71

GIS in environmental monitoring and assessment

L LARSEN

This chapter deals with some aspects of using GIS in environmental monitoring systems. Issues concerning real-time monitoring, data quality, the use of GIS in combination with mathematical modelling, and other possibilities for creating GIS-based monitoring systems are examined. The discussion of environmental systems highlights examples of local and regional real-time monitoring and decision support. Hydrographic examples concerned with monitoring the Ringkøbing Fjord, Denmark and the Øresund Sound between Denmark and Sweden clearly demonstrate the value of GIS in environmental applications.

1 INTRODUCTION

When it comes to GIS environmental modelling applications, in many respects GIS software can be considered comparable to a programming language. Unfortunately, however, the typical environmental GIS users are focused on environmental issues and only rarely do they have the additional technical knowledge necessary to develop new GIS applications. As a consequence, most domain experts are forced to work with GIS that have predefined underlying data structures and 'standard' interfaces.

This chapter will deal with the issues to be considered by the designers and programmers of such turn-key applications within the areas of environmental monitoring and assessment. Each distinct type of system presents its own demands to the designer and together these requirements may form a 'requirements matrix'. Some characteristic examples of applications will be given together with a closer look at the demands that the individual applications make.

First it is useful to distinguish between the various types of environmental monitoring and assessment systems. In monitoring systems emphasis is placed on data collection, pre-processing, and quality control. Analysis systems focus on using tools to manipulate and model data. Information systems, on the other hand, are more concerned with the storage and management of data (Ji and Mitchell 1995).

2 MONITORING SYSTEMS IN GENERAL

There are many different types of monitoring systems. Many of them automate the process of data collection and (pre-) processing – a task often hidden from the ordinary user. Monitoring itself may be implemented in several different ways depending on the type of system under study. When designing an environmental monitoring system, the following factors should be taken into consideration:

- the acceptable time delay is likely to range from true real-time monitoring to manual sampling with a following laboratory analysis;
- the requirement to control quality may range from showing pure raw data to a complete quality assurance/quality control (QA/QC) procedure;
- there is often a distinction between manual and fully automated data sampling systems.

Whatever method is used for the actual monitoring, the process involves the following steps:

1. a communication task which takes data from a sensor (or other information source) and communicates it to a receiving monitoring system;
2. pre-processing the data using steps such as calibration, checking, and formatting;
3. storing the data in some sort of database;
4. presenting the data in an appropriate form to users.

Hitherto monitoring processes, and thus monitoring systems, have been rather mechanical. Depending on the specific task, monitoring may have been done with the assistance of one or more specialised standard systems, such as supervisory control and data acquisition (SCADA) systems.

The reason for introducing GIS into the pure monitoring process is mostly connected to a user-interface requirement. By introducing GIS at this stage it is possible to utilise mapping functions to display objects such as measurement stations. Furthermore, it can be of great value to keep the complete system within the framework of the GIS, especially if the required data processing tasks involve spatial analysis.

3 THE ROLE OF GIS IN ENVIRONMENTAL MONITORING

GIS, not surprisingly, has a very important role to play in environmental monitoring. GIS is ideally suited as a tool for the presentation of data derived from distributed measurement stations (e.g. field-based water quality sensors). Unfortunately, however, most GIS have some severe shortcomings when it comes to dealing with the typical data obtained from such measurements, namely time series data. The techniques for dealing with time series data are covered more thoroughly elsewhere (Peuquet, Chapter 8). In a nutshell, time series are long consecutive runs of data, such as the temperature measured every half hour at a certain point. Since most standard GIS software packages do not possess adequate tools for handling temporal data, they must be extended or auxiliary applications interfaced. For a discussion of the approaches to integrating GIS and external software systems see Abel et al (1994); Federa and Kubat (1992); Goodchild et al (1992); Maguire (1995); Steyaert and Goodchild (1994).

The time series data routinely collected for environmental monitoring very often have two significant analytical and display problems. First, they typically relate to points, when data based on areal units would often be more useful (a problem of spatial object type). Second, the temporal sampling incidence is often too frequent, resulting in large volumes of data. GIS offer relatively simple means of dealing with each of these problems. First, with regard to spatial resolution, a measurement point may be permanently assigned to a representative area using a simple point-to-area transform (see Martin, Chapter 6), such as those based on Thiessen tessellations (Boots, Chapter 36). A different option is to use standard GIS gridding and contouring facilities to interpolate between the point measurements across the whole study area. Second, with regard to temporal resolution, standard database selection capabilities may be used to extract data pertaining to a time value corresponding to other data to which it must be compared. Alternatively, standard descriptive statistical functions may be used to reduce data volumes (e.g. calculation of the average or maximum values for characteristic periods: see Anselin, Chapter 17, for an overview of a full range of exploratory spatial data indices). Any of these approaches may be used alone, or in combination.

The data flow and hardware configuration for a combined monitoring and GIS is shown in Figure 1. The illustrated system is a rather complex example implemented as a multi-user, client-server configuration. Apart from showing the basic system architecture, the figure also demonstrates how many functions may be involved in a GIS-based monitoring system. In particular, it should be noted how much of the system is actually dedicated to collecting, processing, and storing data rather than explicit spatial analysis and display operations. Essentially GIS is only used at user workstations, whereas the major part of the system is dedicated to other tasks. This distribution is in most cases reflected in the corresponding implementation and running costs. As a rule of thumb at least 90 per cent of the cost involved in setting up an environmental monitoring system is related to the measurement program, the quality control, and processing of data; only a minor part is related to the programming of GIS-based analysis and display functions.

Often the simple data analysis functions provided by standard GIS software packages are insufficient for dealing with the data monitoring requirements of environmental problems. The reasons for this are many, the most common being:

- the economic aspects of a project do not allow sufficient data to be collected to 'feed' the analysis tools;
- the characteristics of the data make simple extrapolation inappropriate;
- several parameters are interconnected and the required data cannot be measured directly.

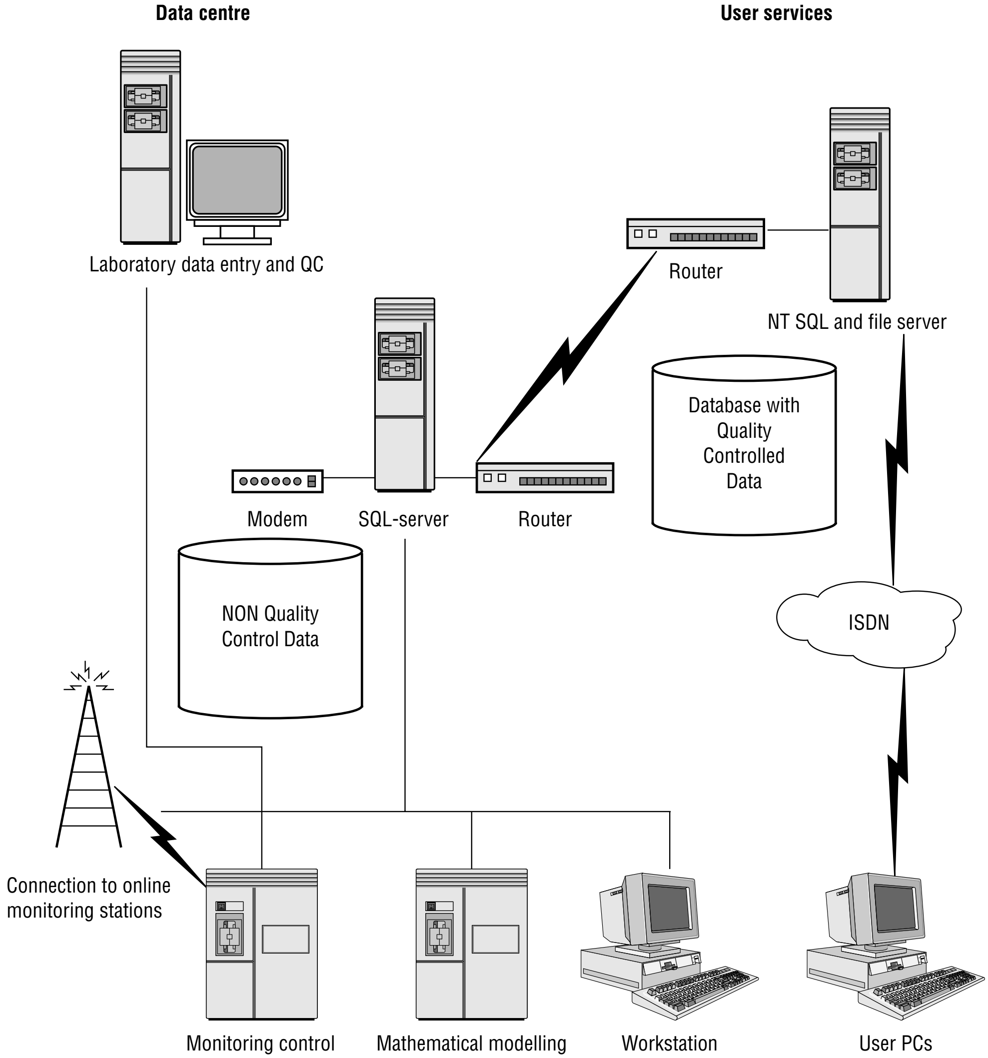

Fig 1. Data flow and hardware network for an example environmental monitoring and assessment system.

In such cases more complex models are needed to reflect the expected environmental situation. In such circumstances, the task of environmental monitoring goes much further than can realistically be achieved within a standard GIS.

4 ENVIRONMENTAL MONITORING AND MODELLING

Environmental monitoring operations are typically very expensive to set up and maintain. Budget constraints often mean that monitoring programmes have to be scaled down and that many systems are barely adequate to meet their objectives. Chemical parameters, for example, are frequently of interest to those who study the environment, but unfortunately appropriate measurement instruments for such parameters are often very expensive to purchase and maintain.

One possible solution to this problem is to combine a reduced field-based monitoring programme with mathematical modelling. Most often the elements of interest (chemicals, oxygen, sediment, smog, etc.) will behave in their carrying medium (water or air) in a very specific way that may be simulated. By setting up a mathematical model describing the dynamics of the carrying component (the water or the air flow) and by monitoring the parameters of interest close to the sources (and, perhaps, other control points) very good estimates of concentrations covering the complete area of interest can be obtained.

As an example, a project measuring, for instance, nitrogen concentration using hundreds of sensors covering an entire area, may be transformed into the following combined monitoring/modelling programme:

- monitor the driving forces for the dynamics, like atmospheric pressure, wind velocity and direction. Such parameters can usually also be monitored with rather inexpensive yet reliable equipment;
- establish a mathematical description of the flow in the area, as a mathematical model;
- monitor the parameter of interest (nitrogen) at a few strategic locations, usually close to possible direct sources and near model boundaries;
- by introducing the nitrogen in the model and using the proper advection/dispersion or similar schemes in the calculation, the complete pattern of concentration may be calculated.

While such an approach of course introduces a number of uncertainties, it will in many cases present a cost effective alternative to pure monitoring by means of sensors; indeed in some cases it may be the only viable alternative.

5 GIS AS AN ANALYSIS TOOL FOR MONITORING DATA

Much too often the use of GIS for environmental monitoring is restricted to the presentation of data and the creation of 'pretty maps'. The inherent powers of GIS as a tool for data integration and analysis are very often underutilised.

The fact that monitoring systems often stop the data analysis process when adequate quality control of the incoming data has been performed prevents, for instance, environmental authorities from using GIS to do further investigations of the causes of pollution. Hopefully, the creation of more and more databases with spatial information will gradually change this so that information on, for example, industrial development may readily be combined on a more ad hoc basis than is the case at the moment.

The ability to aggregate data from various inputs and present them in map form is a very important method of strengthening general awareness of environmental conditions. GIS is also a valuable tool in the decision-making process. Those who use GIS to present environmental data as maps or graphs clearly need to be aware of the issues associated with classification, symbolisation, and visualisation, not least because they can affect the conclusions people draw about the data. This important subject is covered elsewhere in this book (see Kraak, Chapter 11; Weibel and Dutton, Chapter 10).

6 EXAMPLES OF MONITORING SYSTEMS

6.1 Real-time monitoring

The Ringkøbing Fjord, a lagoon area in the western part of Denmark, is linked to the North Sea by a narrow channel with a sluice gate. The biotope inside the lagoon is highly sensitive to environmental pressure. The two most important parameters of the water inside the lagoon are its oxygen and salinity because they fundamentally affect which species will thrive. The main (controllable) cause for changes to these conditions is the inflow of seawater to the lagoon. An inflow which is too large may cause a salinity increase, whilst too little may cause oxygen depletion. The sluice gate in the channel connecting the lagoon to the open sea may be used to control this inflow. Both economic and environmental interests are at stake in the Fjord and there is constant debate between farmers, wildlife experts, and fishermen.

The UNIX-based XDISP monitoring system (Plate 64) has the dual purpose of documenting the state of the environment and functioning as an alarm system should a critical situation arise. The system uses a specialist software program to collect data on current velocities, water temperature, conductivity, and oxygen. This is achieved by carrying out background tasks which are scheduled to communicate with the specialised data collection hardware. Data collected using this process are fed into a GIS database which organises and stores the data.

For calculation of the complete patterns of oxygen concentration and salinity, the system uses a combined modelling and monitoring strategy. Because of the real-time requirements of the system, it is not possible to run a full mathematical simulation model to support the measurements. Instead a database with a large number of characteristic flow

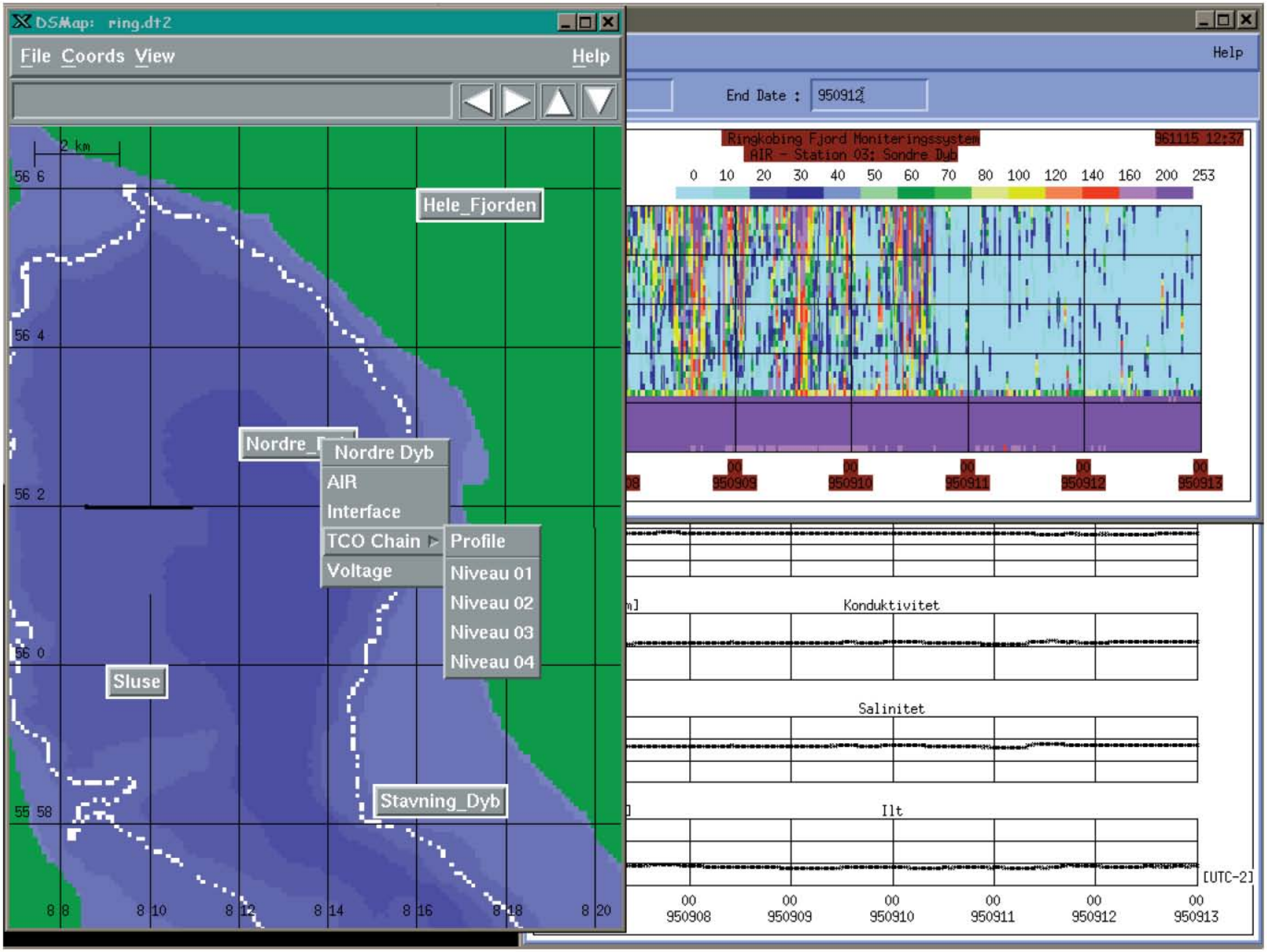

Plate 64
The XDISP monitoring system, applied to the Ringkøbing Fjord, western Denmark.

patterns has been created using a mathematical model. For each point in time the combined set of measurements is taken and compared with the database results using a pattern matching algorithm. The best matching flow pattern is then extracted from the database and used for further calculations to produce the final concentration map. This method may be used in areas where certain fixed patterns of flow are always present.

By using the GIS capabilities the present state of the important parameters may always be evaluated in close to real time. This approach also allows comparison with historic measurements thus providing an excellent basis for further discussion. For instance, the present situation can be compared directly with historic events that have resulted in well-known consequences to the flora and fauna of the lagoon. As the system provides very high resolution results even very local phenomena, like conditions in a fish farm, may be evaluated.

6.2 Local area monitoring

6.2.1 Background

EAGLE (Thorkilsen et al 1997) is a system used to control the aquatic environment close to the construction site of a major bridge and tunnel project. It is a very good example of how a GIS can be used in local environmental monitoring. The system has been developed for Øresundskonsortiet, who are responsible for the construction of the fixed link between Denmark and Sweden, a combined bridge and tunnel crossing the Øresund Sound. The system is part of a wider project concerned with the development of an environmental information and management support system for Øresund.

In the construction phase of the fixed link, a large number of environmental issues concerning the marine environment must be monitored and evaluated. The state of the ecosystem is one of the most important parameters in management decisions about dredging and reclamation work. Data such as hydrographic parameters, sediment transport, eelgrass growth, mussel coverage, fish migration, water quality, and bird life are taken into account in assessing the status of the environment. The EAGLE system contains information about the present state of the ecosystem and interacts with a forecast modelling system. Together these components are used to evaluate various construction scenarios in order to balance economic and environmental interests.

The EAGLE system monitors a large variety of data online. It receives results from backward projections and forecasting models and evaluates the results against a large number of environmental criteria. In the event that constraints are violated, a series of actions is triggered. The events and actions are saved by the system for later analysis and as documentation for the authorities.

The information system part of EAGLE is used by the authorities and other interested parties to monitor the progress of the project and to follow the decisions and field observations closely. EAGLE is constructed using ESRI's ArcView GIS, together with other specific-purpose programming tools. The main part of the system runs on PC hardware, employing both local and wide area network technology.

6.2.2 Project description

Concern about the long-term environmental effects of increased sedimentation and reduced water flow between the North Sea and the Baltic has led to extensive dredging to compensate for the blocking effect of the bridge construction. Unfortunately, such large dredging operations may have severe impacts upon the local environment. To avoid this, the legislation covering the project has included dredging performance criteria and a complex monitoring and control programme has been established. The EAGLE system is part of this procedure.

6.2.3 Environmental issues and requirements

During the construction, the major environmental concerns relate to the area where about 7 million cubic metres of mainly clay and chalk-based seabed is being dredged. This has resulted in extensive sediment plumes in the shallow water areas surrounding the construction site itself.

An extensive environmental assessment concerning both the local and global effects of the link was carried out prior to the design of the bridge, but as such assessments need to be done using the conditions of a so-called 'normal year' there is nothing to ensure that the conditions simulated during the assessment will be similar to the actual conditions. This is particularly true for the construction phase which covers a four-year period only. Because of this uncertainty, intensive monitoring is needed during development and an organisation must be ready to evaluate the results and to take remedial action on a very short timescale in order to avoid permanent damage to the environment. The more sensitive parts of the local environment concern the land-based fauna, the marine flora, and the marine fauna of the area. The bridge will eventually border a major wildlife protection area.

The two governments involved and the corresponding environmental protection agencies expressed a number of fairly general criteria when authorising the work. One example criterion is that during construction the biomass in the area may not be reduced by more than 25 per cent. Obviously such parameters cannot be controlled on a day-to-day basis and, consequently, the daily control has to be done on simpler and more pragmatic criteria, referred to as 'operational criteria'.

The operational criteria have been chosen in such a way that they are relatively easy to transform into the general criteria of the project. As an example, eelgrass has been chosen as a central plant to monitor as it is an important part of the ecosystem in the area and it is sensitive to sediment concentrations in the water. In a similar fashion, a large number of other criteria have been established which may be evaluated on the basis of measurements and put into a monitoring programme.

6.2.4 Monitoring programmes

In order to control the environmental impact directly and provide sufficient information to support remedial actions at short notice, a number of monitoring activities are performed on a routine basis. The project involves four different monitoring programmes, all supplying data to the EAGLE system where results can be evaluated and compared:

- Background monitoring: mainly hydrographic data, such as water levels and currents, are monitored constantly in order to maintain a complete background profile of the hydrographic and meteorological conditions in the area.
- Spill monitoring: constant monitoring of the sediment plumes is being carried out on a 24 hour basis. These data are used when reporting on spill quantities and form input to the sediment modelling process.
- Feedback monitoring: continuous monitoring of the key operational criteria is carried out to evaluate their usefulness.
- Control monitoring: overall qualitative monitoring is carried out to register any possibly unforeseen effects.

6.2.5 Modelling

Several of the monitoring activities are combined with modelling activities. The following models run on a routine basis in the system:

- Hydrodynamic modelling: DHI-MIKE 21 (Warren and Bach 1992) models the complete hydrodynamic regime of the area in two dimensions. The results are used as input for the sediment transport model.
- Sediment transport modelling: the sediment transport and the sedimentation are modelled using a combination of MIKE 21PA and MIKE 21MC standard models. These models input the measured and budgeted spill from the dredging operations.
- Eelgrass growth: using the output from the sediment model the shadowing effect causing the eelgrass growth to slow down or stop is calculated. Combining this with other parameters, like water depth, natural light, temperature, and nutrition, the expected effect of the sediment plumes on eelgrass growth is modelled.

The modelling activities are mainly run using 'retrospective forecasts'; for example the known weather and other boundary conditions for the previous period are used as an input to the model. The results of the model can then be used to extrapolate the relatively sparse measurements into a total coverage of the project area.

At regular intervals the same models are used in forecast mode to provide an updated environmental impact assessment (EIA) for the complete construction period, using the measured data up to the start of the modelling period. This procedure will gradually reduce the uncertainty of forecasts and thus provide an even better foundation for decisions on remedial actions. This will help avoid violation of any of the consents given for the project.

6.2.6 Feedback loop

All results from the modelling and monitoring programmes are compared to a set of operational criteria to see if the results identify whether any criteria are violated. In instances of violation, a predefined action, or set of actions, is triggered and reported in the system. The criteria and the actions are organised in an escalating loop as is shown in Figure 2.

A triggered action (normally the first action is intensified monitoring) will always produce a new set

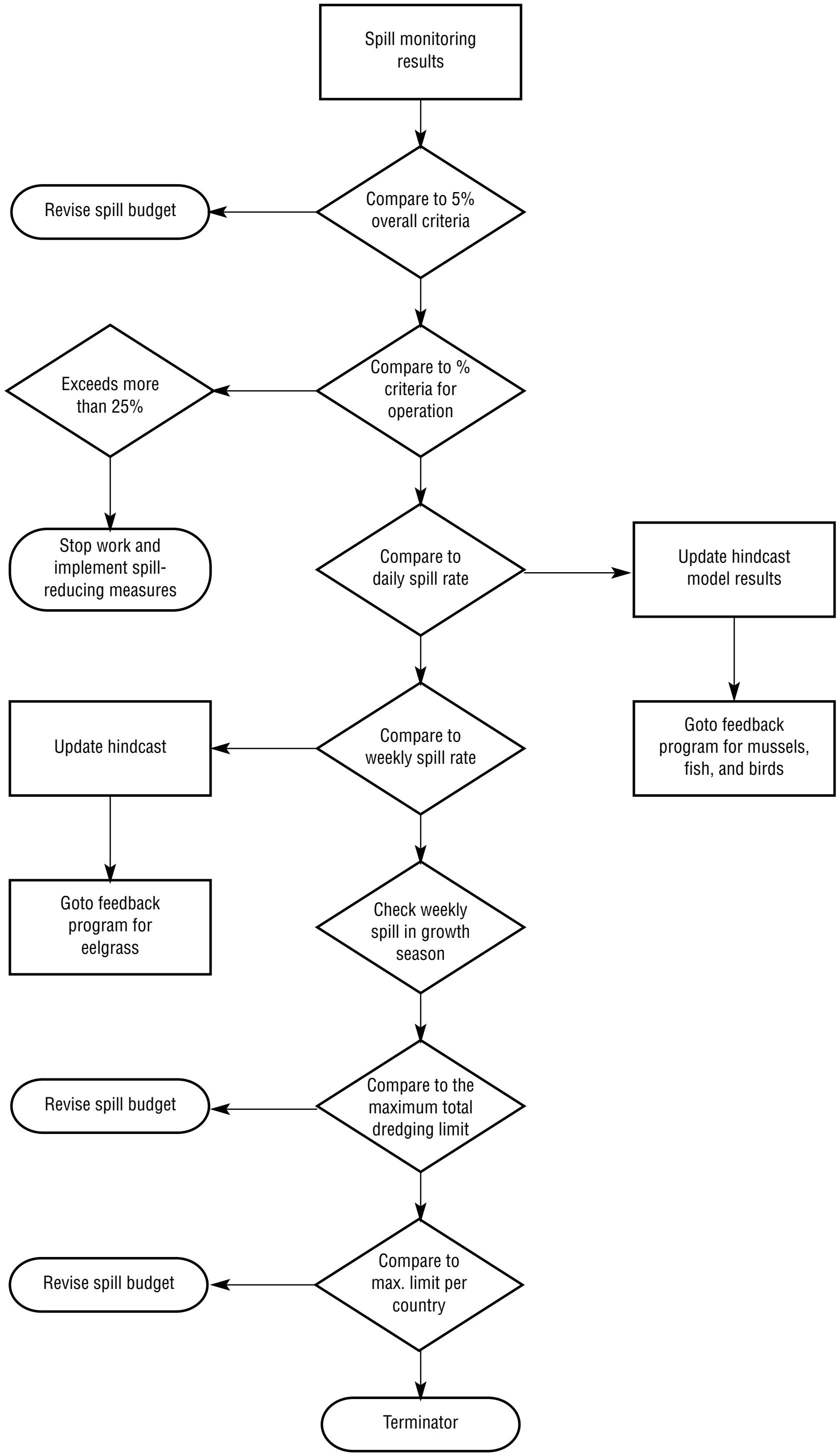

Fig 2. The feedback mechanism within the Øresund Sound monitoring model.

of data which again can be checked against the performance criterion. This will continue until either the situation is proved to be normal, or – in the event of serious danger to the environment – remedial action (ultimately stopping the construction work) has been taken.

6.2.7 The EAGLE system

As can be seen from the above description, the procedures for environmental monitoring and feedback are very complex and involve large volumes of different data types. To assist the environmental decision-makers in achieving the necessary overview of the system and to support the right decisions, the GIS-based information system, EAGLE, was created as an adjunct to the XDISP monitoring system.

EAGLE is able to display relevant modelling, monitoring, and decision process data in a consistent environment. The basic data flow of EAGLE is illustrated in the EAGLE Main Menu shown in Plate 65. A database based upon Microsoft SQL-Server running under Windows-NT is constantly updated by the organisations responsible for environmental monitoring and modelling, and is distributed from a central file server to a range of users.

Users can access EAGLE from either the local area network or through a wide area network based upon ISDN connections. An automatic program update is incorporated into the system. Whenever program files or other files residing locally on the user machines are updated, new files are automatically transferred to the machines without manual intervention.

6.2.8 Sub-systems

EAGLE comprises the following sub-systems:

- a feedback module which provides an easy and rapid overview of all the different criteria involved in the evaluation process – as illustrated in the instance of spillage in Plate 66;
- an overview menu for feedback evaluation;
- an incident database, which logs every incident of environmental importance;
- a general presentation module which allows users to carry out their own full environmental assessment rather than rely upon conclusions drawn by other experts (individual interests and concerns may be investigated at a very detailed level).

Presentational information that may be extracted using EAGLE includes the following:

- sedimentation: data on sediments in the water are contained in the database and may be presented as either concentration isolines or as curves showing measurements versus time;
- satellite images: remote sensing information (primarily in the form of satellite imagery) has been added to track sediment plumes. These images may in turn be compared with measurements and model result plots;
- bird statistics: studies of the wildlife in the areas around the construction site result in statistics, such as nest counts and size statistics. These data may be presented using charts (e.g. bar and pie charts) on top of the basic maps held in the system;
- coastal morphology: as a reference for the 'before' situation, a study of the coastal morphology in the area was carried out and documented with coastline data and photographs. These data are all available online for reference;
- common mussels/sedimentation: the net sedimentation as measured and modelled is stored in the database and may be presented as separate layers to be compared, for example, to the formation of the common mussel, a species that will easily be affected by extensive sedimentation;
- spill reports: a major cause of environmental problems in this particular project is the spilling of sediment during dredging and reclamation. A separate part of EAGLE is devoted to reporting the direct monitoring of spills. This part of the system also reports the progress of the construction work itself. Reports made on a daily basis are supplemented with weekly reports containing quality controlled measurements only.

7 CONCLUDING REMARKS

The current state of GIS in environmental monitoring remains very much focused on the fact that GIS is an ideal tool for producing 'pretty pictures' which can also, to a certain extent, be used as a programming tool for user interfaces. GIS is used to a much smaller degree as an active component of environmental monitoring systems. As the field matures it is to be expected that environmental monitoring and GIS will become much more closely integrated. At the same time, GIS are becoming more and more user-friendly, making

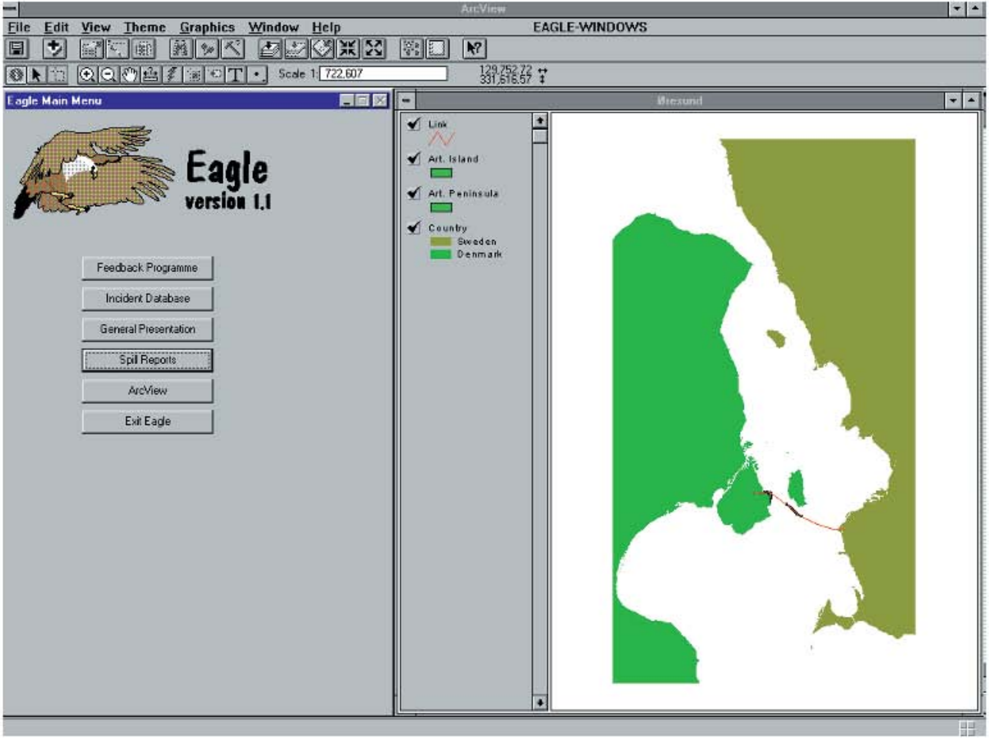

Plate 65
Main entrance menu to the EAGLE system.

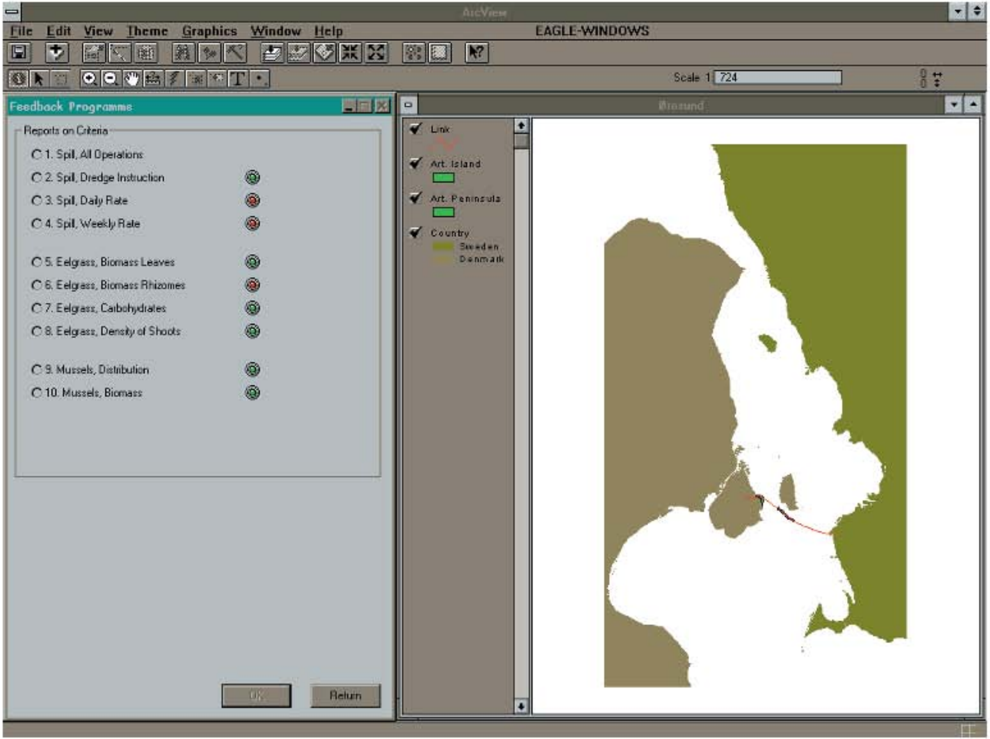

Plate 66
Use of feedback module to monitor effects of change.

them much more relevant as tools for non-GIS experts, such as senior managers and domain experts from other professional areas (Egenhofer and Kuhn, Chapter 28).

Once data are collected and stored in well-organised databases, the possibilities for well-designed GIS applications are tremendous, not only within one database but also using combinations of different networked databases. The rapid development of network technology will no doubt also stimulate the development of distributed databases (Coleman, Chapter 22). New GIS products are now Internet-aware and, together with advances in spatial database technology, possibilities exist for creating dynamic systems able to perform operations on distributed databases. Applications based on technologies such as 'data drilling' are now possible over the Internet. These types of application will be less and less sensitive to the original purpose of the database being queried (Goodchild and Longley, Chapter 40).

The trend towards network technology is also interesting because it offers the possibility for data aggregation. Almost all active environmental monitoring systems are local or regional systems aimed at monitoring specific components of the environment and helping to solve specific environmental problems. One consequence of the rise in environmental awareness is the need for exact information, as this is the only way for scientists and authorities to evaluate the most appropriate measures and regulations. In such situations it will be invaluable to be able to extract information from the increasing number of local monitoring systems and to aggregate that information into more globally-oriented monitoring systems (see Wilson, Chapter 70).

To achieve such a level of integration and corporation, a high degree of standardisation is required to be in place. Since almost all monitoring systems are established by government authorities (or by requirement of a government) a standardisation effort should have a good chance of success at least at a national level. By forming standards for how systems communicate on the network and how measurements are specified, with respect to quality, measurement method etc., it will be possible to utilise monitoring results made locally for other more general purposes in a larger scale monitoring effort (Chapal and Edwards 1994).

All in all, GIS will be a component of every environmental monitoring system within the next few years. This is quite simply because this type of data calls for the utilisation of GIS capabilities, and when one considers that GIS is becoming simpler to use and much cheaper to buy, it is hard to imagine a future for environmental monitoring systems without it (Schroeter and Olsen 1996).

References

Abel D J, Kilby P J, Davis J R 1994 The systems integration problem. *International Journal of Geographical Information Systems* 8: 1–12

Chapal S E, Edwards D 1994 Techniques for visualisation and quality control. In Michener W K, Brunt J W, Stafford S G (eds) *Environmental information management and analysis: ecosystem to global scales*. London, Taylor and Francis: 141–59

Federa K, Kubat M 1992 Hybrid geographical information systems. *EARSel Advances in Remote Sensing* 1: 89–100

Goodchild M F, Haining R, Wise S 1992 Integrating GIS and spatial analysis: problems and possibilities. *International Journal of Geographical Information Systems* 6: 407–23

Ji W, Mitchell L C 1995 Analytical model-based decision support GIS for wetland resource management. In Lyon J G, McCarthy J (eds) *Wetland and environmental applications of GIS*. New York, Lewis Publishers: 31–45

Maguire D J 1995 Implementing spatial analysis and GIS applications for business and service planning. In Longley P A, Clarke G (eds) *GIS for business and service planning*. Cambridge (UK), GeoInformation International: 171–91

Schroeter H, Olsen L 1996 The evolution of a space/earth information system. In Lautenschlager M, Reinke M *Climate and environmental database systems*. Boston (USA), Kluwer: 25–35

Steyaert L T, Goodchild M F 1994 Integrating geographic information systems and environmental simulation models. In Michener W K, Brunt J W, Stafford S G (eds) *Environmental information management and analysis: ecosystem to global scales*. London, Taylor and Francis: 333–57

Thorkilsen M, Dietrich J, Larsen L C, Nielsen A 1997 Environmental and geographical information system for dredging control. *Proceedings CEDA dredging days 1997*. Central Dredging Association: 109–17

Warren I R, Bach H K 1992 MIKE 21: a modelling system for estuaries, coastal waters and seas. *Environmental Software* 7: 229–40