, recreation, fisheries and conservation.

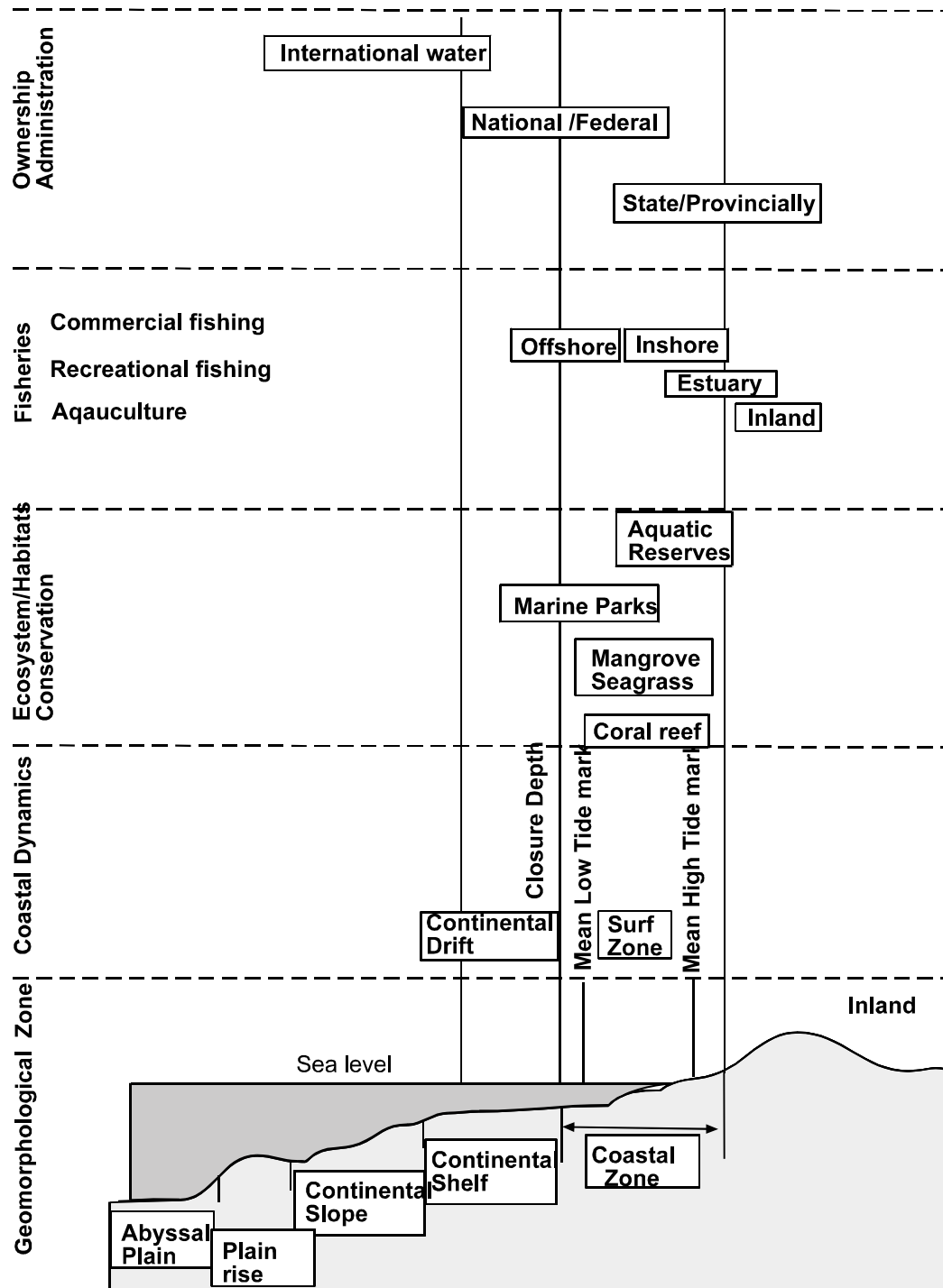


Figure 1. Overlapping biophysical, economic, institutional and organisational boundaries in coastal area

2.1 Categories of Coastal Applications

Current GIS applications in the coastal zone are diversified and case-based studies, mainly focusing on vector-based applications. These applications can be categorised as (a) coastal mapping, (b) environmental monitoring, (c) coastal process modelling, (d) navigation and port facilities management, (e) coastal environmental/hazard assessment, (f) coastal management/strategic planning, and (g) coastal ecological modelling.

Coastal mapping

This type of applications is mainly focused on thematic mapping in the coastal zone, such as mapping chlorophyll concentration using TM data (Chen *et al.* 1996), coastal wetland mapping using historical data (Schauer, *et al.*, 1992; Van Der Veen *et al.* 1997), sea grass/mangrove mapping (Williams and Watford 1997, Watford and Williams 1998), and marine seabed mapping (Jeffries-Harris and Selwood, 1991; Lauro *et al.* 1999). One example of such application is the mapping of critical events related to phytoplankton blooms in Western Europe and North America (WGHABD, 2001).

These applications commonly utilise remotely sensed data, such as satellite images, airphotos and sonar survey, combined with ground truth and other existing vector data layers. The GIS functions used in this type of application are typically the clustering (or classification), image processing, raster-vector conversion and overlay functions.

Environmental monitoring

Environmental monitoring is one of the routine tasks in CZM, which include monitoring water quality and habitat/biodiversity, and beach watch. Examples include: i) monitoring sea turtle movement (Maktav *et al.* 2000), ii) tracking lobster along the East Coast of Australia (Steve and Craig, personal communication), iii) monitoring oil spill (Gaarrett and Jeffress, 1993, , iv) real-time bay/beach watch (Hecht 1991; Patterson and Dawson, 1991b), and v) analysing animal movements in the marine environment (Hooge *et al.* 2000).

Environmental monitoring also involves tagging samples, presenting the result of sampling over geographical space, and/or monitoring pattern changes in time. Linking spatial data and non-spatial data is the key function for this exercise.

Coastal processes modelling

Modelling of physical environment change in the coastal zone includes the simulation of effects of sea-level rise (Ruth and Pieper 1994, Grossman and Eberhardt 1992, Zeng and Cowell 1998, 1999, Hennecke 2000), the assessment of human intervention of shoreline change (Huang *et al.* 1999), the use of historical data to predict future coastline change (Sims *et al.* 1995) and the study of beach morphodynamics (Humphries and Ligdas, 1997). Currently, most models adopt a 'loose-couple approach', as described by (Sui 1998), which adds customer-built programs to a commercial GIS package and uses GIS for data management and display. The integrated GIS modelling is expected to grow rapidly in the coming years.

Navigation and port facilities management

This type of applications has evolved from traditional use of nautical maps to channel monitoring on a routine basis, maintenance and route planning. For example, New South Wales Waterway used GIS for waterway resource management. They also used GIS, along with the Global Positioning System (GPS), for planning and monitoring the water sports events at real time in the 2000 Olympics Games (ESRI, 2000). The GIS functions required include integrated GPS tracking system with network analysis and relevant query functions.

Coastal environment/hazard assessment

There are two subcategories of the applications of this kind, namely, short-term and long-term tasks. The former is exemplified with monitoring and predicting oil spilt (Belore, 1990), while the

latter is demonstrated by coastal hazard/vulnerability assessment due to climate change (Lee *et al.* 1992, Sims, *et al.*, 1995; Deniels *et al.* 1996, Hickey *et al.* 1997, Zeng and Cowell 1999, Hennecke *et al.* 2000, Esnard *et al.* 2001), assessing the impact of thermal water outlet from a power plant (Chen *et al.* 2001) as well as the evaluation of potential risk area by septic tanks (Swart 1995) and coastal wetland assessment (Downs *et al.* 1993).

This type of application is characterised by model integration, linking other coastal model or multi-models with GIS for simulating/predicting different scenarios.

Coastal management/strategic planning

Similar to coastal environment/hazard assessment, this application also involves assessing sustainability of the environment, and social and economic viability. Some of the examples are:

- a) Fisheries management: including planning, site selection for aquaculture (NSW Fisheries 1999, Nath *et al.* 2000), conservation, recreational fishing and fish closure that shows the restricted fishing area gazetted and regulated by the Government,
- b) Marine park planning that uses multicriteria analysis to investigate the interaction between different factors and constrains, and provides solutions to conflict situations, and
- c) Aquaculture Industrial Development Plan (see below).

Coastal ecological modeling

This is one of the most challenging application types. Examples are the identification of bio-regions using neural network analysis (Ortiz 1994), prediction of the stream habitats and fish diversity (Meixler and Bain 2000), and tracking spatial/temporal habitat changes by applying the multi-dimensional spatial analysis (Parham and Fitzsimons 2000). This type of applications is focused on integrating ecological models with GIS for the research of ecological system behaviour.

In summary, to extend Jones's work (1995), all the categories of GIS applications in coastal zone can be categorised into three levels listed below (Table 1).

- a) Level 1: as data management and mapping tools,
- b) Level 2: as basic data analysis (query) and mapping tools, and
- c) Level 3: as decision-supporting tools (modelling / simulation).

Table 1. Categories of GIS applications in coastal zone.

Category	A	B	C	D	E	F	G
Level 1	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Level 2	No	No	Yes	Yes	Yes	Yes	Yes
Level 3	No	No	Yes	No	Yes	Yes	Yes

Most current implementations of Coastal GIS are still at Level 1 and Level 2. It is expected that Level 3 implementations will rapidly increase in the near future as the continuing improvement in GIS functions and more user-friendly interface become available in the market.

2.2 A Case Studies of Fisheries GIS

To demonstrate these three levels of application, an example of GIS application in Fisheries is outlined here. For more detailed information about the application project please see Zeng *et al.* (1999).

The objective of the fisheries is to ensure the appropriate use of fisheries resources and conservation of coastal environment. The role of the Fisheries GIS is to provide management and decision-support tools for coastal environment and resource management. To achieve the cooperative goal, all components of fisheries, including routine operation, fishery management and aquaculture planning, conservation and research, have to collaborate, share datasets and contribute value-added datasets for further development (Figure 2). Based on the business case, the level of

each component has been defined and the appropriate GIS functions were selected as shown in Table 2. The Fisheries GIS structure and its usage are illustrated in Figure 3.

Table 2. GIS Functions versus level of applications for Fisheries

Level	Fishery Management Operation	Aquaculture Planning	Fishery / Habitat Conservation	Fishery Research
1	RDBMS Display/ Mapping	RDBMS Display/ Mapping	RDBMS Display/ Mapping	RDBMS Display/ Mapping
2	Query Overlay Regional analysis	Query Overlay Regional analysis	Query Overlay Regional analysis	Query Overlay Regional analysis
3	Random sampling	Multi-variable analysis Fuzzy set analysis Rule-based model (RBM)	Multi-variable analysis Fuzzy set analysis Rule-based model	Multi-variable analysis Fuzzy set analysis Rule-based model Random simulation

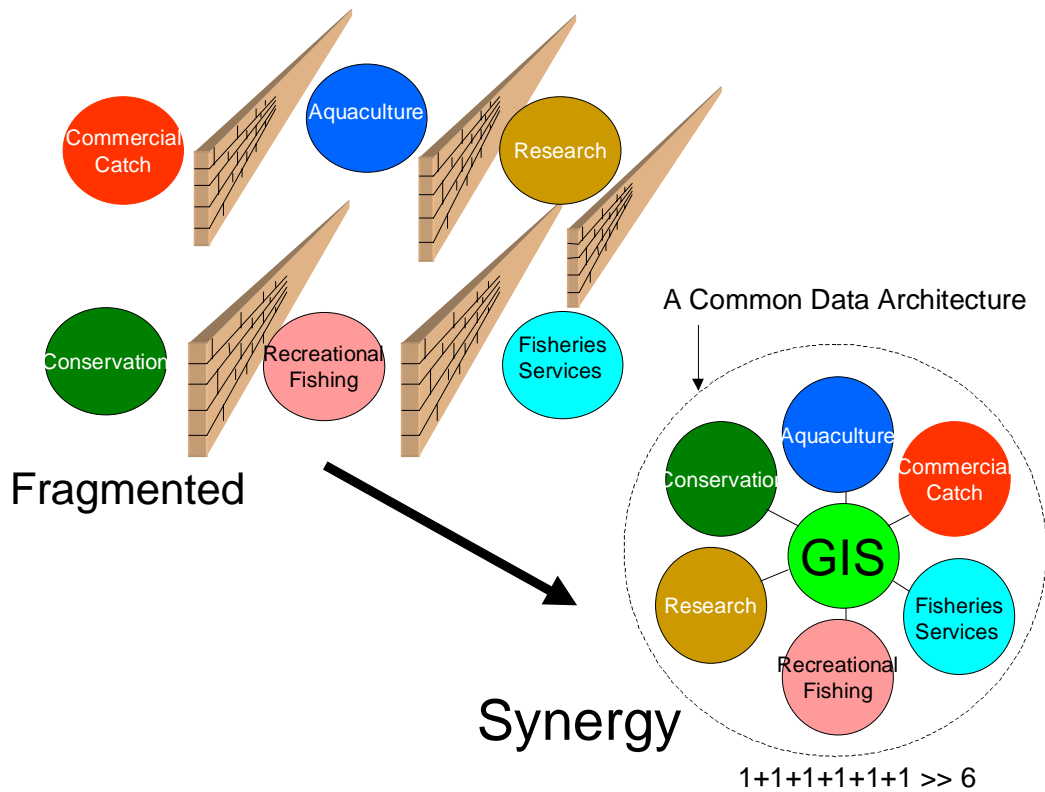


Figure 2. Integrated approach of Fisheries GIS

This system supports different divisions for various operation purposes, which are listed below.

Conservation

- Seagrass and mangrove mapping (Figure 4) using image processing techniques in raster-based GIS.
- Environmental assessment for habitats using multicriteria analysis and decision trees.
- Aquatic reserves and recreational fishing (Figure 5) (as above).
- River surveying.

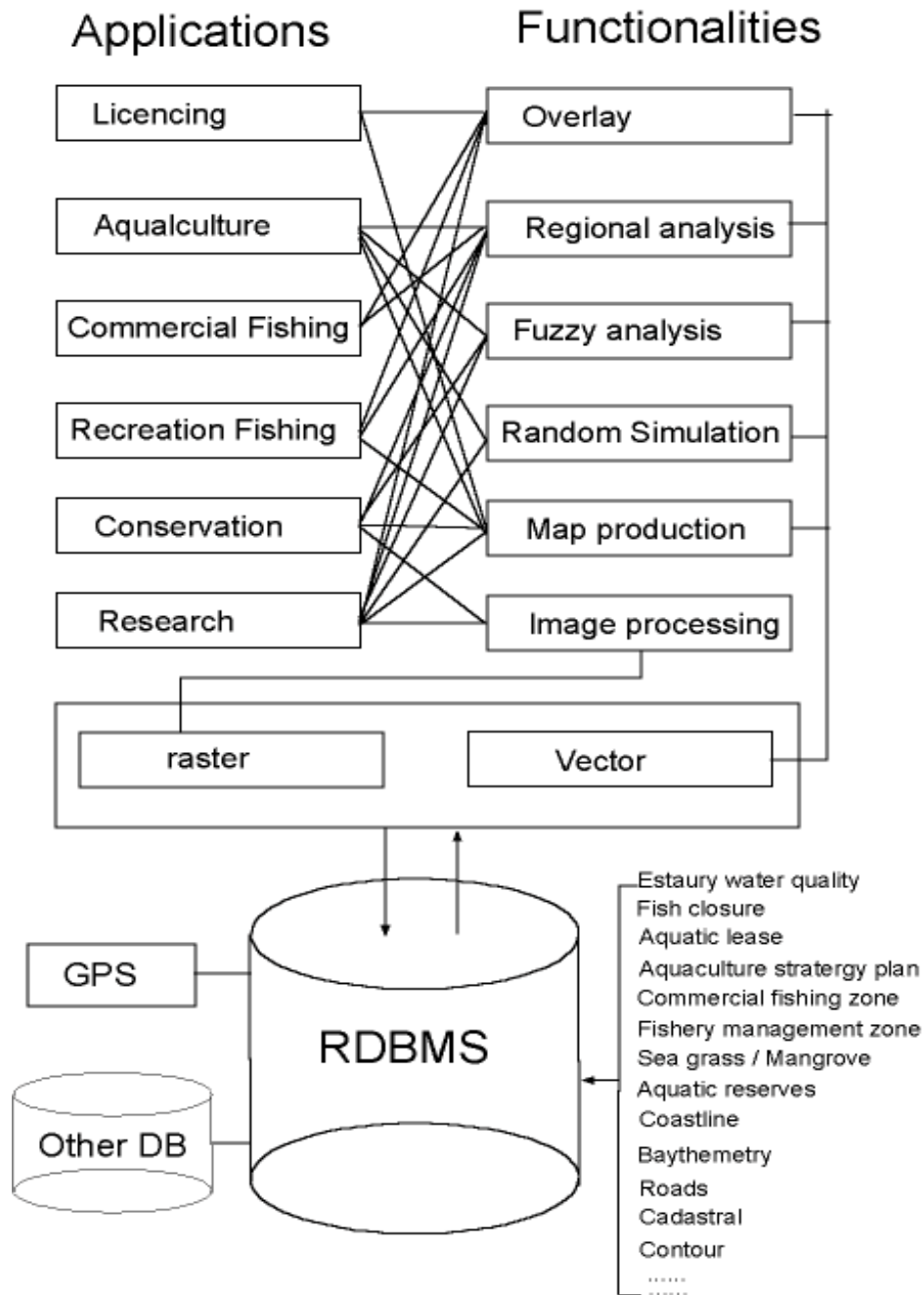


Figure 3. Functions and applications of Fisheries GIS.

Aquaculture

- a) Aquatic lease management/mapping (Figure 6) using GPS survey, RDBMS construction and automatic mapping.
- b) Aquatic site selections (Figure 7) using methods of fuzzy set analysis (Zadeh 1965, Kaufman 1975, Zinmemmen 1991), exemplified by Zhou and Charnpratheep (1996), and Zeng and Zhou (2001). The fuzzy analysis module is designed for the purpose of planning, strategic assessment and optimal site selection.
- c) Strategies planning (Figure 8).

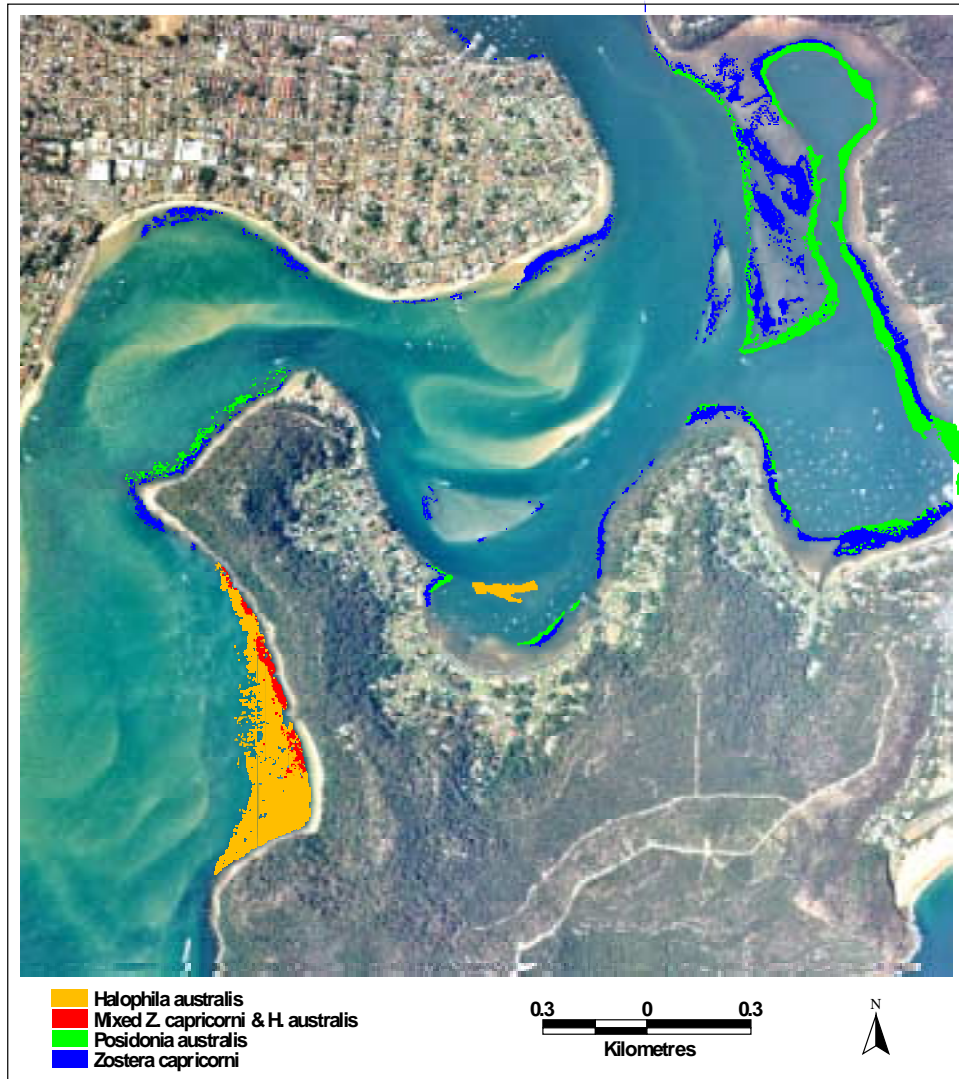


Figure 4. Seagrass mapping using remotely sensed data.

Fisheries management

- Fishery Administrative Districts Boundary (Figure 9). This data layers can be linked to the other RDBMS for utilities and resources analysis.
- Threatened species studies (Figure 10)
- Fish closures . The restricted fishing areas are gazetted and regulated by the Government.
- Commercial fishing zone.
- Environmental Impact Assessment (EIA) and Economic-Social Impact Assessment (ESIA).

Research

- Lobster tagging (Figure 11).
- Estuaries fisheries assessment.

Recreation fishing survey

- Mapping survey results.

All different aspects of fisheries need to be integrated and share the data that are collected by different divisions and individual projects. With integrated approach to Fisheries management,

GIS application have greatly enhanced the effectiveness and efficiency of operations of the organisation.

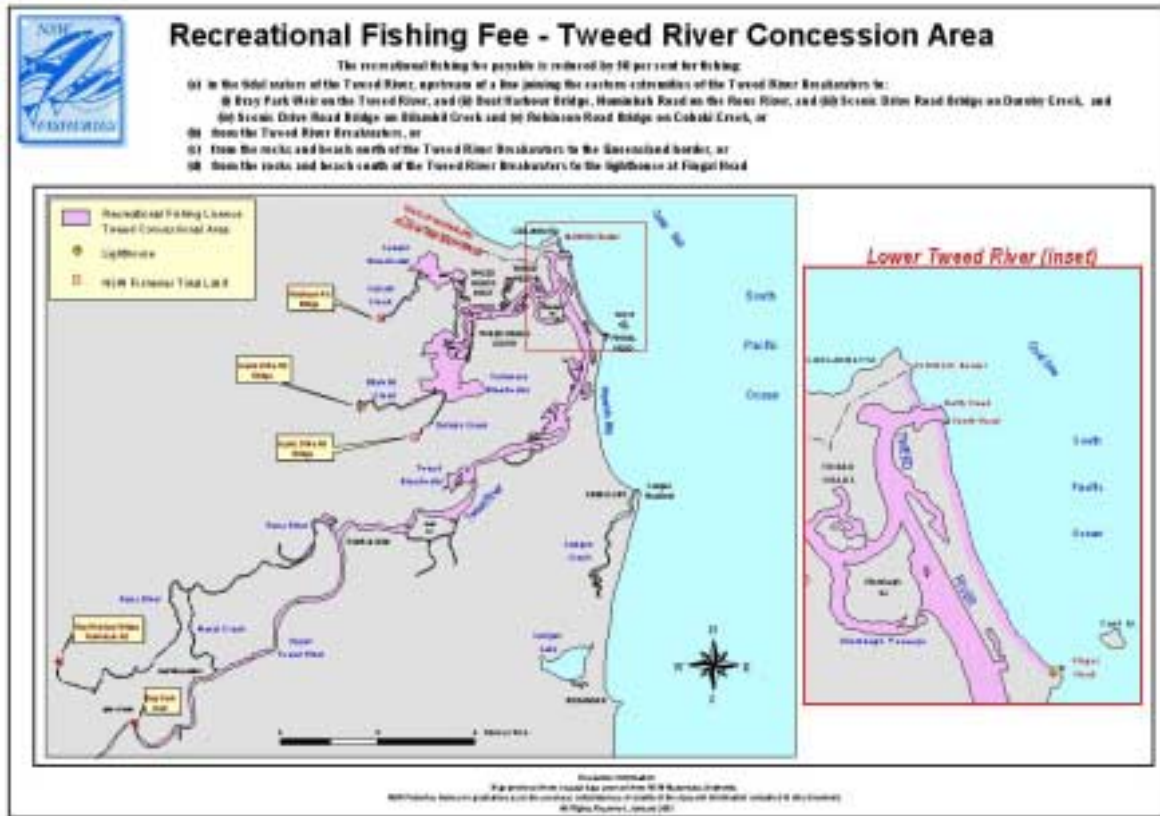


Figure 5. Aquatic reserves and recreational fishing map.

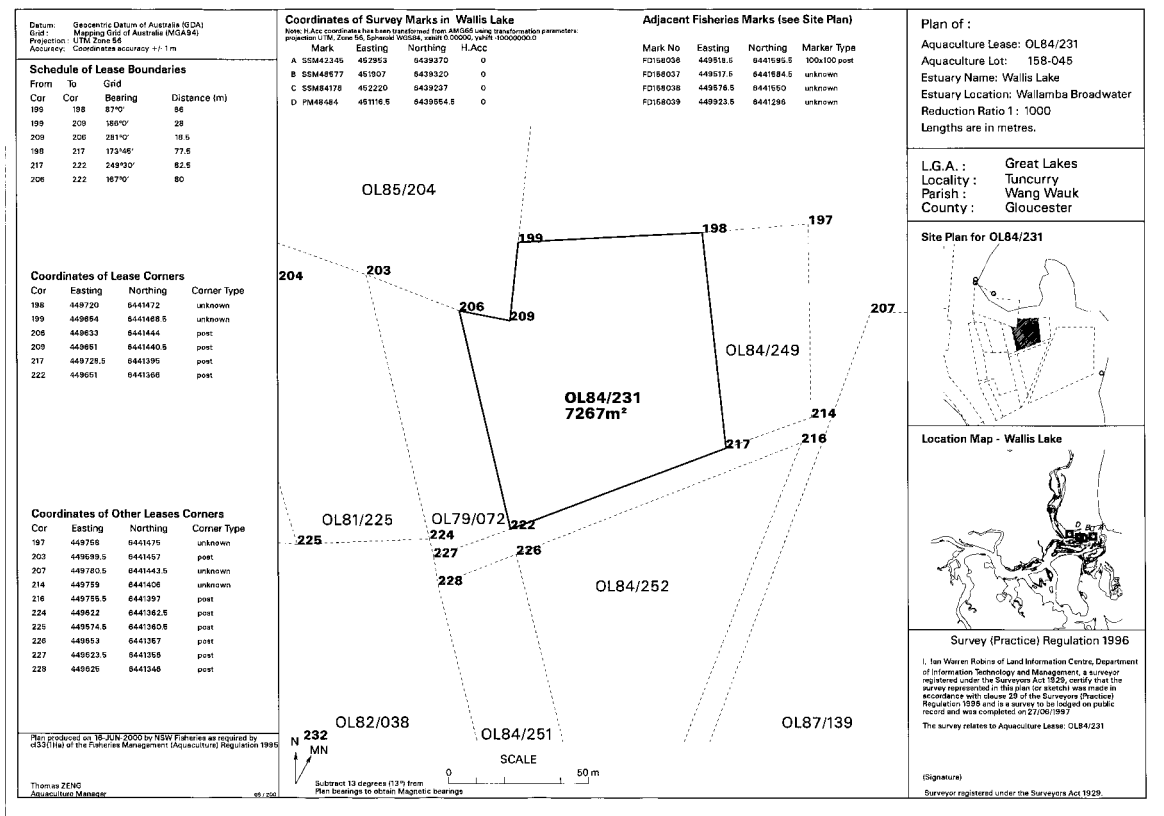


Figure 6. Aquatic lease plan - automatically generated from a GIS coverage and RDBMS.

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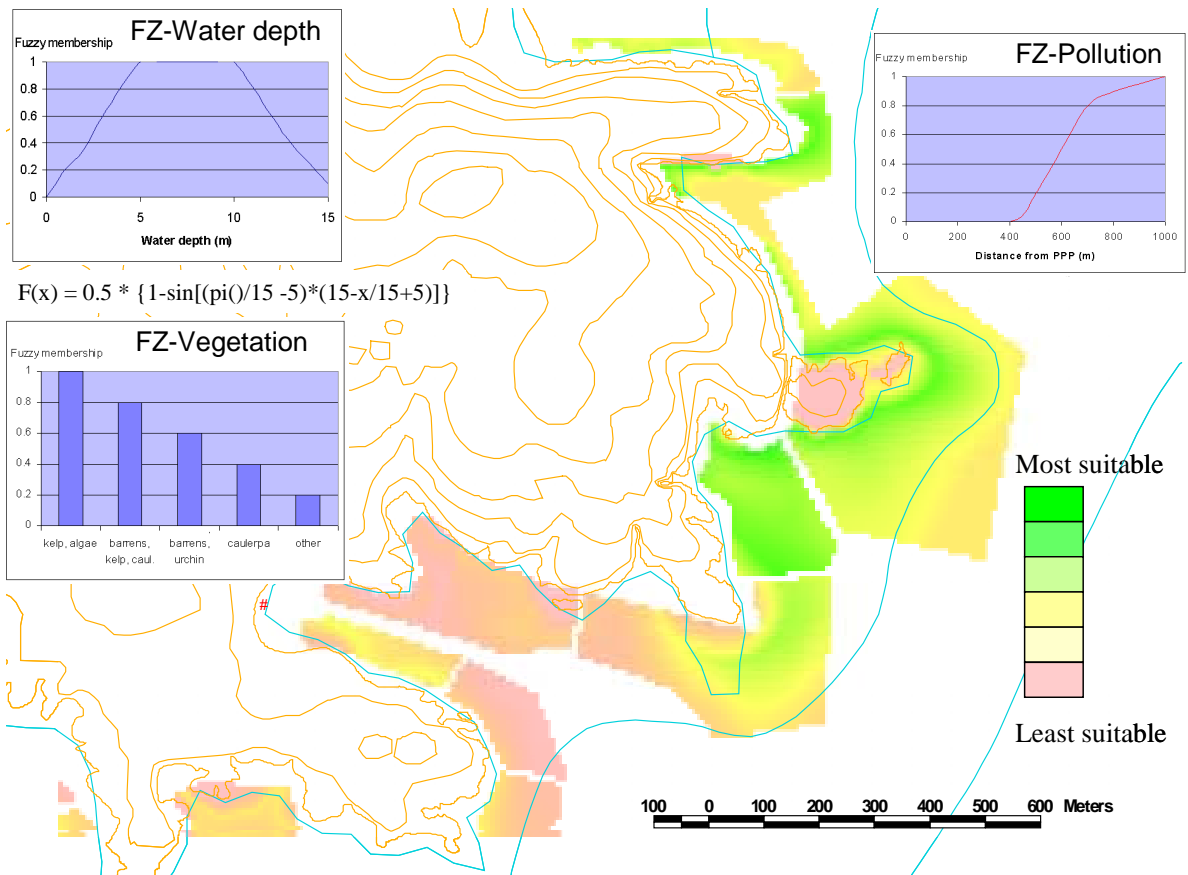


Figure 7. Aquaculture site selection using Fuzzy GIS Modeling.

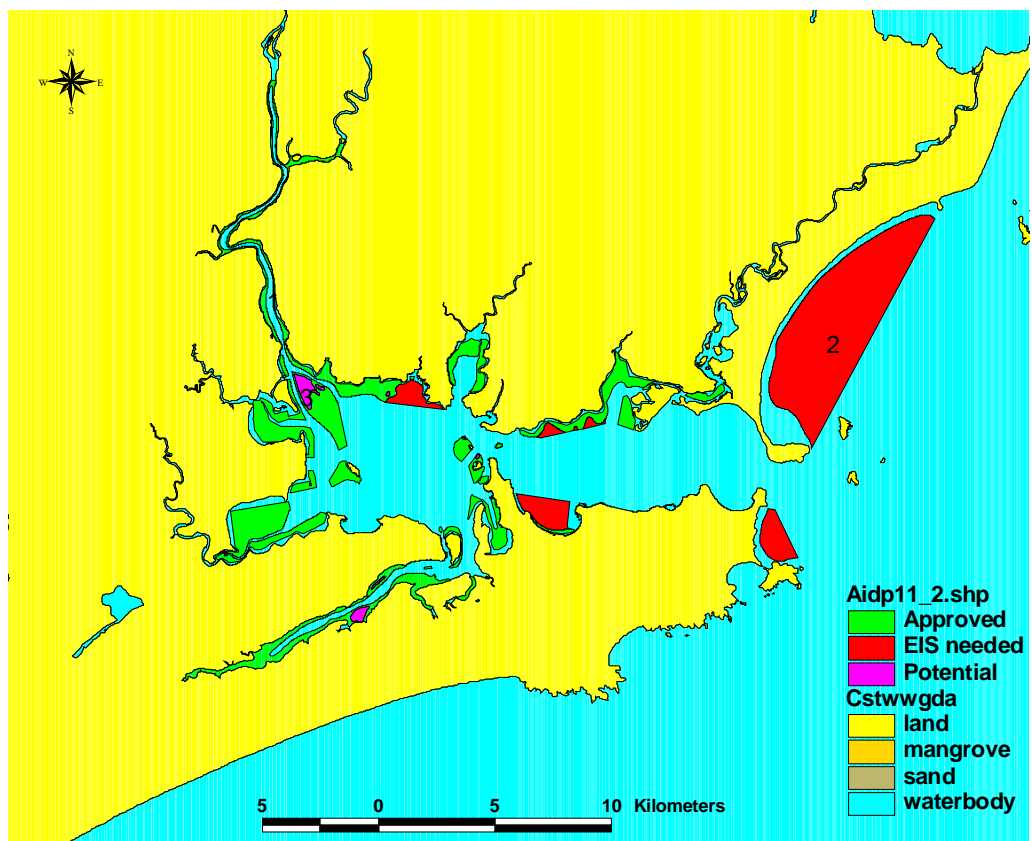


Figure 8. Aquaculture industry development planning.

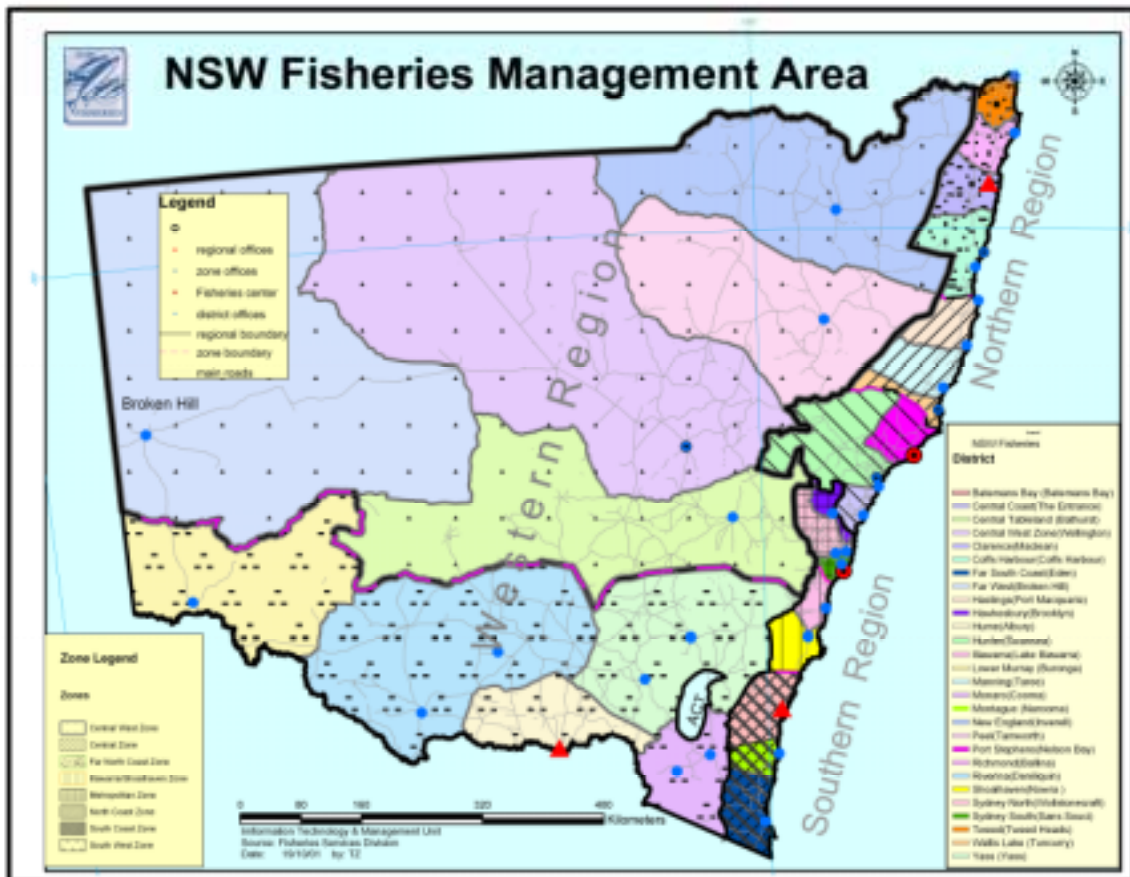


Figure 9. Fishery administrative district boundaries – linked to RDBMS for resource planning.

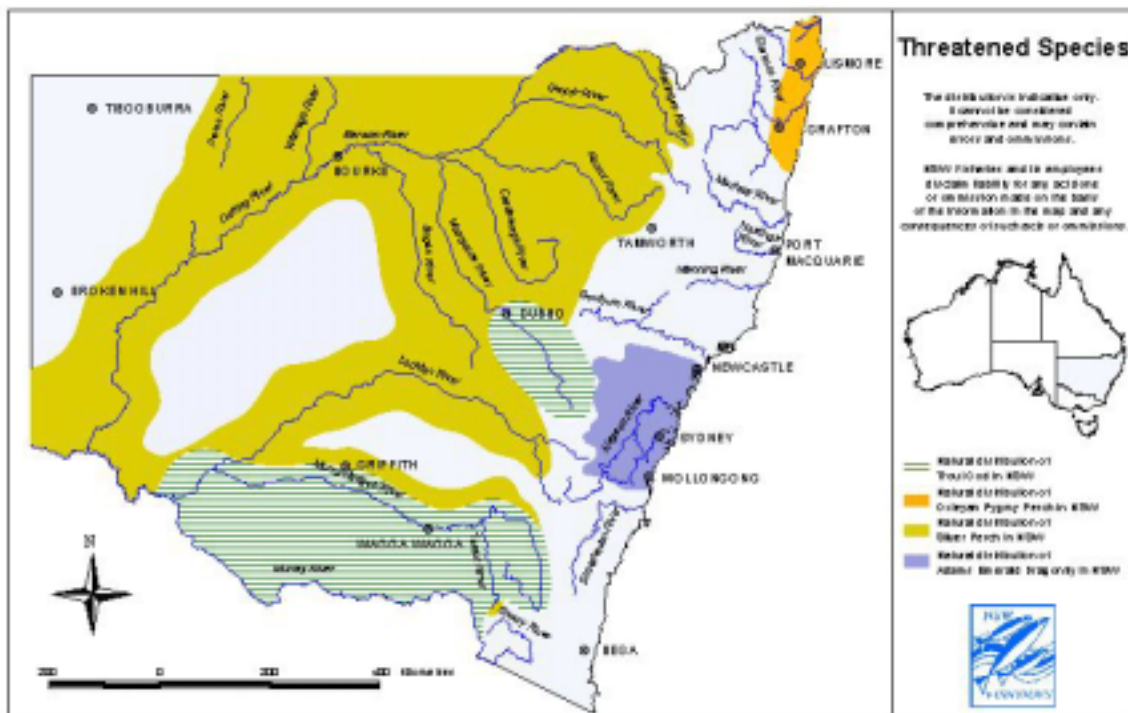


Figure 10. Threatened species distribution

Distance and direction travelled by tagged lobsters

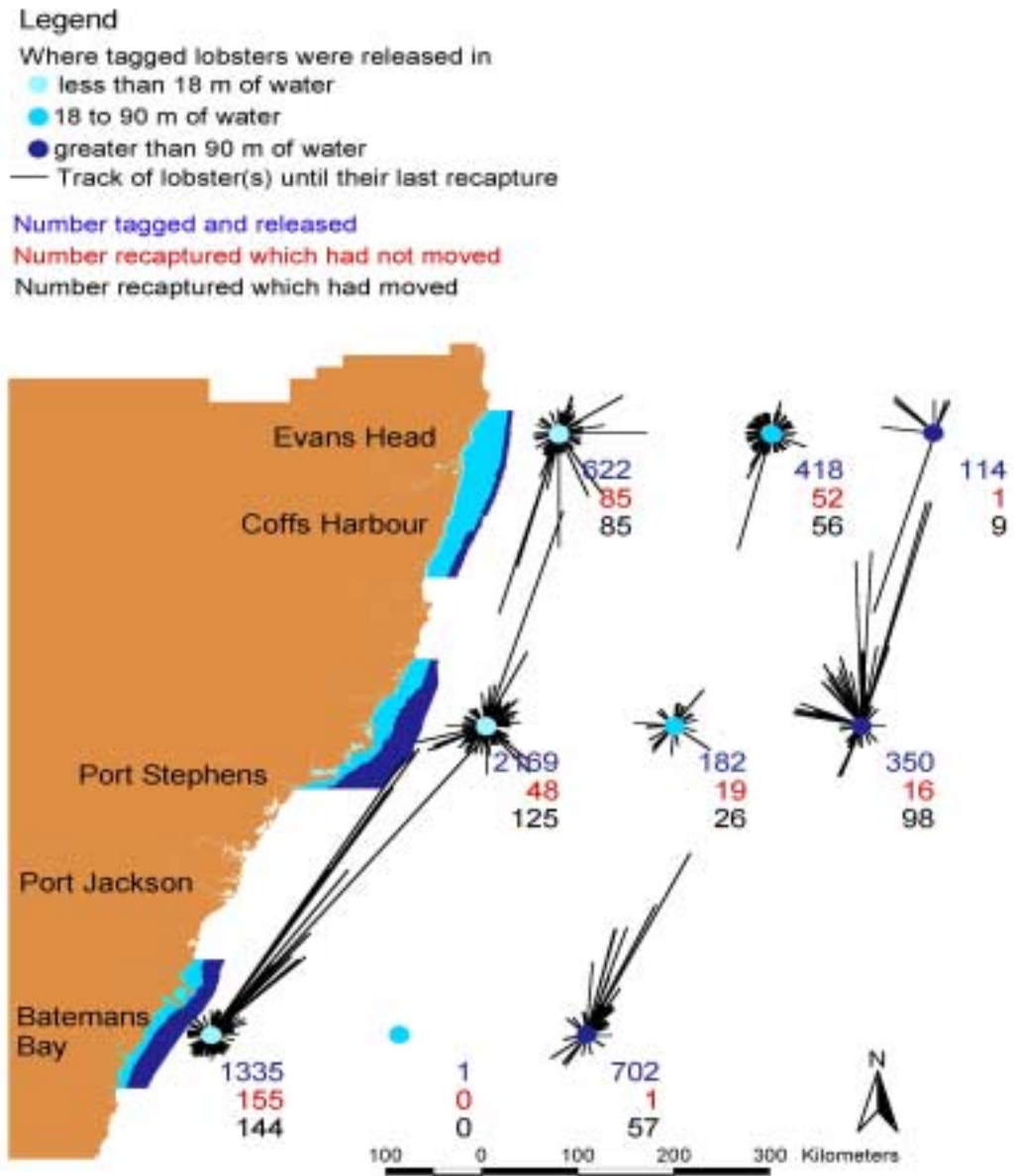
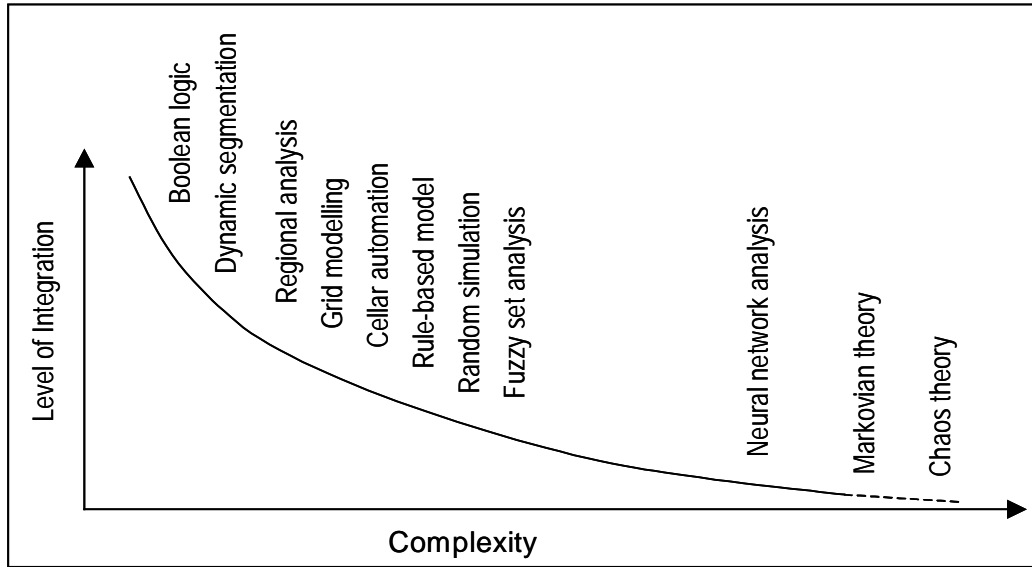


Figure 11. Tagging lobster movement in the Southern-East Australian coast.

3 Functions Versus Applications in Coastal Environment

There are two different perceptual meaning of GIS functions. One refers to the ‘role’, such as management tools, decision supporting tools and research tools (Barllett 1993). The other refers to the ‘technical capability’ that a GIS can provide operationally. The latter is the focus of this section.

As described above, different user groups have different perceptions and requirements for GIS functions (Green, 1995). Most coastal community members recognize the potential of spatial data. However, they may not realise the balance between the level of intended application and the corresponding GIS functions required.



Applications	Level 1	Level 2	Level 2/3	Level 3	Level 3	Level 3	Level 3	Level 3	Level 3	Level 3
Navigation	y	y	y							
Fisheries	y	n	y	y	y	y	y	?	?	?
Conservation	y	n	y	y	y	y	y	?	?	?
Coastal mapping	y	n	y	y	y	y	y	?	?	?
Environment assessment	y	y	y	y	y	y	y	y		
Strategy planning	y	y	y	y	y	y	y	y		
Sand Mining / Dragging	y	n	y	y						
Environment Monitoring	y	y	y	y	y	y	y	?	?	?
Coastal protection	y	y	y	y	y	y	y	?	?	?
Hazard assessment	y	y	y	y	y	y	y	y	?	?

Figure 12. Coastal application and corresponding integration of GIS functionalities.

There has been a common syndrome of imbalance between functionality and application. Some users do not have adequate GIS functionality for their intended application, while the others do not realise that they purchased the surpass GIS capability that they probably will never need. This ‘under value’ or ‘over sell’ of GIS could be harmful for the implementation of GIS in CZM.

To success in a GIS application, besides available resource and time, one should attempt to keep the balance between the level of application and the required functionalities. The general requirements of GIS functionality for coastal applications are determined by the characteristics of coastal issues. It is therefore necessary to examine the characteristics of coastal issues, prior to discuss the GIS functionality.

3.1 Common Characteristics of Coastal Issues

Coastal issues have some characteristics in common:

- a) **Zonalisation:** Traditionally, different interest groups have investigated coastal area from different prospective and classified the area into zones (Figure 1), such as the habitat zone, surf dynamic zone, navigation zone, aquaculture zone and fisheries management zone. Therefore, it is obvious that classification and zonal analysis functions are essential in Coastal GIS.
- b) **Multiple variables:** The coastal system has a hierarchy structure that is composed of many subsystems interacting with each other. A particular user group tends to have its focus on a portion of coastal system or subsystems with multiple variables interacting upon it. Therefore, multivariable analysis or multi-criteria analysis functions are important components for Coastal GIS.
- c) **Dynamic:** Coastal system and its subsystems are dynamically interacting over space and time. Coastal GIS should be structured in the way that the data and models of dynamic processes (if defined) can be accommodated and operational. The ability of model integration is a crucial criterion for coastal GIS and it is one of the most challenging tasks in the development of coastal GIS.
- d) **Uncertainties:** It is well recognised that coastal processes are fraught with uncertainties (Cowell and Thom, 1994; Zeng, *et al.*, 1997) and most coastal decisions were made under uncertainty (Funtowicz and Ravets, 1995; Otter and Capobianco, 2000), thus the precaution principle should be adopted. Therefore, coastal GIS should be able to cope with the uncertainty.

GIS application in coastal zone can benefit from the methods of assessment of error propagation (Heuvelink, 1993, Lanter and Veregin, 1992) and techniques of handling uncertainties that are routinely used in the fields of Artificial Intelligence (AI) (Zadeh, 1976; Kauffmann, 1975; Zenmmerman; 1991, Kasabov, 1996, Openshaw and Openshaw, 1997).

3.2 Functions Versus Applications

From the above discussion, it can be ascertained that the relationship between the functionalities and application levels of Coastal GIS should be investigated for each project. From GIS application point of view, the level of application should be firstly defined and then the appropriate GIS functions be selected. Based on the review of current GIS applications in coastal zone, a summery of GIS functionalities (existing and potential) versus the level of applications is given in Figure 9. With a higher application level, the required functions aggregate, from simple analysis to multiple-criteria analysis functions, then integrated model of 'close-couple' and 'loops-couple'.

Currently, the majority of GIS applications in coastal zone have reached Level 1 and Level 2. Their needs for Level 3 development will continues to grow, when new models of particular scientific fields become available from different user groups and improvement of user interface becomes available from commercial vendors (Figure 12).

4 Discussions

In the past two decades, integrated coastal zone management (ICZM) (Cicin-Sain and Knecht, 1998; Post and Lunding, 1996) has been put into practice and become widely accepted approach for coastal zone management. The ICZM aims to ensure that the decision is made with thoughtful consideration of all user groups and sustainability of the coastal environment. GIS, as a decision-support tool, will play more important role in the processes of ICZM. Therefore GIS training has been given a high priority in CZM education.

The development of Coastal GIS not only provides a powerful tool for coastal management, but also has an impact on the practice of coastal management, and on the police and management planning. Coastal GIS applications and technology development are inherently interacting. The needs call for better GIS functions. Therefore, the development of coastal GIS should be aligned with the principle of ICZM.

In general, there are four fundamental characteristics for a coastal GIS:

Integrated approach of four aspects, including:

- a) integration of different level of application,
- b) integration of vector and raster (data and functions),
- c) integration of knowledge of different expertise, and
- d) integration of different scales in time and space.

Because of the nature of integration, GIS applications should consider long-term integration. This includes the vertical integration that involves different application (and potential) levels, and horizontal integration that involves other interest groups. Therefore, issues must be addressed from database design, data sharing to tool-making (analysis functions) and experience sharing.

Zonal focused:

Most case studies have shown that the interested objects are polygon features or zones (e.g. aquatic reservation zone, fish closure zone, fisheries management zone, coastal hazard zone, fish habitat zone and coastal development zone). New methods for zonal analysis (e.g. Zeng, *et al.*, 1997) can be implemented into Coastal GIS.

Multicriteria analysis:

- a) multi-factors controls

Since coastal system has a complex hierarchical structure with multi-forcing exerting on each of subsystem, no matter which aspect of the system to be investigated, multi-variable analysis is a essential methods in the coastal environment.

- b) multidiscipline approach for decision

Other than the multi-factors, there are multiple interest groups of coastal community, therefore, good solutions to any coastal issues can only be derived from multidiscipline approach.

Equipped with uncertainty handling tools:

Fuzzy set analysis, probability, random simulation and Neural Network. Further development of Coastal GIS is challenged by true 3D GIS functions (similar to those having been used in 2D environment) and the presentation / display of the results of 3D GIS modelling. Finally, it is the hope of the authors that this paper will be an integrated part of the development of Coastal GIS.

5 Conclusions

Coastal GIS development involves many aspects ranging from data model, system architecture to analysis methods. Coastal GIS development and application are challenge tasks facing both users and developers.

From the users' point of view, Coastal GIS applications should consider the following important points:

First, it should be developed according to the proposed applications, in terms of budget and ongoing budget, time frame, data structure, file systems structure, GIS functions required and the expected outcome from the analysis to support your objectives and how to handle the ongoing expansion.

Second, the level of application needs to be defined to match your objectives. Based on this, one can seek among the available and new GIS functions suitable for the required tasks.

Third, many coastal data are commonly needed by different fields of coastal management, therefore, when developing a GIS database, it should begin with 'a bigger pictures' in mind - considering the re-usage and sharing of datasets standardising the data and ensuring the data consistency and integrity.

From the development point of view, the major challenge is the Level 3 applications, where more integrated modelling functions are needed. The primary issue is selection of coastal models to be integrated into GIS. As the coastal models themselves are diversified and continuously improving and new models are developing, more user-friendly interface is needed, such as module-builder in graphic form (e.g. Grid Modeller (ESRI, 1994)) that are routinely used in computer simulation.

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