

GIS technology and spatial analysis in coastal zone management

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Abstract

This paper reviews methods and tools of spatial analysis, their integration and application to coastal zone management. Following a definition of the coastal zone and a short description of its peculiarities and unique management problems, the paper first describes the major tools for spatial analysis, and in particular, GIS and remote sensing, spatially distributed simulation modeling and optimization, and expert systems, as well as their integration in information and decision support systems.

This is followed by a short review of the main paradigms of spatial analysis such as environmental impact analysis, risk assessment, and policy analysis, and specific problems such as zoning and site selection. Special emphasis is given to the issues of industrial development in coastal zone management.

Examples from the literature are used to illustrate concepts and trends, and the discussion addresses the role of information technology in spatial analysis and its application to coastal zone management in particular.

Key words. GIS, Remote sensing, Coastal management, Modeling.

Introduction

Coastal zone, for the purpose of this paper, shall mean the area, on both sides of the actual land-water interface, where the influences of land and water on each other are still a determining factor - climatically, physiographically, ecologically, or economically. Within a European perspective, this means a coastline of (fractal theory notwithstanding) at least 148,000 km, with an estimated 200 million people living within 50 km of it. And while overexploitation with its subsequent pollution and degradation can be found everywhere, no comprehensive coastal zone management scheme yet exists for Europe (Stanners and Bourdeaux, 1994).

The coastal zones around the world's oceans and inland seas, including the numerous small islands, share a number of characteristics that define both their value and their vulnerability:

- The coastal zone shows a high population density with a large number of urban conglomerations, and in consequence, in most countries, a fast population growth;
- Again as a consequence, they are characterized by a high concentration of economic, and in particular industrial activities with all the resulting problems of resource consumption, waste management and technological risk.

High levels of population and industrial activities cause high resource requirements, water and energy being the most obvious ones.

Population and industry also induce passenger and freight traffic, which, for the coastal zone, includes both shipping as well as land-based forms of transportation, and of course air traffic.

On the coastal water side, we have fisheries and aquaculture, exploiting a generally highly productive ecosystem, that is not only productive in its own right, but plays an extremely important role in the aquatic ecology as a breeding and nursing ground for many commercially important fish species. Very specific, and valuable as well as vulnerable typical coastal ecosystem include estuaries, salt marshes, mangroves, sea grass meadows and coral reefs (e.g., Lean and Hinrichsen, 1992).

Off-shore activities such as oil and gas, as well as mining are additional forms of exploitation of the coastal zone. A most important form of land-use is recreation, which is often the dominant economic activity in many parts of the area.

While these activities, and in particular fisheries and recreation, would benefit most from a pristine environment, they, like all the other forms of land-use and resource exploitation, in fact often seriously degrade the coastal environment. In addition, the coastal zone is also the recipient of all water borne waste streams, including non-point sources primarily attributable to agriculture, its fertilizers and agrochemical, and all the treated and untreated wastewater the hinterland produces in the respective catchments. They all are draining into the coastal waters.

A systematic classification of coastal zone uses can be found in Vallega (1993), they include: Seaports, Shipping (carriers, routes, navigational aides), Sea pipeline, Cables, Air transportation, Biological resources, Hydrocarbons, Metalliferous resources, Renewable energy, Defense, Recreation, Waste disposal, Research, Archaeology, Environmental preservation and protection. These are further subdivided into a total of 250 kinds of uses, all focussing more or less on the aquatic part of the coastal zone. All of these activities compete, for space, for resources, and for the waste absorption capacity of the coastal zone. The intensity of activities that characterize the coastal zone implies competition for the use of the available land, in particular, since many activities such as industrial and recreational use are mutually exclusive.

Other specific problems include, on the one hand, the exposure of the terrestrial zone to marine impacts, and on the other terrestrial impacts on the coastal waters.

The first group includes such phenomena as storms, tides, and surges, the occasional tsunami, and the prospect of sea level rise, coastal erosion, salt water intrusion in rivers and aquifers caused by (often man made) low-flow and excessive withdrawal.

The second group includes problems such as coastal pollution from a variety of sources including polluted rivers, more local waste water outflows, unsustainable coastal fisheries, and more exotic problems such as genetic pollution from aquaculture.

Somewhere in between are problems related to shipping accidents such as oil spills and not so accidental spills, and losses from off-shore activities, or, on the terrestrial side, classical pollution problems from urban and industrial development, or the socio-economic problems of rapid urban development. All these problems have an obvious and often dominating spatial aspect, which makes coastal zone management a spatial problem.

An illustrative and most recent example of coastal zone problems is given by Ajjour and Drabih (1997) for the Gaza, Palestine: while covering only 44 km in length and about 74 square kilometers by the author's definition, the list of problems includes: Destruction of beach landscape, Destruction of natural coastal habitat, Wastewater discharges, Dumping of solid waste and construction waste directly on the beach, Beach erosion, Unplanned (random and scattered) development, Conflicting land uses, Lack of awareness of the public and government. As economy on coastal zones increases there are increased pressures on natural resources which render very difficult to foresee the environmental dynamics without proper scientific and high level technological tools.

To solve conflicts and/or find optimal solutions the integration of recent tools such as Geographic Information Systems (GIS), Image Processing Systems (IPS), Remote Sensing (RS), with Data Management, Data Analysis and Modeling, looks to be a promising exercise. As a matter of fact in the general information and guidance on developing and implementing an Integrated Coastal Management (ICM) program, UNEP (1995) includes specific tools and techniques of GIS and data management to face problems of protected areas, ecosystem management, impact assessment, economic evaluation and risk assessment, and searching the Internet with ICM (Integrated Coastal Management) and GIS as keywords yields a surprising number of returns. In this paper we try to present the state of the art of GIS technology and its applications in coastal zone management.

GIS technology and coastal management

Coastal zone management, by definition, is spatial management. Spatial management means the distribution and allocation of space, ultimately of parcels of land, (with or without water covering it) to alternative uses or activities, or the control of processes that in turn may affect space, such as emissions. Many of the underlying processes within the domain of environmental (both physical and ecological) modeling can be represented by spatially distributed models that describe environmental phenomena in one (for example, in river models), two (land, atmospheric and water quality models, models of population dynamics), or three dimensions (again air and water models). The increasing development and use of spatially distributed models replacing simple spatially aggregated or lumped parameter models is, at least in part, driven by the availability of more and more powerful and affordable computers (Loucks and Fedra, 1987, Fedra and Loucks, 1985).

The term "Geographic Information Systems" (GIS) means a set of computer tools to capture, manipulate, process and display spatial or geo-referenced

data. By GIS technology we mean the integration of all the methods and tools that can be useful to establish a decision support system (DSS) for spatially related problems. Notwithstanding in the specialized literature (e.g. Holsapple and Whinston 1991) DSS is mainly viewed as a mathematical technique or set of techniques for optimizing something under some constraints, we consider DSS in its broad meaning as an information system that can be used to support decisions.

The system needs the following components: GIS, Data analysis and Image processing, Modeling and Expert systems, Simulation and optimization and a suitable User Interface. These components are discussed as follows.

Geographic Information Systems (GIS)

A Geographic Information System (GIS) is a set of computer tools designed to efficiently capture, store, update, manipulate, analyze, and display all forms of geographically referenced information (e.g., ESRI 1992). A GIS typically links data from different sets, using geo-referencing, i.e., spatial coordinates, as a common key between different data bases. The power of a GIS stems from its ability to combine many data sets and display them in a common framework as thematic maps. To obtain thematic maps the GIS may have internal software tools for database and data analysis and image processing, or may be easily interfaced with external software. There are many GIS on the market, commercial and public domain GIS and they are all different each other. They may answer more or less easily and completely to the following typical questions depending on how they have been designed:

- *Spatial identification*: find locations where certain condition are satisfied, including the logical (Boolean) or arithmetic combination of multiple layers (overlay analysis);
- *Trends*: find the differences within an area over time or along spatial dimensions;
- *Patterns*: find correspondences between distribution of different attributes; calculate similarity between patches, fractality, indices of fragmentation, and so on.
- *Modeling*: answer "What if" questions.

However to answer more complex questions one needs to combine (static) geographic data layers with dynamic and spatially distributed models.

Data Analysis and Image Processing

Many GIS have internal data analysis and image processing functions that can calculate different pattern indices such as fragmentation, fractality, entropy, etc. (Turner1989). Some GIS such as IDRISI, ILWIS, GRASS have the possibility to treat remote sensing data coming from LANDSAT, SPOT, NOAA, etc. by using the maximum likelihood algorithm and fuzzy set theory (IDRISI). GRASS allows also to use sophisticated neural network algorithms (Openshaw 1993, Fisher 1993, 1994), however these GIS do not offer the possibility to treat ancillary data of specific Operational Geographic Units (OGU). These may be pixels, polygons, set of pixels and sets of polygons, for hierarchical classifications and

ordinations by methods such as cluster analysis and factor analysis (Arentze, Borgers and Timmerman 1996) or fuzzy set theory (Fabbri and Chung 1996). These methods are still available only on external packages. However, all modern GIS support convenient data import and export functions. Many packages are available for data analysis, however, except the method of maximum likelihood they rarely include methods of classification and ordination based on probability (Feoli and Zuccarello 1996). The advantages of using such functions derive from the fact that similarity between OGUs may be tested in a probabilistic way within the data sets representing the system under study. With probabilistic similarity functions the similarity may be tested within and between time intervals. These functions based on Goodall's probabilistic index (Goodall 1964) have been included in the information system developed by ICS/UNIDO (Feoli 1995) especially for applications in coastal zone management and for treating remote sensing data (Altobelli et al. 1995).

MODELING AND EXPERT SYSTEMS

In GIS, the basic concept is one of location, of spatial distribution and relationship, basic elements are spatial objects. In environmental modeling, by contrast, the basic concept is one of state, expressed in terms of numbers, mass, or energy, of interaction and dynamics; the basic elements are "species", which may be biological, chemical, and environmental media such as air, water or sediment.

The overlap and relationship is apparent, and thus the integration of these two fields of research, technologies, or sets of methods, that is, their paradigms, is an obvious and promising idea (Fedra 1994,1995).

Simulation and optimization modeling is a powerful tool of analysis, and forecasting. Another example of possible integration is provided by quantitative numerical models and rule-based, qualitative expert systems. Expert systems can be used just as any other model to assign a value to an output variable given a set of input variables; they do this, however, by using rules and logical inference rather than numerical algorithms.

In the context of models, expert systems are often used to help configure models (implementing an experienced modelers know-how to support the less experienced user) and estimate parameters. A number of these "intelligent front end systems" or model advisors have been developed in the environmental domain (Fedra, 1992).

A rule-based approach can also be a substitute for a numerical model, in particular, if the processes described are not only in the physical and chemical, but in the biological and socio-economic domain. An example could be environmental impact assessment based on a checklist of problems, which can be understood as a diagnostic or classification task. A qualitative label is assigned to potential problems, based on the available data on environment and planned action, and a set of generic rules assessing and grading the likely consequences. An example of such a rule-based system for impact assessment is described in Fedra et al (1991).

And finally, a model can be integrated into the inference chain of an expert system. Recent examples of environmental expert systems are given in Hushon (1990), Fedra (1992) and Wright et al. (1993).

The possibility to integrate models in place of rules in an expert system and at the same time use embedded rule-based components in models provides a very rich repertoire of building blocks for interactive software systems, that link policy level information with the underlying data and methods through hierarchies of methods and intermediate data. The flexibility to use, alternatively or conjunctively, both symbolic and numerical methods in one and the same application allows the system to be responsive to the information at hand, and the user's requirements and constraints. This combination and possible substitution of methods of analysis, and the integration of data bases, geographical information systems, and hypertext, allows to efficiently exploit whatever information, data and expertise is available in a given problem situation. The approach is based on a model of human problem solving that recursively refines and redefines a problem as more information becomes available or certain alternatives are excluded at a screening level. Learning, i.e., adaptive response to the problem situation and the information available, and the ability to modify function and behavior, as more information becomes available, is a characteristic of intelligent systems.

In this context the application of cellular automata modeling, coupling cellular automata and differential equations, may offer new tools for modeling by GIS. The cellular automata concept is based on a set of contiguous cells with rule-based interactions, e.g., fluxes between cells. These rules may come from numerical models or from logical models. Cellular automata modeling could help to simulate many alternative scenarios in coastal areas both concerning pollution of water and /or urban and industrial development (Camara, Ferreira and Castro 1996; Roy and Snickars 1996, Sanders 1996).

SIMULATION AND OPTIMIZATION

Another example of the integration of different methods is the coupling of simulation and optimization: optimization usually requires an (often-gross) simplification of the problem representation to become tractable. Simulation models, on the other hand, while capable of representing almost arbitrary levels of detail and complexity, are rarely capable of solving inverse problems, i.e., determining the necessary set of inputs or controls to reach a desired outcome. One can, however, combine the approaches in that a simplified model (e.g., steady state and spatially aggregated) is used as the basis for optimization; the result of the optimization is then used as the basis for a more detailed, e.g., dynamic and spatially distributed simulation model, that also keeps track of the criteria, objectives and constraints used for the optimization, but with a higher degree of spatial and temporal resolution, and possibly a more refined process description. If, in the simulation run, constraints are violated or objectives not met, the corresponding values can be tightened or relaxed in the optimization to obtain a new solution which again is subjected to more detailed examination with the simulation model.

Modeling of marine systems has a considerable tradition in both physical and biological oceanography. For summary treatments, more recent model

comparisons, and some classics in the field see, for example, Riley et al., (1949); Nihoul, (1975); Goldberg et al., (1977); Kremer and Nixon, (1978); Falconer et al., (1989); Fransz et al., (1991).

However, most of these approaches are designed to improve scientific understanding of physical and biological processes, with the notable exception of some of the fisheries models that have obvious management implications (e.g., Andersen and Ursin, 1977). Other management oriented and model based studies of marine systems include the RAND Corporation classic on the Oosterschelde (Bigelow et. al., 1977) or the recent study of the North Sea MANS, Management Analysis North Sea (Rijkswaterstaat 1988; and Klomp, 1990). Here, as well as in a number of similar projects including models, the emphasis is on environmental and resource management issues, and decision support rather than primarily scientific progress.

THE USER INTERFACE

Analysis in GIS is based on the map paradigm; maps in inherently static objects, and the basic level of analysis is (Boolean) map overlays. Complex relationships, and dynamic processes, may require another layer of tools, namely simulation models, to be integrated with a GIS.

The integration of GIS and environmental models can come in many forms. In the simplest case, two separate systems, the GIS and the model, just exchange files: The model obtains some of its input data from the GIS, and produces some of its output in a format that allows import and further processing and display with the GIS. This seems to be a rather common approach, since it requires little if any software modifications. Only the file formats and the corresponding input and output routines, usually of the model, have to be adapted. Depending on the implementation however, a solution based on files shared between two separate applications, usually with a different user interface, is cumbersome and possibly error prone if it involves a significant amount of manual tasks. Deeper integration provides a common interface and transparent file or information sharing and transfer between the respective components. Possible ways are the use of higher-level application language or application generators increasingly common as built-in features of commercial GIS packages as the basis of numerous integrated applications. Application generators and modeling capabilities with commercial GIS also offer the possibility of tight integration within the limits of the respective package options. An alternative is to use an open GIS tool kit, that uses a standardized interface, such as GRASS (Gardels 1988, Fedra and Kubat 1993). Modules of the overall GIS system (which really is a set of tools with a standardized pipeline-type flexible coupling) can be included in modeling applications. The X Windows system and a number of interface building toolkits make this a rather efficient integration strategy. Any integration at this level, however, requires a sufficiently open GIS architecture, that provides the interface and linkages necessary for tight coupling.

Using such predefined tools and components, while efficient for fast prototyping, can also be restrictive: investments in toolkits always carry the temptation to

reformulate problems in terms of the available tools rather than the other way round.

Another alternative is the use of do-it-yourself tool kits that provide both customized GIS functionality as well as interface components for simulation models. A recent example of integration that draws together GIS, models, spreadsheet, and expert systems in a programmable system is RAISON (Lam and Swayne, 1991).

Integrated environmental management information and decision support systems, built around one or more coupled models, numerical simulation models or rule-driven inference models, and integrated with GIS, feature:

- An interactive, menu-driven user interface, that guides the user with prompt and explain messages through the application. No command language or special format of interaction is necessary, the computer assists the user in its proper use; help and explain functions can be based on hypertext and possibly include multi-media methods to add video and audio technology to provide tutorial and background information; in other words, they must be easy to use even for the non-specialist.
- Dynamic color graphics for the model output and a symbolic representation of major problem components that allow easy and immediate understanding of basic patterns and relationships. Rather than emphasizing the numerical results, symbolic representations and the visualization of complex patterns support an intuitive understanding of complex systems behavior; the goal is to translate a model's state variables and outputs into the information requirements of the decision making process; the coupling to one or several data bases, including geographical information systems, and distributed or remote sources of information in local or wide area networks, that provide necessary input information to the models and the user. The user's choice or definition of a specific scenario can be expressed in an aggregated and symbolic, problem-oriented manner without concern for the technical details of the computer implementation; data on chemical properties of the substances of concern, used in pollution fate and transport models, are one obvious example;
- Embedded Artificial Intelligence (AI) components such as specific knowledge bases allow user specifications in allowable ranges to be checked and constrained, and ensure the consistency of an interactively defined scenario; as a special case this could also include QSAR methods that can be implemented in a combination of rule-based methods and algorithmic methods;
- And they are, wherever feasible, built in direct collaboration with the users who are after all experts in the problems areas these systems address.

The examples of integration discussed above mainly refer to internal integration, i.e., linking components of an information system. There are, however, two more important dimensions to integration that need to be considered: integration with the user and integration with the information sources of a system (compare **Figure 1**). Important issues here are interaction and visualization, intelligence, and customization, that is the integration into the institutional framework of a system's intended use.

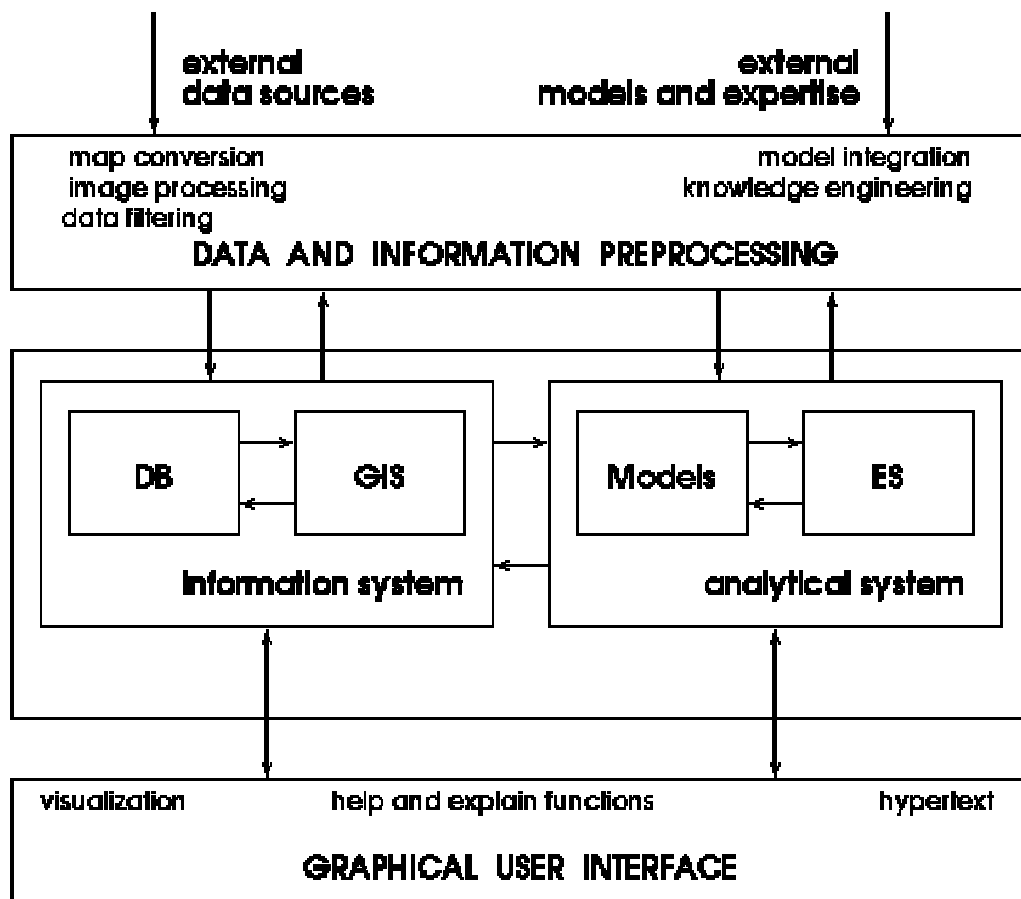


Figure 1: Linking spatial analysis with information resources and the user

Interaction is a central feature of any effective man-machine system: a real-time dialogue, including explanation, allows the user to define and explore a problem incrementally in response to immediate answers from the system. Fast and powerful systems with modern processor technology can offer the

possibility to simulate dynamic processes with animated output, and they can provide a high degree of responsiveness that is essential to maintain a successful dialogue and direct control over the software.

Visualization provides the band-width necessary to communicate and understand large amounts of highly structured information, and permits the development of an intuitive understanding of processes and interdependencies, of spatial and temporal patterns, and complex systems in general. Also, many of the problem components in a real-world planning or management situation, such as risk or reliability, are rather abstract: a graphical representation of such concepts makes them tangible objects that can literally be manipulated and understood intuitively.

Intelligence requires software to be knowledgeable not only about its own possibilities and constraints, but also about the application domain and about the user, i.e., the context of its use. Defaults and predefined options in a menu system, sensitivity to context and history of use, built-in estimation methods, learning, or alternative ways of problem specification depending on the user can all be achieved by the integration of expert systems technology in the user interface and in the system itself.

Customization is based on the direct involvement of the end-user, and the consideration of institutional context and the specifics of the problem domain in systems design and development. It is the users view of the problem and their experience in many aspects of the management and decision making process that the system is designed to support. This then must be central to a system's implementation to provide the basis for user acceptance and efficient use.

Decision support systems, and their interfaces, are representations of the problems they address as much as of the planning and decision making processes they are designed to support. In the latter field, if not also in the former, their users are the real experts. Thus, their expertise and experience needs to be included in the systems. As a consequence, users must be involved in the design and development, so that they can accept responsibility and ownership for the software system.

Institutional integration also must look at aspects such as user training, data entry, maintenance issues of keeping systems current and operational, providing adaptations and updates, etc. Any complex information system has more than one user at more than one level of technical competence and with different roles within an institution. Different users have different requirements that need to be supported: flexibility and adaptability are therefore important features. Systems must be able to grow with their users. Therefore, the institutional commitment and technical infrastructure to keep a system alive and evolving are as important as the scientific and technical quality of the original software system.

DECISION SUPPORT SYSTEMS

The management of natural resources requires the integration of often very large volumes of disparate information from numerous sources; the coupling of this information with efficient tools for assessment and evaluation that allow broad, interactive participation in the planning, assessment, and decision

making process; and effective methods of communicating results and findings to a broad audience.

Information technology, and in particular, the integration of data base management systems, GIS, remote sensing and image processing, simulation and multi-criteria optimization models, expert systems, and computer graphics provide some of the tools for effective decision support in natural resources management.

The ultimate objective of a computer based decision support system for natural resources management is, or should be, to improve planning and decision making processes by providing useful and scientifically sound information to the actors involved in these processes, including public officials, planners and scientists, and the general public.

This decision relevant information must be:

- Timely in relation to the dynamics of the decision problem; depending on the nature of the problem (planning, training, operational management), this may imply for operational forecasting considerably better-than-real-time performance.
- Accurate in relation to the information requirements; this requires the use of state-of-the-art tools, methods, and models, and the necessary input data.
- Directly understandable and useful; this implies that the output of any formal, numerical method can be presented in a format that is directly and reliably understandable, that is graphical and symbolical, in multi-media formats rather than purely textual and numerical.
- Easily obtainable, i.e., cheap in relation to the problems' implied cost, which, however, in the case of coastal zone management may be considerable.

Decision support is a very broad concept, and involves both rather descriptive information systems as well as more formal normative, prescriptive optimization approaches. Any decision problem can be understood as revolving around a choice between alternatives. These alternatives are analyzed and ultimately ranked according to a number of criteria by which they can be compared; these criteria are checked against the objectives and constraints (our expectations), involving possible trade-offs between conflicting objectives. An alternative that meets the constraints and scores highest on the objectives is then chosen. If no such alternative exists in the choice set, the constraints have to be relaxed, criteria have to be deleted (or possibly added), and the trade-offs redefined.

However, the key to an optimal choice is in having a set of options from which to choose that which indeed contains an optimal solution. Thus, the generation or design of alternatives is a most important, if not the most important step. In a modeling framework, this means that the generation of scenarios must be easy so that a sufficient repertoire of choices can be drawn upon.

The selection process is then based on a comparative analysis of the ranking and elimination of (infeasible) alternatives from this set. For spatially distributed and usually dynamic models -- natural resource management and, as a member of this class, coastal zone management problems most commonly fall into this category -- this process is further complicated, since the number of

dimensions (or criteria) that can be used to describe each alternative is potentially very large. Since only a relatively small number of criteria can usefully be compared at any one time (due to the limits of the human brain rather than computers), it seems important to be able to choose almost any subset of criteria out of this potentially very large set of criteria for further analysis, and modify this selection if required.

Modeling for decision support, or model based decision support systems for environmental and resource management problems have been discussed and advocated for a considerable time (de Wispelaere, Schiermeier and Gillani, 1986; Fedra and Reitsma, 1990; Fedra, 1991; Holcomb Research Institute, 1976; Labadie et al., 1989 and Loucks, Kindler and Fedra, 1985). Success stories of actual use in the public debate and policy making process are somewhat more rare, in particular at the societal rather than commercial end of the spectrum of possible applications.

The specific role of integrated DSS, including models integrated with expert systems and GIS wrapped into interactive graphical user interfaces is primarily in their heuristic and didactic value. Graphical displays such as topical maps are an easy to understand form of communicating complex information. They can generate a widely accepted and familiar format for a shared information basis supporting an open debate.

Because of the complexity and high dimensionality of alternatives that include spatially distributed variables -- for example, the concentration of air pollution in a city or downwind of a major power plant (project) or soil erosion in a river basin affected by changing land-use -- the effective display e.g., as a topical map, is an important component of providing decision relevant information, and understanding the physical aspects of the decision problem. Similarly, the ability of expert systems to describe their function in terms of near-natural language rules and explain, step by step, their reasoning, supports understanding, and thus acceptance.

Analysis paradigms

Paradigms of analysis and decision support range from simple descriptive information systems that present the status quo to still descriptive, but analytic scenario analyses that answers WHAT-IF questions, and ultimately to prescriptive or optimization approaches. Resource management problems usually involve a mixture of natural science and engineering aspects, as well as socio-political and economic elements. While measurable phenomena and causal relationships characterize the former domain, the latter is better characterized by subjective or collective values and judgements, preferences, perceptions and expectations, and plural rationalities rather than a universal, agreed upon yardstick. And in the scientific and engineering domain, assessment also involves forecasting, designing and analyzing WHAT -- IF scenarios, which is an inherently difficult problem in almost any domain (e.g., Biswas and Agarwala, 1992; Colombo, 1992, and fraught with usually large uncertainties.

Coastal zone environmental and resource management problems are complex and multi-disciplinary in nature. They involve the need to forecast future states of complex systems often undergoing structural change, subject to sometimes-erratic human intervention. This in turn requires the integration of quantitative science and engineering components with socio-political, regulatory, and economic considerations. Finally, this information has to be directly useful for decision-making processes involving a broad range of actors. It seems obvious that no single method can address all these requirements credibly and satisfactorily. Another way of organizing the various approaches to management information systems, spatial analysis decision support is in terms of broad application areas and conceptual frameworks such as environmental impact assessment, risk assessment, or policy analysis.

Environmental impact assessment (EIA) is a well-known and widely applied assessment methodology. It is, by definition, project oriented, and designed, in its various stages, to identify, and compare, likely environmental consequences of a major development project. While not in itself a spatial analysis method, EIA increasingly draws upon the application of GIS and spatially distributed models to estimate impacts.

Similarly, in the domain of risk assessment, spatially explicit tools are being used (Fedra 1997). The European regulatory framework for technological risk is based on Directive EEC 82/501, its amendments (87/216 EEC, 88/610 EEC) and its latest version (96/82 EEC). The directives and their national implementations focus on information about risk, primarily substance oriented, as the central element of risk management. Within this framework, a number of specific classification criteria are defined for the reporting of accidents to the Commission; in addition to the substances involved, health and economic criteria, these include explicit spatial criteria such as:

Permanent or long-term damage to terrestrial habitats:

- 0,5 ha or more of a habitat of environmental or conservation importance protected by legislation,
- 10 or more hectares of more widespread habitat, including agricultural land

Significant or long-term damage to freshwater and marine habitats

- 10 km or more of river or canal,
- 1 ha or more of a lake or pond,
- 2 ha or more of delta,
- 2 ha or more of a coastline or open sea

Significant damage to an aquifer or underground water

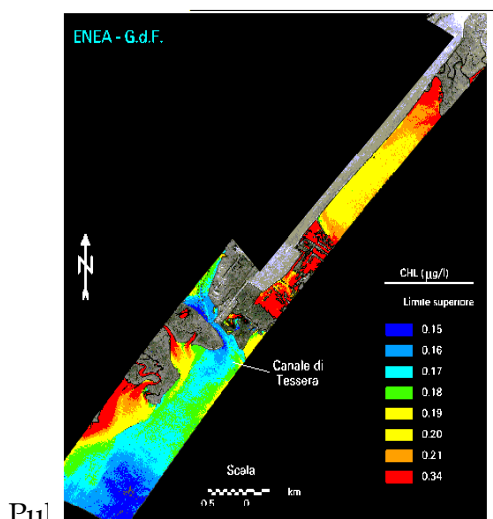
- 1 ha or more.

These classification criteria, however, are only used to classify accidents for reporting. Given the high concentration of industrial facilities in the coastal zone, risk assessment is of obvious relevance to integrated coastal zone management. An example of land-use planning around a coastal industrial site, using a multi-criteria approach, is presented by Papazoglou et al. (1997). In risk assessment, an important element is risk communication and perception, an obvious application domain for GIS and topical maps. Carvalho and Coelho (1997) discuss coastal risk perception in a case study of the Aveiro district in Portugal, with coastal erosion as the main area of concern.

Application Examples

Applications of GIS and spatial models to coastal zone management problems span a wide range of issues. At the recent MEDCOAST 97 conference (September 11-14, Qawra, Malta) an entire section of the proceedings (Özhan 1997) is specifically dedicated to GIS and remote sensing applications. The section includes remote sensing applications, primarily based on CZCS (Coastal Zone Color Scanner) primarily analyzing surface water colors and temperature, in an attempt to locate and quantify historical trends (Barale and Zin, 1997) and terrestrial influences, respectively. Mapping of biological marine resources using GIS technology is described by Gaofalo et al. (1997), who create, and overlay, a set of topical maps centered on 36 target species of fish, crustaceans and cephalopods. Meaden and Do Chi (1996) describe the general applicability of GIS to fisheries. Also Abdel-Aal, (1992) addresses the modeling of shoreline change phenomena. Other sources of remote sensing data include airborne digital photographic systems (Curr et al., 1997) or side-scan sonar for benthic littoral surveys (Pasqualini et al., 1997). A more methodology oriented example is given in Romao et al., (1997). They discuss multi dimensional visualization tools in coastal zone management, using an oil spill model as an example of a dynamic, process-oriented components integrated in a GIS environment.

The above examples all refer to classical GIS applications with basically static data layers and overlay analysis as the major analytic method, mapping of resources the main objective. More complex analyses require the integration of various models. The integration of coastal water quality models dealing with the water quality consequences of the design and location of ocean (waste water) outfalls is described in Fedra (1994). The system was implemented for a number of locations in the Irish Sea, with a case study for Swansea Bay. The Swansea Bay area is heavily industrialized, leading to water quality problems not only from domestic wastewater and sludge with organic material, BOD, and coliform bacteria, but also from several industrial sources containing heavy metals (Collins et al., 1980). An example of application of a GIS for analyzing spatial pattern of industries in a coastal industrialized area of NE Italy to assess surface water pollution is given by Altobelli et Al. (1996). Another one with several remote sensing applications is given for the Venice Lagoon by Borfecchia et Al. (1997), (Figure 2(a,b)).



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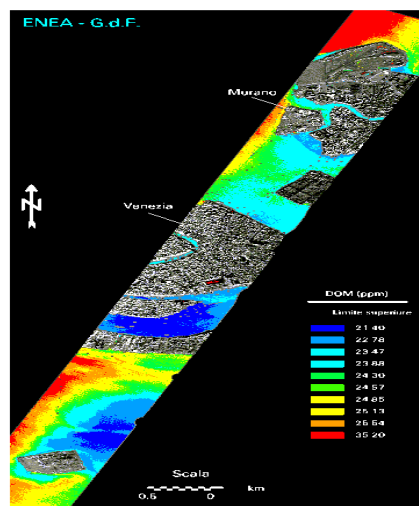


Figure 2(a,b) *Examples of the distribution and concentration of dissolved organic matter (DOM) in two localities of the Venice Lagoon.*

Recent applications of simulation models in this field include, for example, Lewis and Riddle, (1989) and Krohn et al., (1991). Mates and Scheinberg (1991) discuss a model with emphasis on recreational activities, and Barnes (1988) looks at non-point sources and a cartographic approach. A food chain model for PCB accumulation is presented by Connolly (1991), and Reed et al., (1989) discuss a complex model system, namely the Natural Resource Damage Assessment Model System for Coastal and Marine Environments that is primarily oriented towards accidental spills. Economic aspects in the case of effluent charges and chlorine residuals from the forest industry polluting the Baltic Sea are considered by Hultkrantz (1991).

The model system for Swansea Bay simulates the fate and distribution of various types of pollutants, such as conservative tracers, BOD, or coliform bacteria from one or several outfalls or offshore dumping locations.

The system includes in a structure memorized in **figure 3**:

- A data base of these major sources of pollution, e.g., wastewater treatment plants and outfall pipelines, linked to
- Geographical information system (GIS) components that can manage spatial data such as land-use information or bathymetry, as well as observational data, such as flows, tidal records, or water quality measurements;
- An interactive and graphical interface to both model scenario editors as well as for running the models visualizing the dynamic model output; coupled to
- The scenario editors, an embedded expert system for scenario editing and parameter estimation; and as a post-processor of model results,
- An expert system for impact assessment; coupled with both the expert system's rule base as well as the editor functions and
- The overall help and explain functions, a hypertext system for additional textual information.

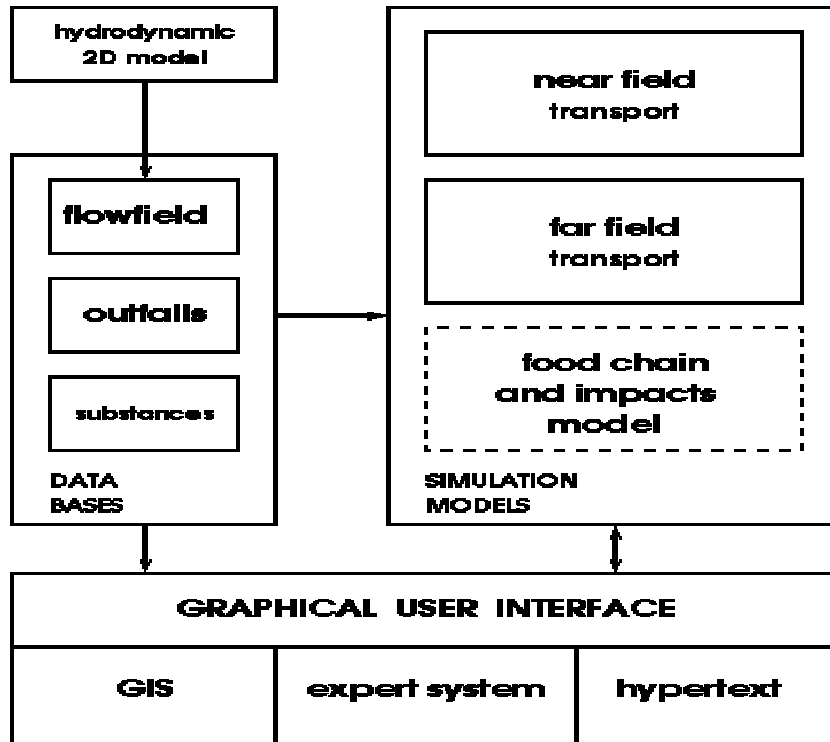


Figure 3: Integration example of simulation models with a GIS

A similar, more recent application involves POM; the Princeton Ocean Model to the Saronikos Gulf in Greece, as part of the ECOSIM Environmental Telematics project (<http://www.ess.co.at/ECOSIM>). The Saronikos gulf is a semi-enclosed coastal sea lying to the south of Athens, a city of 3.5 million population. 720,000 m³ of domestic wastes per day are released inside the Inner Gulf through the Central Metropolitan Outfall after undergoing secondary treatment. Further to that, industrial wastes are discharged in the Elefsis Bay in the northern part of the gulf.

The coastal water model is based on the well-known academic community model, the Princeton Ocean Model (POM). POM is a sigma-coordinate, 3-D thermodynamically active model that has been primarily designed for coastal water studies. A research group at the University of Athens has developed a new module of POM for the dispersion of passive tracers. The scheme can simulate several surface and subsurface sources with different pollutant load (**figure 4**). This module has been tested in several areas and has been proved to be an effective tool for monitoring the fate of tracers in the coastal environment. The sources can be either point sources (e.g. rivers, sewage...) or linear-sources (landfills).

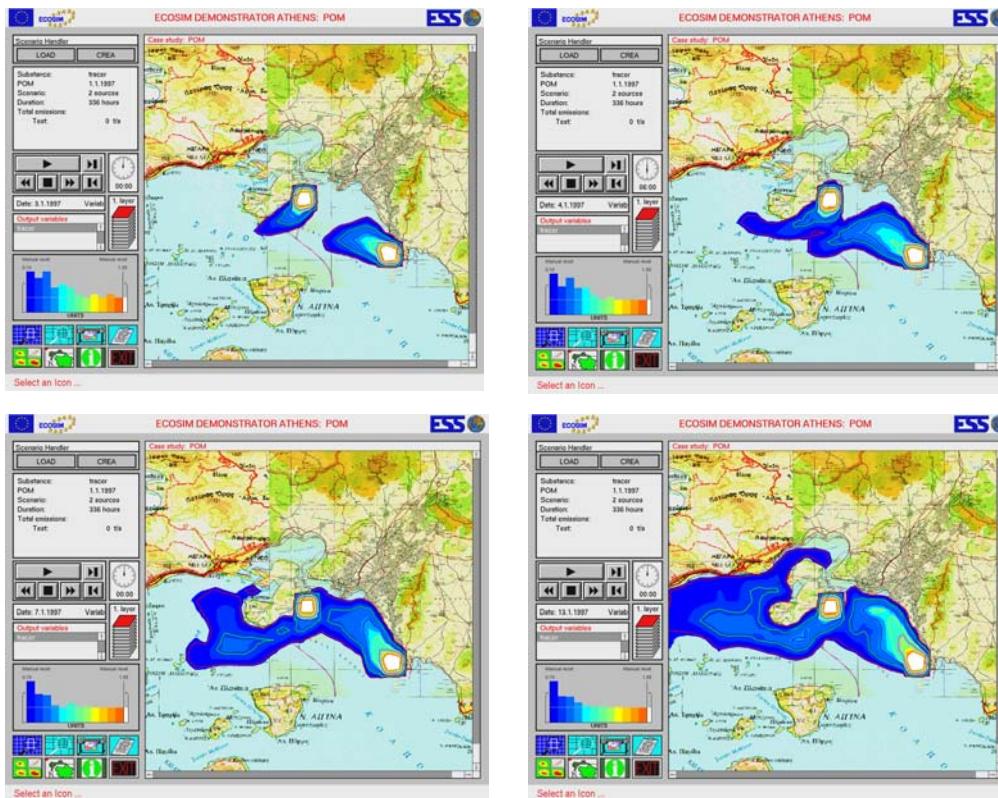


Figure 4: Animation of dynamic model results as map overlays

A similar approach of coupling a hydrodynamic and pollutant transport model with a GIS is described by Tsanis and Boyle (1997), while Durand et al. (1997) use SPOT satellite derived maps of suspended matter to compare with their 3D numerical study of the Ebro delta zone hydrodynamics.

Direct applications to overall management issues are rare; Anderson and Skrizhevskaya (1997) describe an ambitious approach that also is supposed to include socio-economic aspects in an integrated coastal management approach for the Ukrainian Black Sea Region, where they associate with a list of ICM issues the corresponding GIS activities (**figure 5**).

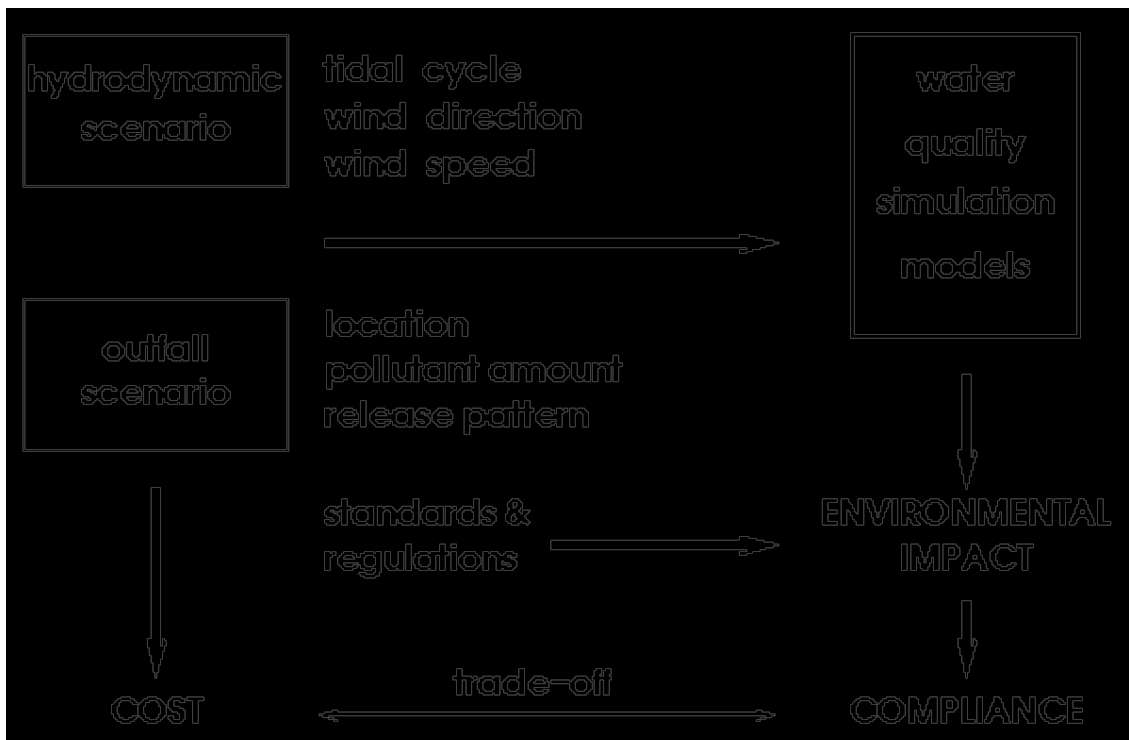


Figure 5: Integrating spatial analysis in a management framework

Discussion

Integrated coastal zone management is an inherently and increasingly complex task. To provide formal yet practical decision support requires a new approach, that supports a more open and participatory decision making process. A new paradigm of man-machine systems is needed where the emphasis is no longer on finding an optimal solution to a well-defined problem, but rather to support the various phases of the problem definition and solving process.

Problem owners and various actors in the decision making process have a central role; supporting their respective tasks requires man-machine interfaces that are easy to use and easy to understand: the paradigm of the thematic map offered by GIS is a powerful tool for this purpose. The map provides a familiar, and visually attractive and easy to interpret framework that integrates other, often more abstract information well.

An effective decision support system must first of all provide a common, shared information basis, framework and language for dialogue and negotiation. The dialogue between the actors in the decision making process is extended to a dialogue with the DSS, which plays the role of a technical expert and bookkeeper rather than an arbiter.

This requires that information provided is adequate for and acceptable to a broad range of users involved in the respective assessment and decision making processes, including analysts, technical managers, regulators and

policy makers, as well as the affected citizen, interest groups and the general public(Sundeep and Walsham, 1997).

An information system that can cater to all these needs must be based on more than good science and solid engineering. It requires a number of special features as well as an approach that takes psychological and institutional aspects as well as scientific and technical ones into account.

From a technical point of view, many of the basic tools are available, the underlying concepts well developed. And new technologies such as wide area networks and in particular the Internet, globally distributed client-server applications, multi-media and virtual reality, and their promise of easy access to potentially large volumes of information are rapidly becoming available. Of course, many problems such as the availability and quality of data remain and will always remain, since new and emerging problems will always require new data. Uncertainty of data and models and the limits of predictability are inherent in the study of natural systems, and decision support systems must address and communicate this uncertainty to make it a useful component of decision-making strategy rather than a problem.

The need for better tools to handle ever more critical environmental and resource management problems is obvious, and the rapidly developing field of information technology can provide the necessary machinery. The integration of models and geographic information systems, expert systems, and interactive graphics, generating a virtual reality version of the decision problem, is a promising and challenging development in environmental systems analysis, strategic decision support, and applied informatics. Integrated coastal zone management is one obvious, and promising, application domain. The biggest challenge, however, seems to be the integration of new information technologies and more or less mature formal methods of analysis into institutional structures and societal processes, that is, putting these tools to work in practice.

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